Impact of Winter Cooling on Water Vertical Entrainment and Intensity of Phytoplankton Bloom in the Black Sea

E. A. Kubryakova*, A. A. Kubryakov, S. V. Stanichny

Marine Hydrophysical Institute, Russian Academy of Sciences, Sevastopol, Russian Federation
*e-mail: elena_kubryakova@mail.ru

Vertical entrainment of nutrients and phytoplankton from the subsurface layers in autumn – winter is a cause of the surface phytoplankton bloom in the Black Sea in winter. Relationship of the winter heat flux and the sea surface temperature (SST) with the integral and surface phytoplankton biomass is assessed based on a series of simulations performed due to a 1D-biogeochemical model. The results show that during severe winters, intensity of phytoplankton bloom is 50% higher than that in warm winters. Winter entrainment of nutrients influences the phytoplankton biomass in the subsurface layer in summer, namely, after cold winters its maximum value exceeds the analogous one after warm winters by ≈30%. In-situ data is used to estimate the relation between the upper mixed layer depth and density, and the integral concentration of nitrates and phosphates in various regions of the basin. It is revealed that growth of the upper mixed layer density from 1014.0 to 1014.2 kg/m^3 results in increase of the integral concentration of nutrients in the upper layer by 2–2.5 times in the center and on the periphery of the basin; and when the density value achieves 1014.5 kg/m^3 the integral concentration becomes higher by 4–5 times. Thus the upper mixed layer density serves a good indicator of intensity of the nutrients inflow to the sea upper layers. Impact of winter cooling upon the upper mixed layer density is investigated using the model and *in-situ* data. It is shown that density equal to 1014.2 kg/m^3 is achieved in the basin center at SST 7.5–8° C, and on the sea periphery – at 6.5° C. The maximum density value 1014.8 kg/m^3 is recorded in the center of the sea (depth exceeds 2000 m) at SST < 5.5° C. During the same atmospheric conditions, the vertical nutrient transport is different in various regions of the Black Sea, which can affect the spatial features of bloom intensity in the basin.

Keywords: Black Sea, winter cooling, vertical entrainment, upper mixed layer, biochemical modeling.

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Introduction. The study of the Black Sea biological productivity changes related to the physical processes is necessary to understand the functioning of the basin ecosystem under conditions of changing climate. Remote and in-situ data of recent years indicate that phytoplankton bloom and the highest concentrations of chlorophyll *a* in the Black Sea surface layer related to it are observed in autumn-winter period [1–4]. At this time winter convection and intensive wind mixing result in the entrainment of deep waters into the sea surface layer [4]. When the upper layer density approaches the one of the upper boundary of the layer of the maximum concentrations of nitrates and phosphates, nutrients are actively entrained into the euphotic layer. Due to strong haline stratification, in the Black Sea the maximum mixed layer depth are, on average, small (≈ 50 m in the central part of the basin). Therefore, the illumination in the mixed layer is, in most cases, sufficient for the division of phytoplankton cells [5]. One more cause of chlorophyll *a* surface concentration increase in autumn-winter period is the phytoplankton entrainment from the layer of its subsurface maximum, which is located at 20–40 m depths in the warm period of the year [6–8].

In a number of works [3, 4] it was shown that interannual variability of chlorophyll *a* concentration is closely related to the minimum winter temperature of the sea surface (SST) which is an indicator of winter severity and vertical mixing intensity. The bloom of phytoplankton, for example coccolithophores, in the warm period of the year significantly depends on winter cooling and on the amount of nutrients supplied during the winter, the phosphates in particular [9, 10]. Among other important mechanisms of nutrient supply, horizontal cross-shelf transport can be noted. It significantly affects interannual changes in chlorophyll *a* concentration [11–15].

The amount of available in-situ data is limited in winter, and satellite measurements provide information only about chlorophyll *a* concentration on the surface. For this reason, the relationship between the winter cooling intensity, vertical entrainment and biological productivity of the basin has not been adequately studied. Under such conditions one-dimensional physical-biogeochemical models serve as convenient tools for studying the vertical water exchange effect on the ecosystem functioning [see, for example, 16].

In [17], rather weak connection between the upper mixed layer (ML) and thermal characteristics was noted, which is due to the effect of dynamic factors on the pycnocline position. As the distribution of chemical elements over the depth in the Black Sea is tied to isopycnals, the mixed layer density is a convenient indicator of the intensity of nutrient entrainment into the vertical water exchange. In this work the effect of winter cooling on the ML density, vertical entrainment of waters and the variability of the phytoplankton biomass in the Black Sea is studied on the basis of satellite measurements of temperature and chlorophyll *a* concentration, hydrological measurements, the data obtained from Bio-Argo floats and a series of model calculations.

Data and methods. In this study the daily maps of chlorophyll *a* concentration and SST with 4 km spatial resolution are analyzed on the basis of *MODIS-Aqua* spectroradiometer measurements from 2004 to 2013. Chlorophyll *a* concentration is calculated according to standard *OC*3*M* algorithm [18]. The data are downloaded from *NASA's OceanColor Web* archive [19]. In autumn-winter period chlorophyll *a* concentration calculated by this algorithm can contain significant errors partially related to the impact of cloudiness. To filter these errors, an algorithm described in [15] was applied.

Historical array of hydrologic and hydrochemical measurements of the Bank of Oceanographic Data of Marine Hydrophysical Institute (BOD MHI) (URL: http://www.mist-mhi.ru/) from 1990 to 2015 [20] is also used. The data on vertical temperature distribution, salinity, concentration of nitrates (NO_3) and phosphates (PO_4) were studied.

The measurements of temperature and salinity profiles by the data from *Argo* profiling floats over 2004–2017 are also analyzed. Moreover, the measurements of three Bio-Argo floats for the period from 2014 to 2017, which provided the data on vertical distribution of chlorophyll *a* concentration with high vertical resolution (1 meter) [21], were taken. The data were downloaded from *IFREMER* archive [22].

One-dimensional physical-biogeochemical model is applied in the work to study the winter cooling effect on vertical structure of the basin and phytoplankton bloom. It includes hydrodynamic block constructed on the basis of *Princeton Ocean Model* (*POM*) [23] and biogeochemical one developed on the basis of one-dimensional model. There is a one-way relationship between the blocks: vertical turbulent diffusion coefficient and temperature obtained in the hydrodynamic part are used as input parameters for calculation of biogeochemical characteristics. Diatomic algae and flagellates, bacterial plankton, micro- and mesozooplankton, *Noctiluca* are among them. In addition, this model includes chemical elements that take part in the nitrogen cycle and oxidation-reduction reactions. More details are given in [24, 25]. Seasonal variability of atmospheric parameters for model calculations was determined from the data of *ERA-40* reanalysis carried out at the European Center for Medium-range Weather Forecasts (*ECMWF*) with a time discreteness of 6 hours [26].

Winter cooling impact on phytoplankton bloom intensity according to satellite data and results of numerical experiments. Seasonal variability of SST and chlorophyll *a* concentration obtained from *MODIS-Aqua* data and averaged over the deep part of the basin (the depths > 500 m) is in anti-phase. High values of chlorophyll *a* concentrations (0.9–1.0 mg/m^3) are characteristic of the period of low SST and are observed from November to February, and the minimum ones (0.5–0.6 mg/m^3) fall on July (Fig. 1, *a*). In cold period of the year vertical mixing related to the surface cooling and impact of storms is intensified in the Black Sea. At first, the mixing causes phytoplankton entrainment from the layer of its subsurface maximum (20–40 m depths) in October – December and then – an intensive flux of nitrates and phosphates from the lower layers. In winter these two processes lead to the occurrence of chlorophyll *a* maximum concentration on the surface in the Black Sea central part. This maximum is recorded by both satellite [1–4] and field [27] measurements.

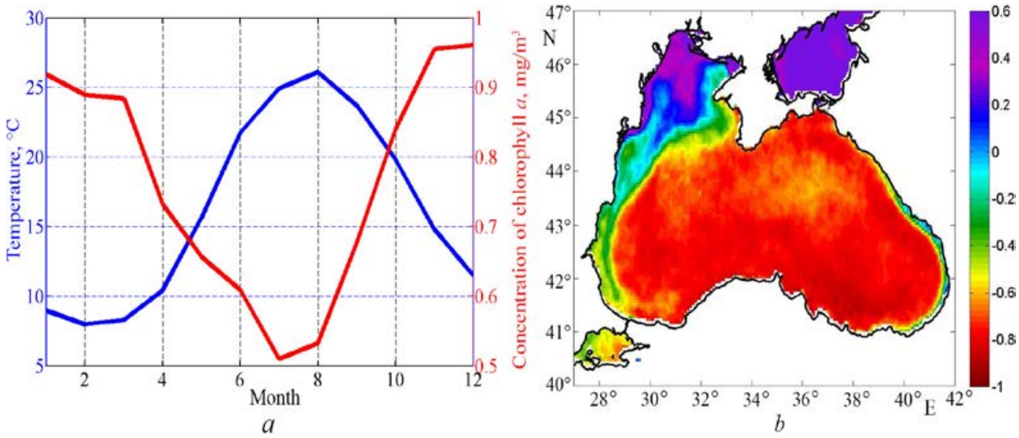

Fig. 1. Seasonal variability of the chlorophyll *a* concentration and the surface temperature in the deepwater part of the sea (> 500 m) (*a*); map of the correlation coefficient between the chlorophyll *a* concentration variability in each point of the sea and the basin-average sea surface temperature (*b*)

In Fig. 1, *b* the map of coefficients of correlation between the chlorophyll *a* concentration in each point of the sea and a mean SST over the basin is shown. The series were smoothed by low-frequency 30-days filter and the main part of the signal is seasonal variability. For the main part of the basin, high negative correlation values (from –0.8 to –1.0) are typical. They testify that for the mentioned areas vertical winter entrainment is the main factor causing the surface phytoplankton bloom in the Black Sea. Exceptions are the shelf zones which are under effect of coastal runoff of large and medium rivers at the north-western shelf and in the south-eastern part of the sea. In these regions chlorophyll *a* concentration correlates well with river runoff variability at a seasonal scale. The maximum values are observed in April – May when the rivers carry out the maximum amount of organic and inorganic substances [3, 27].

Satellite data provide data on chlorophyll *a* concentration variability only in the upper layer of the sea. However, in the summer period the highest concentrations are in the thermocline layer and below it [6, 7, 27, 28]. Recently (from 2014), three Bio-Argo floats with bio-optical gauges were deployed in the deep part of the Black Sea. On the basis of fluorimetrical measurements, these instruments provide information on the vertical distribution of chlorophyll *a* concentration with high vertical resolution (10 days, 1 m by the depth). According to these data, seasonal variability of chlorophyll *a* integral concentration averaged over 0–60 m layer (blue line in Fig. 2, *a*) was calculated. Seasonal variability of chlorophyll *a* integral and surface concentrations have a number of differences. The peak of integral chlorophyll *a* concentration fall on March, and according to in-situ data [27] it is observed in February – March. Then follows a sharp minimum in April probably related to grazing and/or mass die-off of phytoplankton on the background of intense warming, leading to a cessation of nutrient flow into the upper layer. According to the in-situ data [27], on average over 1973–1997 the minimum values of integral chlorophyll *a* concentration were observed in May.

According to data of Bio-Argo floats, the second pronounced maximum caused by chlorophyll *a* concentration increase in 15–35 m layer is observed in August. Such an increase in summer was also recorded according to data of field observations [27, 29]. In September – October chlorophyll *a* concentration decreases, and from November it begins to grow. In winter (December – March) high integral values of chlorophyll *a* concentrations are recorded, which corresponds to the data of measurements [27].

In order to study the winter cooling impact on the phytoplankton bloom in the central part of the sea, a modification of 1D-biogeochemical model [16], presented earlier in [24], was applied. A detailed parameterization of processes in the model is given in [16, 24]. Variability of atmospheric parameters was set on the basis of climate fields obtained from *ERA*-40 reanalysis data over 1971–2001 for the deep part of the Black Sea (the depths > 500 m). These fields were used to carry out 60-years climate calculation of the Black Sea biogeochemical parameters. Periodic solution achieved during the last 30 years of calculation is determined as a basic one in this work.

In this work diatoms are considered as the dominant group of phytoplankton in the Black Sea [8]. Fig. 2, *b* shows the seasonal variability of their surface and integral biomass, as well as the vertical distribution of these parameters from the model data (Fig. 2, *c*). Variations of the surface and integral biomass correlate rather well with the data of in-situ and satellite observations on the chlorophyll *a* concentration. The maximum of diatom biomass concentration on the surface falls on December – February, and on average in the water column – on January – March. In [30, 31] the maximum of diatom biomass was also recorded in March. The lowest diatom biomass values are characteristic of the sea surface in the warm period of the year, from April to September. This correlates with a satellite data on the chlorophyll *a* concentration [1–4]. The minimum value of the integral concentration is observed in April – May, and in July – August a secondary maximum is observed, which agrees with the description of phytoplankton dynamics in [8]. However, the summer maximum in the model is somewhat lower than the one according to the data of Bio-Argo floats which must be related with the fact that cross-shelf exchange with nutrients (which intensifies in summer period) was not taken into account in 1D-model. In Fig. 2, *c* the main features of vertical phytoplankton distribution (winter phytoplankton bloom, covering the entire mixed layer, and a subsurface maximum in the layer below 25 m in summer) can be clearly seen. These features are in good agreement with the data of Bio-Argo floats which reveal a subsurface peak of chlorophyll *a* concentration in the thermocline layer, as well as with the results of phytoplankton dynamics modeling in the Black Sea obtained in previous research [16, 31]. It should be pointed out that the presented results do not fully reconstruct the basin ecosystem variability because such important factors as coccolithophoride bloom, the dynamics of phosphates, etc. are not taken into account in the calculations. Nevertheless, for the purposes of this work the main features, such as winter bloom and the subsurface maximum in summer are reconstructed rather well in model calculations with the simplifications.

In order to study the winter cooling impact on phytoplankton development the model experiments with different heat fluxes in a cold period (Fig. 3, *a*) were carried out. Positive values of heat fluxes correspond to the winter period, i.e. the flux is directed from the sea to the atmosphere: positive values correspond to cooling, negative – to warming. Positive values of heat fluxes corresponding to cooling were multiplied by k coefficient equal to 0.5; 0.75; 1.0; 1.25; 1.5; 1.75 in different experiments, i.e. the heat fluxes increased and decreased concerning the basic one (black color in Fig. 3, *a*) by 25, 50 and 75%, respectively.

SST seasonal variability at different variants of calculation is given in Fig. 3, *b*. The values of the minimum SST vary from 3.5° C in the experiment with k = 1.75 to 9.5° C in the experiment with k = 0.5. It should be noted that real variations of the heat flux in the Black Sea region are smaller, and the observed range of the minimum SST in the central part of the sea is 5–9° C, which corresponds to the experiments with k = 0.5–1.25. It was decided to carry out the calculations with larger changes in heat flux values in order to demonstrate more illustrative relationship between the surface temperature and the phytoplankton biomass.

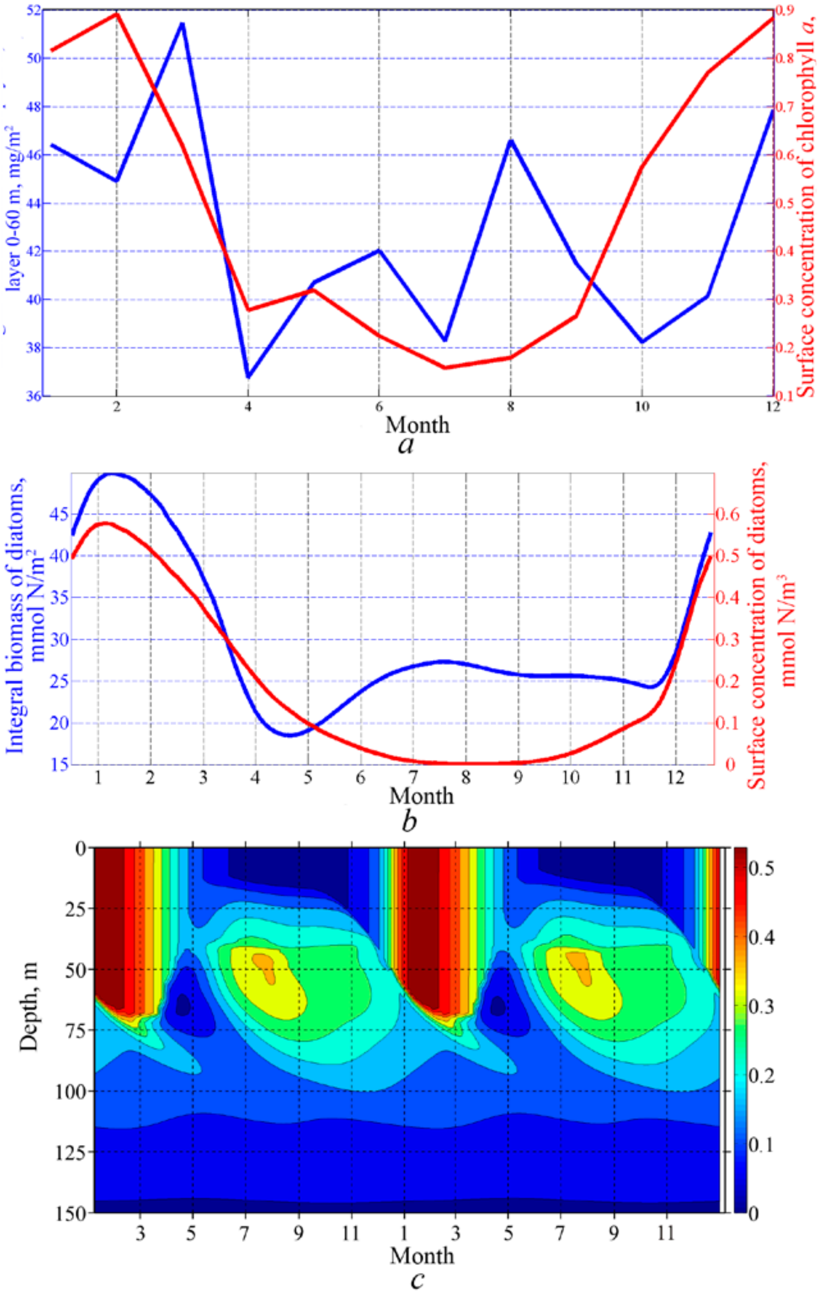

Fig. 2. Seasonal variability of (*a*) the chlorophyll *a* concentration: integral one over the 0–60 m layer (blue line) and on the surface (red line) calculated using the Bio-Argo floats measurements, (*b*) the diatom biomass: integral one (blue line) and on the surface (red line) based on the model data, and (*c*) modelled vertical distribution of the diatom biomass with depth, mmol N/m^3

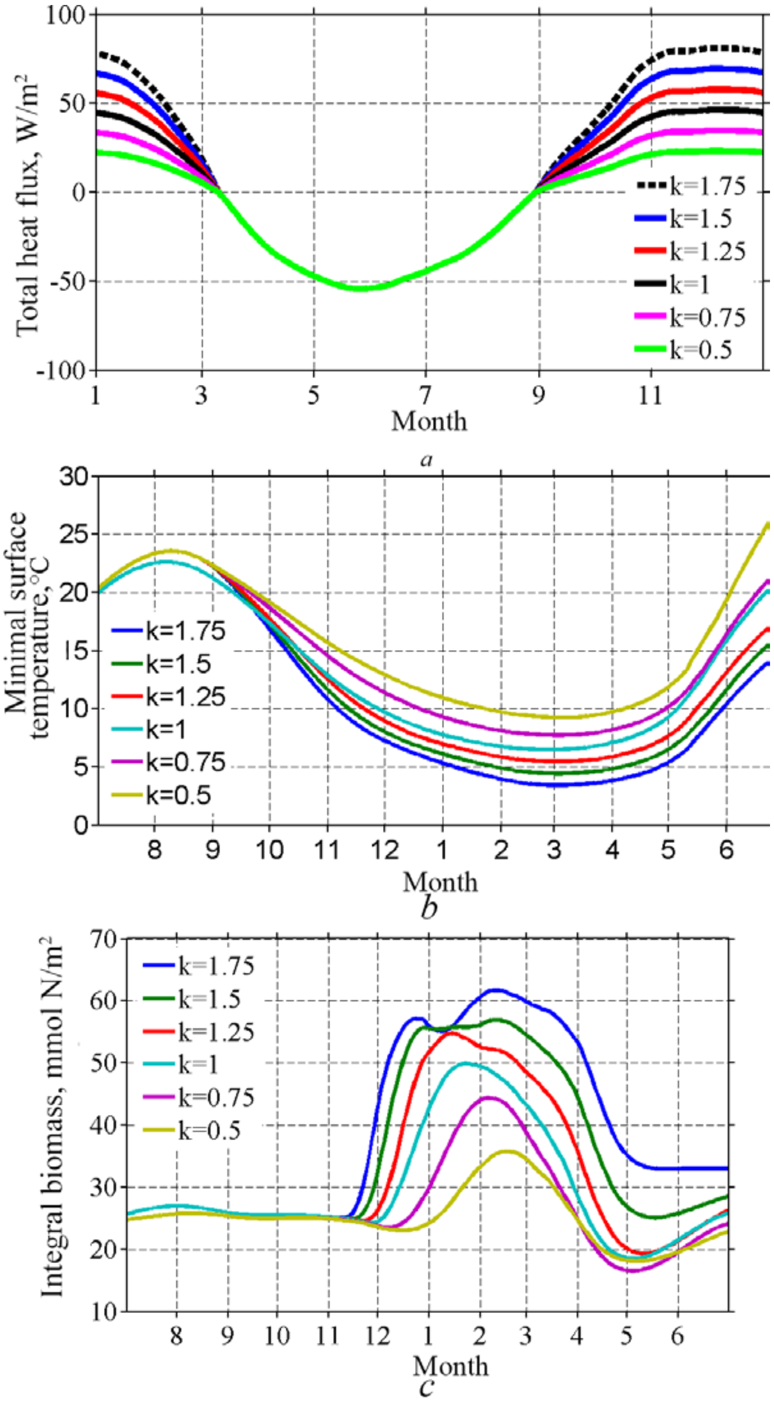

Fig. 3. Seasonal variability of heat fluxes (*a*), the minimum surface temperature (*b*) and integral diatom biomass (*c*) for various model experiments

In Fig. 3, *c* seasonal variability of phytoplankton integral mass according to the results of the performed experiments is represented. The colder is the winter, the more biogenic elements are entrained into the upper layers and the more is the phytoplankton integral biomass. The maximum value of integral biomass varies from 55.0 mmol N/m^2 for the experiment with k = 1.5 to 35.0 mmol N/m^2 for the experiment with k = 0.5. Except for the experiment with k = 1.75 (very cold winter with the minimum SST equal to 3.5° C), all the experiments indicate the presence of one main maximum of the phytoplankton biomass. In cold winters the peak of phytoplankton bloom is observed earlier than in warm ones.

Within 5–9° C temperature range the dependence of the maximum integral biomass of diatoms on the minimum SST is a linear function (Fig. 4, *a*). At the same time, the growth of the maximum surface biomass of diatoms reduces at the temperature decrease (Fig. 4, *b*) as the phytoplankton is redistributed over a larger layer when vertical mixing increases.

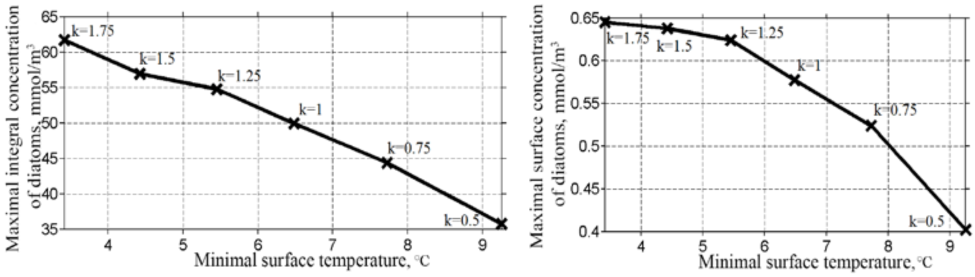

Fig. 4. Dependence of the maximum integral (*a*) and the maximum surface diatom biomasses (*b*) upon the minimum surface temperature

Model estimates reveal that variation of winter heat flux on ≈25% changes the biomass of diatoms on ≈10%. When the minimum temperature decreases from 9 to 5° C the integral biomass increases in 1.5 times from 36 to 56 mmol N/m^2, and the surface one – from 0.4 to 0.6 mmol N/m^2. Thus, when winter changes from the normal (7° C) to the severe one (5° C), phytoplankton biomass will be higher by ≈25%, and at the change from warm (9° C) to severe winter – by ≈50%.

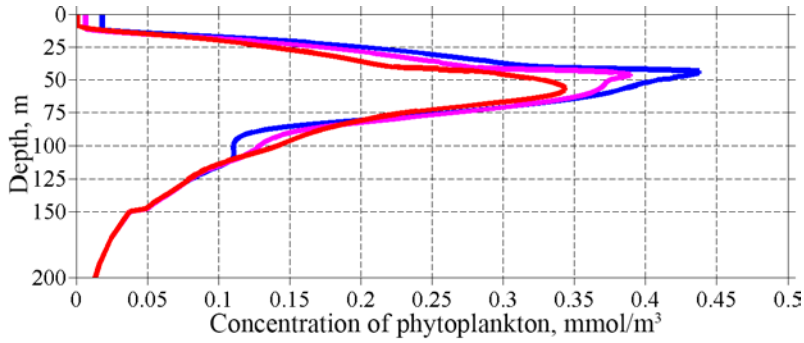

Fig. 5. The diatom concentration profile for July for different experiments: blue line – at k = 1.25 (cold winter), purple line – at k = 1 (basic calculation) and red line – at k = 0.75 (warm winter)

The impact of winter cooling intensity is indicated by the model calculations not only during the maximum of bloom, but also in the following months, including the summer. The examples of vertical distributions of diatoms for July following the cold (k = 1.25), "normal" (k = 1.0) and warm (k = 0.75) winter are shown in Fig. 5. In the subsurface peak the phytoplankton biomass increases from 0.33 to 0.38 and 0.44 mmol N/m^3 for k, equal to 0.75; 1.0; 1.25, respectively. In summer, in a layer of subsurface maximum and on the surface the phytoplankton concentration is higher after the coldest winters, as more nitrates are regenerated after a rapid winter bloom. Thus, the calculations show that winter conditions also affect the characteristics of summer phytoplankton bloom. It should be noted that in real conditions in the spring-summer period the cross-shelf exchange of nutrients also has a significant impact on the bloom [14, 15], which is not taken into account in this model.

Winter convection impact on the entrainment of deep waters in different regions of the Black Sea. The Black Sea is highly stratified basin and the distribution of chemical elements in them is closely connected with the location of isopycnic lines [32] which can significantly vary depending on vertical movement of waters related to the basin dynamics. The depth of ML (H) in winter also significantly depends on dynamic conditions because sharp pycnocline largely limits vertical mixing [17]. When the ML density reaches the value corresponding to the upper boundary of the maximum layer of nutrients, their entrainment into the upper euphotic layer begins. In 1D-model spatial variability of isopycnic lines is not taken into account. In order to estimate the cooling impact on entrainment of waters in different regions of the Black Sea, a historical array of hydrological and hydrochemical measurements from BOD MHI was used. In Fig. 6, *a* the profiles of NO_3 and PO_4 concentration (averaged over 1990–2015) and their ratios NO_3/PO_4 constructed with respect to the density of waters are shown. The obtained distributions correspond to the known results of previous works [see, for example, 32]. The peak of nitrate concentration is within 1014.2–1016.0 kg/m^3 density interval and it reaches its maximum value (equal to 4 $mmol/m^3$) on 1015.5 kg/m^3 isopycnic line. Phosphate concentration begins to increase smoothly in the layers of more than 1014.2 kg/m^3 density, reaching its intermediate maximum (1.2 $mmol/m^3$) in the oxygen zone at 1015.6 kg/m^3 density. Below, in sub-oxygen and hydrogen sulfide zones PO_4 phosphate concentration sharply increases. The value of NO_3/PO_4 ratio increases from 5.5 to the maximum equal to 6.3 for 1014.2 $mmol/m^3$ density (at 35–50 m depths) and then it begins to decrease. The features of the Black Sea chemical structure and their causes are considered in detail in [32].

Mean vertical density distribution in the Black Sea characteristic of different isobaths (1000–2200 m) (Fig. 6, *b*) was calculated by hydrologic data. The obtained distribution corresponds with previously described results [20]. Cyclonic circulation in the basin results in the raise of isopycnals in the deep part of the sea and lowering in the continental slope area. For instance, for 2000 m isobath isopycnal ρ = = 1014.5 kg/m^3 is situated, on average, at 50 m depth and for 1000 m isobath it is situated 20 m deeper – at 70 m depth.

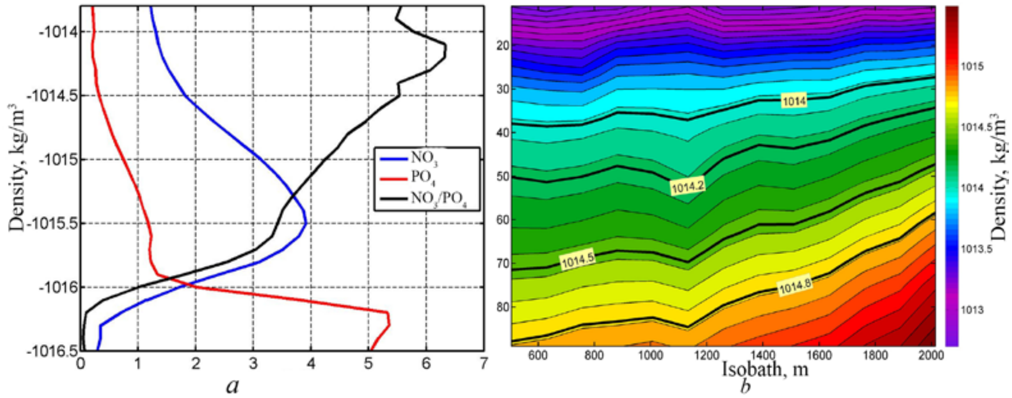

Fig. 6. Averaged over 1990–2015 profiles of concentrations of nitrates NO_3, mmol/m^3 (red line) and phosphates PO_4, mmol/m^3 (blue line), and their ratios NO_3/PO_4 constructed relative to water density (*a*); average vertical density distribution for various isobaths (500–2200 m) in the Black Sea (*b*)

Taking the isopycnic character of nitrate and phosphate distribution [32], a similar diagram for different isobaths can be also constructed for the concentration of nitrates and phosphates. Further, in order to estimate the impact of mixing on the entrainment of nutrients, integral values of nutrient concentration at different ML H depths, i.e. in 0–10 m, 0–20 m, etc. layers, were calculated. Thus, the dependences of mean nitrate concentration and integral phosphate concentration (Fig. 7, *a*, *b*) in the ML on the depth H for different isobaths of the Black Sea were obtained. It is obvious that in the central part of the sea where pycnocline is closer to the surface, the concentrations of nutrients will be higher than in the continental slope area at the same values of H. For example, at H = 30 m mean concentration of NO_3 (Fig. 7, *a*) and PO_4, which determines the rate of phytoplankton growth, will be 0.15 and 0.03 mmol/m^2 for 1000 m isobath; 0.23 and 0.04 mmol/m^2 for 1500 isobath; 0.4 and 0.07 mmol/m^2 in the central part of the sea (2100 m isobath). NO_3 integral concentration at H = 30 m will be 2.4; 3.6 and 6.4 mmol/m^2, PO_4 – 0.4; 0.7 and 1.1 mmol/m^2 (Fig. 7, *b*) for 1000, 1500 and 2100 m isobaths, respectively.

Having analyzed NO_3/PO_4 ratio change with the mixing depth for different isobaths, it can be noted that the ratio value rises at the increase of depth value H to 35, 45 and 50 m for 2200, 1500 and 1000 m isobaths, respectively, and then it begins to decrease. Thus, at the same values of the depth H an amount of entrained nutrients can vary several times in different regions of the sea. These differences are due to spatial inhomogeneity of density vertical distribution significantly related to the dynamics of waters.

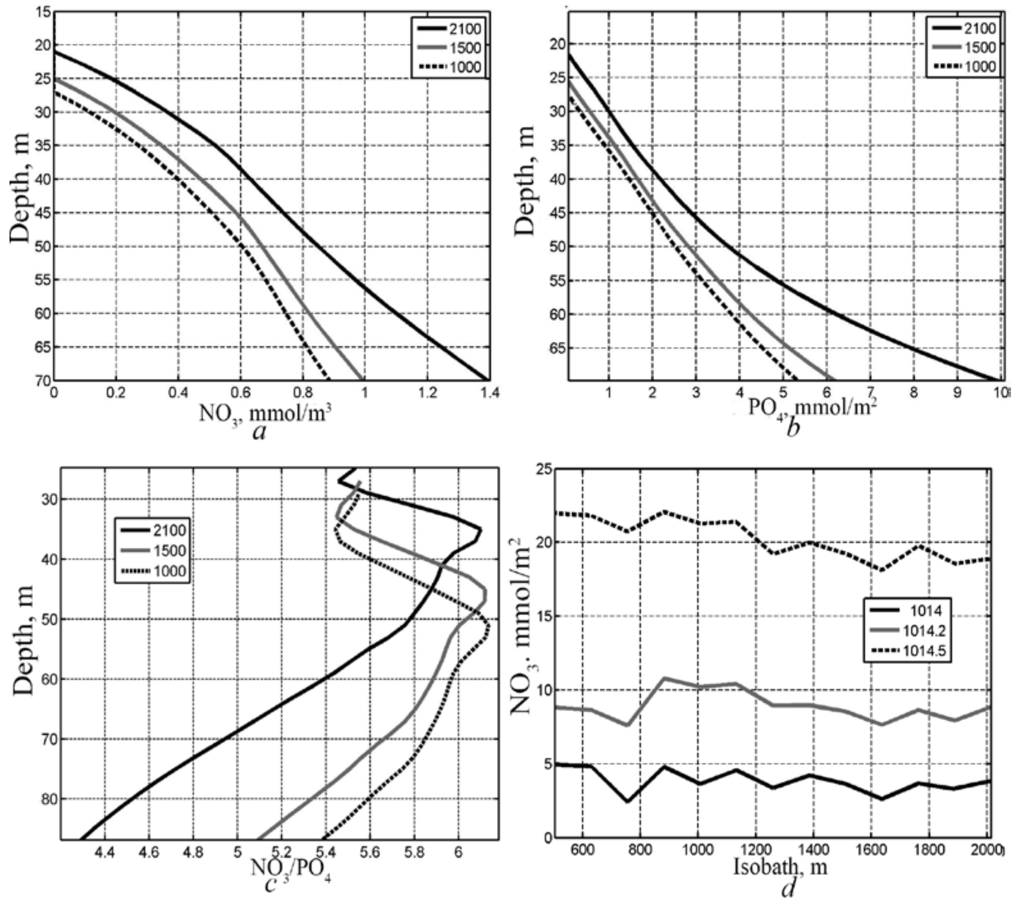

Fig. 7. Dependence of average concentration of nitrates NO_3, mmol/m^3 (*a*), integral concentration of PO_4, mmol/m^2 (*b*) and the relation NO_3/PO_4 (*c*) in the upper mixed layer upon its depth for various isobaths of the Black Sea (black dashed line denotes 1000 m, grey solid line – 1500 m and black solid line – 2200 m); integral concentrations of NO_3 (*d*) in the layer above the ispoycnal 1014.0 kg/m^3 are marked by black dashed line, 1014.2 kg/m^3 – grey solid line and 1014.5 kg/m^3 – black solid line

In order to estimate the relation of entrainment of nutrients and the ML density, integral concentrations of NO_3 and PO_4 in the layer located above the isopycnals (1014.0; 1014.2 and 1014.5 kg/m^3) were calculated. At the ML density equal to 1014.0 kg/m^3 integral concentrations of NO_3 Fig. 7, *d*) and PO_4 for different isobaths of the basin are 4–5 and 0.5–0.9 mmol/m^2, respectively. At the ML density increase up to 1014.2 kg/m^3, at the periphery the integral concentrations increase in 2–2.5 times up to 8–10 and 1.3–1.8 mmol/m^2 values for NO_3 and PO_4. Density change from 1014.0 to 1014.2 kg/m^3 corresponds to the ML depth increase just by 5–8 m (see Fig. 6, *b*). At the ML density increase from 1014.0 to 1014.5 kg/m^3 integral concentration of NO_3 and PO_4 increases in 4–5 times up to 18–22 and 3.2–3.7 mmol/m^2, respectively. It should be pointed out that since the position of chemical elements in the basin is tied to isopycnals, NO_3 and PO_4 concentration dependence on the ML density is almost the same for different regions (isobaths) of the Black Sea. At the same time, the ML depth can sharply change due to dynamic effects, such as a passage of mesoscale anticyclones, for example. Therefore, we will consider that the ML density is more reliable indicator of nutrient entrainment, which is responsible for the phytoplankton bloom.

Average dependence between the SST and density at 20 m depth was calculated by satellite and in-situ measurements (dashed line in Fig. 8, *a*) performed in February – March in the central part of the sea (> 2000 m depths) and by the model calculation (solid line in Fig. 8, *a*). According to the obtained dependences, the density equal to 1014.2 kg/m^3 (approximately corresponding to the depth at which an intensive entrainment of nitrates begins) is reached at SST equal to 7.5–8.0° C. More intensive entrainment of phosphates, which begins at 1014.5 kg/m^3, takes place at SST equal to 6° C in the center of the sea. The highest density values in the Black Sea (> 1014.6 kg/m^3) were recorder very rarely, in extremely severe winters at SST below 5.5° C in the center of the sea. Such conditions were observed only a few times – in 1985, 1988, 1993 and 2012. The dependence obtained according to the modeling results within typical 6–9° C range of temperatures coincides well with the data of observations. Consequently, the intensity of nutrient entrainment in the model corresponds to the actual data quite well. This is an indirect confirmation of the validity of the obtained conclusions on the cooling impact on the phytoplankton bloom intensity.

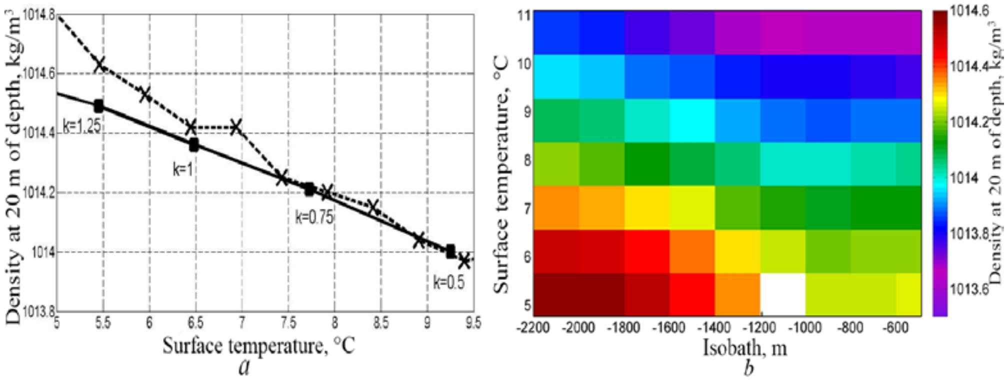

Fig. 8. Dependence between the sea surface temperature (° C) and water density (kg/m^3) at 20 m depth calculated based both on the satellite and direct measurements (dashed line) carried out in the central part of the sea (the depths below 2000 m) in February-March and on the modeling results (solid line) (*a*); diagram of density variability at 20 m depth (kg/m^3) at the sea surface temperature varying for different isobaths (*b*)

To describe spatial relation between the entrainment of waters and cooling, a diagram of density variability at 20 m depth at SST change for different isobaths (Fig. 8, *b*) was plotted. In the center of the basin the density equal to 1014.2 kg/m^3 is reached at higher temperatures (SST = 8,5° C) than at the periphery (SST = 6,5° C). Such differences are related to the raise of isopycnals and higher salinity of waters in the center of the sea [20]. Thus, the growth of nutrient concentrations and phytoplankton bloom at first will be observed in the center of the sea, and only then at its periphery. If the temperature does not reach the values sufficient for the nutrient entrainment on the slope, it will take place only in the center of the sea. This can be a cause of spatial differences in phytoplankton bloom in the basin [9]. The highest density values (> 1014.5 kg/m^3) are observed in the center of the sea (the depths more than 2000 m), where the domes of cyclonic gyres are located, at 6–7° C SST. In this area the highest nutrient entrainment during the winter cooling can be expected. At an intensive circulation the differences in the density structure in the sea center and at the periphery (and also, as follows, the differences in integral concentration of nutrients) will be more pronounced.

It should be pointed out that the assumption about extremely strong relationship between the concentration of nutrients and the position of isopycnic surfaces is an approximation. The proximity of the shelf and intensive cross-shelf exchange on the continental slope can lead to increased concentrations of nutrients in this part of the basin. Then the entrainment of waters with the same density will have a stronger impact on the primary production at the periphery of the basin.

Discussion and conclusions. Vertical entrainment of phytoplankton and nutrients into the surface layer is an important factor determining an intensive autumn-winter phytoplankton bloom. In this work on the basis of 1D-physical biogeochemical model the relation between winter cooling intensity and phytoplankton biomass was determined. Experiments with different heat fluxes showed that integral and surface phytoplankton biomasses increase by ≈ 50% under conditions of cold winter compared with the warm one.

The results of the model show that winter cooling intensity affects the time of winter bloom peak. In cold winters it is observed one month earlier than in warm ones as the mixing faster reaches the layer of nutrient maximum. At the same time, in [33] it is represented that in severe winters when the ML depth exceeds the Sverdrup's critical depth, there can be not enough illumination for the development of phytoplankton, which leads to the opposite effect – the later bloom. In the model used in the work seasonal variability of photosynthetic parameter was set according to the results of [34]. In this work, on the basis of in-situ measurements it is shown that the values of the photosynthetic parameter increase in two times in winter. The authors attribute this to an increase in the available amount of nutrients. Therefore, in our calculations the decrease in illumination had practically no effect on the phytoplankton bloom in winter, even at the greatest mixing depths (~ 70 m). It is necessary to continue research of the relationship between illumination conditions and the vertical distribution of phytoplankton in order to understand better the mechanisms of phytoplankton bloom in the basin.

Model calculations also indicated that phytoplankton biomass in the subsurface summer maximum also depends on winter cooling and in the peak is higher by ≈ 30% in the years after cold winters. It should be pointed out that in warm period horizontal cross-shelf transport of nutrients has greater and often decisive importance for the ecosystem [11, 13, 15]. Both factors – winter entrainment and horizontal transport – act simultaneously. They often have opposite variability, since in warmer years the circulation weakens [35], which favors the generation of eddies and an increase in horizontal transport in the basin [15]. Direct relationship between SST and chlorophyll concentration C_a in the basin with the highest correlations at its periphery [15] indicates that the role/significance of horizontal transport is likely to be greater at the continental slope and is comparable to the vertical mixing effect in the central part of the basin. The amount and chemical composition of river runoff are also subject to significant interannual variations which are the most important cause of changes in the biogeochemical structure of the basin waters [36].

On the basis of in-situ data the estimates of the relationship between the depth, the ML density and the integral concentration of nitrates and phosphates in various regions of the Black Sea are given in the work. Integral concentration of nutrients in the ML grows in 2–3 times at the increase of its density from 1014.0 to 1014.2 kg/m^3 and in 5–6 times when the density reaches 1014.5 kg/m^3 value. The relationship between the winter SST and entrainment of deep waters is obtained. It is shown that in the center of the sea at ≈ 7,8° C water density reaches the value equal to the upper boundary of nitrate maximum layer which is 1014.2 kg/m^3, and at the SST below 6° C water density in the ML is 1014.4–1014.5 kg/m^3 which corresponds to the upper boundary of phosphate maximum layer. Due to the differences of haline properties and dynamics impact the density equal to 1014.2 kg/m^3 is reached in the center of the sea at higher SST values (8° C) than at the continental slope (6.5° C). These differences can be the cause of spatial features of intensity and time of phytoplankton bloom.

In the given work the impact of seasonal fluctuations of the heat flux on variability of phytoplankton biomass was studied. High-frequency variations of the ML depth in winter related to the daytime warming at weak winds are able to generate stratification in the upper near-surface layer and to cause sharp bursts of bloom [35]. Strong storm winds can sharply mix the upper layers of water and promote intensive flux of nutrients from the deep waters into the photosynthesis zone [37], which can cause anomalous bloom of water during the warm season. These and other natural processes significantly affect the phytoplankton development in the Black Sea, and sometimes they determine its variability. This must be considered in further development of biogeochemical models.

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About the authors:

Elena A. Kubryakova - Junior Research Associate**,** Department of the Oceanic Processes Dynamics, FSBSI MHI (2, Kapitanskaya Str., Sevastopol, 299011, Russian Federation), ORCID ID: 0000-0001-6071-1881, Scopus Author ID: 57188747330, elena_kubryakova@mail.ru

Arseniy A. Kubryakov – Senior Research Associate, Remote Sensing Department, FSBSI MHI (2, Kapitanskaya Str., Sevastopol, 299011, Russian Federation), Ph.D. (Phys.-Math.), ORCID ID: 0000-0003-3561-5913, arskubr@ya.ru

Sergey V. Stanichny – Senior Research Associate, head of Remote Sensing Department**,** FSBSI MHI (2, Kapitanskaya Str., Sevastopol, 299011, Russian Federation), Ph.D. (Phys.-Math.), ORCID ID: 0000-0002-1033-5678, stanichny@mhi-ras.ru

Contribution of the co-authors:

Elena A. Kubryakova – obtaining and processing of data, model calculations

Arseniy A. Kubryakov – the study of relationship between SST and vertical entrainment characteristics

Sergey V. Stanichny – analysis of satellite information

The authors have read and approved the final manuscript.

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