Original Russian Text © V. L. Dorofeev, L. I. Sukhikh, 2023,
published in MORSKOY GIDROFIZICHESKIY ZHURNAL, Vol. 39, Iss. 2 (2023)

Original article

Impact of Parameterization of Vertical Turbulent Diffusion on the Results of Simulating the Phytoplankton Biomass Dynamics in the Deep Part of the Black Sea

V. L. Dorofeev, L. I. Sukhikh ✉

Marine Hydrophysical Institute of RAS, Sevastopol, Russian Federation
✉ *l.sukhikh@gmail.com*

Abstract
Purpose. The paper is purposed at studying the impact of vertical mixing processes in the Black Sea on distribution and dynamics of the basic components of marine ecosystem based on numerical simulation.
Methods and Results. Two variants of the lower trophic level model of the Black Sea ecosystem differing in the way of parameterizing the processes of vertical turbulent diffusion were used. In the first variant, the diffusion coefficients are represented as the functions depending on depth and time. At that, the time dependence is of seasonal character. In the second variant, in order to describe the vertical exchange processes, the turbulent model was added to the circulation one. In both versions, the biogeochemical parts of the models consisting of 15 compartments include the same equations, coefficients, and functions describing the interactions between different ecosystem components in the upper 200-meter layer of the sea. The calculations for 12 years (1998–2009) were done for both versions of the ecosystem model, and the results were compared. The results of modeling the nitrates distribution were compared with the *in situ* measurements in the deep part of the Black Sea taken from the interdisciplinary oceanographic database. Besides, the results of simulating the chlorophyll surface concentration were also compared with the analogous satellite-derived measurement results.
Conclusions. As for the above-noted calculations, seasonal variability of the basic ecosystem parameters is insignificantly different, at that the parameterization of vertical turbulent diffusion produces a certain effect upon the vertical distribution of ecosystem parameters. Interannual variability in both calculations is characterized by a biomass decrease in the euphotic zone of the sea deep part resulted from a negative trend in the amount of nutrients inflowing with the river waters. The annual average concentrations in the sea upper layer corresponding to the first calculation are higher than those obtained in the calculation by the turbulent model. This is related to the fact that the vertical circulation cell formed due to the wind field cyclonic vorticity over the Black Sea results to be more intense for the first calculation. The nitrates entering into the euphotic zone from the underlying layer is provided mainly by advection rather than turbulent diffusion.

Keywords: marine ecosystem, circulation, Black Sea, turbulent diffusion. ecosystem model, nutrients, chlorophyll concentration

Acknowledgments: The study was carried out with support of project No. 0827-2021-0002.

For citation: Dorofeev, V.L. and Sukhikh, L.I., 2023. Impact of Parameterization of Vertical Turbulent Diffusion on the Results of Simulating the Phytoplankton Biomass Dynamics in the Deep Part of the Black Sea. *Physical Oceanography*, 30(2), pp. 245-262. doi:10.29039/1573-160X-2023-2-245-262

DOI: 10.29039/1573-160X-2023-2-245-262

Introduction

When modeling dynamics and state of the marine ecosystem, the essential thing is the quality of the hydrodynamic fields used, which are the input parameters of the equations of the biogeochemical part of the ecosystem model. The most important hydrodynamic processes that affect the exchange of ecosystem components between different layers and regions of the sea are the processes of advection and diffusion, through which nutrients are transported from their sources to the rest of the water area.

One of the main such sources is river runoff. About two thirds of the water entering the Black Sea basin with rivers falls on the northwestern shelf (NWS). At the same time, its area, compared with the area of the entire Black Sea, is insignificant (about 16%) [1]. Due to this, in the NWS waters, an increased content of nutrients and, as a result, bioproductions is observed. With the help of water exchange caused by advection and horizontal diffusion in the sea surface layer, these waters penetrate from the shelf into the central regions of the Black Sea.

The supply of nutrients to the surface layer of the deep-water part of the Black Sea occurs not only due to the inflow of shelf waters, but to a large extent due to vertical exchange processes, which are especially significant in the winter season when a large number of nitrates from the nitrocline layer rises to the surface. Such transport of nitrates is provided mainly by two physical processes: vertical advection and turbulent diffusion, the value of which in the models depends on the parametrization method of the diffusion coefficients. The importance of vertical diffusion processes for the correct reconstruction of the vertical structure of ecosystem parameters was noted in a number of works on modeling the marine ecosystems [2–5].

The purpose of the work is to study the effect of vertical mixing processes in the Black Sea on the distribution and dynamics of the marine ecosystem main components based on the calculations performed. To accomplish this task, two calculations of the ecosystem long-term evolution (from 1998 to 2009) were carried out using two methods of vertical turbulent diffusion parameterization. The results of the calculations were then compared with each other. The work is a continuation of the research cycle [6, 7].

Materials and methods of study

The performed numerical experiments were carried out using two variants of a three-dimensional model of the lower level of the Black Sea ecosystem food chain. Both variants of ecosystem models can be divided into two main parts: 1) a hydrodynamic model (circulation model), which describes the dynamics and thermodynamics of the basin waters; 2) a model of biogeochemical processes, which describes the interaction between various components of the ecosystem model. The hydrodynamic models used in the work are a finite-difference analogue of the system of primitive ocean dynamics equations. Both versions of the hydrodynamic model are based on the circulation model developed for the Black Sea [8]. This is a z-level model with a horizontal step of 4.8 km, which allows one to accurately describe, in addition to large-scale circulation, mesoscale processes (the Kibel – Rossby deformation radius for the first baroclinic mode in the deep part of the Black Sea is ~ 25 km) [1].

The first version of the model contains 35 calculated levels along the vertical, converging towards the sea surface, where the discreteness is 5 m. The vertical turbulent diffusion and viscosity are parameterized using quasi-stationary depthdependent coefficients. Time dependence is seasonal. For an adequate description of hydrodynamic processes in the sea, the boundary conditions on the sea free surface are of great importance. In this work, two-dimensional atmospheric fields near the underlying surface, obtained from the results of the ERA-Interim reanalysis [9], were used as such conditions. To improve the accuracy of the output products of the circulation model (fields of current velocities, temperature and salinity), satellite altimetry data and sea surface temperature measurements were assimilated during the calculations [10].

The second version of the Black Sea circulation model differed from the first one in the parameterization of the vertical turbulent exchange. For a more accurate description of the vertical exchange processes, the turbulent model of quasi-equilibrium turbulent energy QETE [11], which is part of the Mellor – Yamada family of models [12], was added to the circulation model. This model consists of two equations for the evolution of turbulent energy $q^2/2$ and the turbulence scale l. In addition, 40 calculated horizons were used in this version of the model [13]. The horizontal grid, atmospheric effect, and satellite data assimilation were the same as in the first version.

The biogeochemical parts of both versions of the model are a system of fifteen (according to the number of state variables) transport-diffusion equations:

$$\frac{\partial C_i}{\partial t} + \frac{\partial (uC_i)}{\partial x} + \frac{\partial (vC_i)}{\partial y} + \frac{\partial \big((w + w_s)C_i\big)}{\partial z} = K_h \nabla^2 C_i + \frac{\partial}{\partial z}\left(K_v \frac{\partial C_i}{\partial z}\right) + R, \qquad (1)$$

where u, v, w are the components of currents velocities; w_s is a sedimentation rate of diatoms and suspended organic matter (for other components it is equal to zero); $K_\mathrm{h}, K_\mathrm{v}$ are the coefficients of horizontal and vertical turbulent diffusion, respectively; R describes biogeochemical interactions between the state variables C_i, mmolN/m^3.

State variables include two groups of phytoplankton (diatoms and flagellates), two size groups of zooplankton: microzooplankton (< 0.2 mm) and mesozooplankton (0.2–3.0 mm), jellyfish *Aurelia aurita* and comb jelly *Mnemiopsis leidyi*, non-photosynthetic bacterioplankton, dissolved and suspended organic matter, omnivorous dinoflagellate *Noctiluca scintillans*. In this model, nitrogen is considered the only nutrient that limits the phytoplankton growth. The nitrogen cycle also includes three inorganic compounds: nitrates, nitrites and ammonium. The model also includes dissolved hydrogen sulfide and oxygen as separate state variables.

The computational domain horizontally coincides with the corresponding domain for circulation models (accordingly, the grid steps coincide), and vertically it occupies the upper 200 meters of the Black Sea. In this case, the calculated horizons correspond to the circulation models. In the first variant, the biogeochemical part of the ecosystem model has 18 computational levels, and in the second one – 26 levels.

The relationship between the circulation model and the biogeochemical part is one-way in this work. That is, the current velocity fields, temperature, salinity and turbulent diffusion coefficients obtained from the hydrodynamic model are used to compute the parameters of the biogeochemical model as coefficients of the system of equations (1). There is no reverse effect of the parameters of the biogeochemical model on the hydrodynamic fields. In addition, the calculation according to the ecosystem model is carried out in the offline mode: first, the required hydrophysical fields are computed and recorded according to one or another version of the circulation model (current velocities, temperature, salinity and turbulent diffusion coefficients), then they are used as the coefficients of the system of equation (1) in the biogeochemical part of the model (see [6, 7] for more detail).

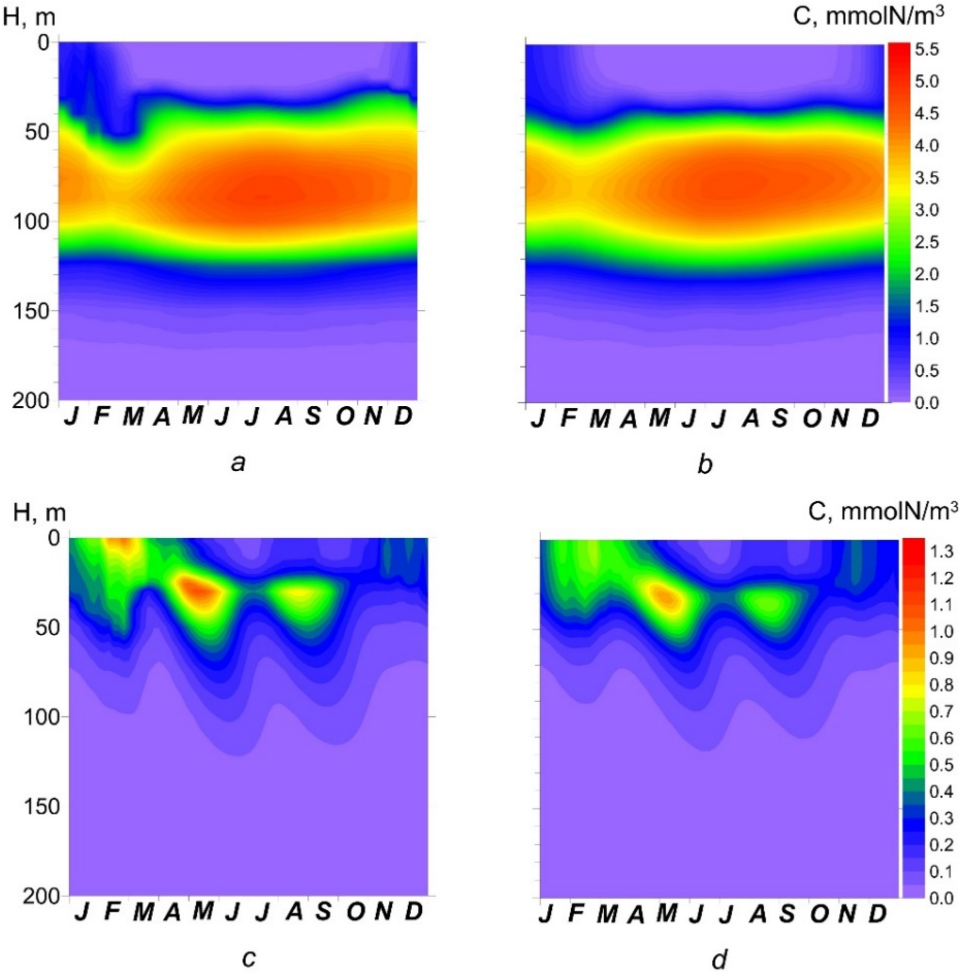
The following boundary conditions were set at the computational domain boundaries: at the upper boundary (sea surface) – zero fluxes of all state variables, except for oxygen; at the lower boundary in the deep part of the sea – the Dirichlet conditions (zero values of concentrations for all ecosystem components, except for ammonium and hydrogen sulfide); at the lower boundary in the shallow part of the sea, where the bottom is the boundary of the computational domain – the conditions for the absence of diffuse fluxes for all the ecosystem components. At the lateral boundaries, with the exception of the mouths of large rivers, conditions were also set for the absence of diffuse flows for all the ecosystem components. At the confluence of large rivers (the Danube, Dnieper, Dniester, Southern Bug, Sakarya, Kyzyl-Irmak, Chorokh, Rioni), nitrate and ammonium fluxes proportional to their concentration and river runoff intensity according to [7], were set.

To assess the quality of the obtained results, they were compared with the data of remote and contact measurements. We used the surface concentration of chlorophyll prepared by V.V. Suslin from satellite observations based on the algorithm developed for the Black Sea using the brightness factor in three spectral channels [15]. To compare the distribution of nitrate concentrations in the deep part of the Black Sea, we used samples of the Black Sea measurements collected over 1998–2003, placed in an interdisciplinary oceanographic database within the framework of the NATO Science for Stability Program (TU-Black Sea).

Results

The results of modeling the dynamics of the Black Sea ecosystem for a period of 12 years from 1998 to 2009 were analyzed. In the considered model of the Black Sea ecosystem, nitrates are the main nutrient, and phytoplankton is the producer of primary production, the first link in the food chain. Therefore, we will dwell on the analysis of their distribution in more detail. To compare the intra-annual variability of these ecosystem parameters obtained in two calculations, we consider the fields obtained by averaging the results over 12 years of calculation. The Hovmöller diagrams illustrating the annual variation of average concentrations of nitrates and total phytoplankton in the upper 200-m layer of the Black Sea over the area of the deep-water part of the basin, obtained from the results of two simulations, are given in Fig. 1.

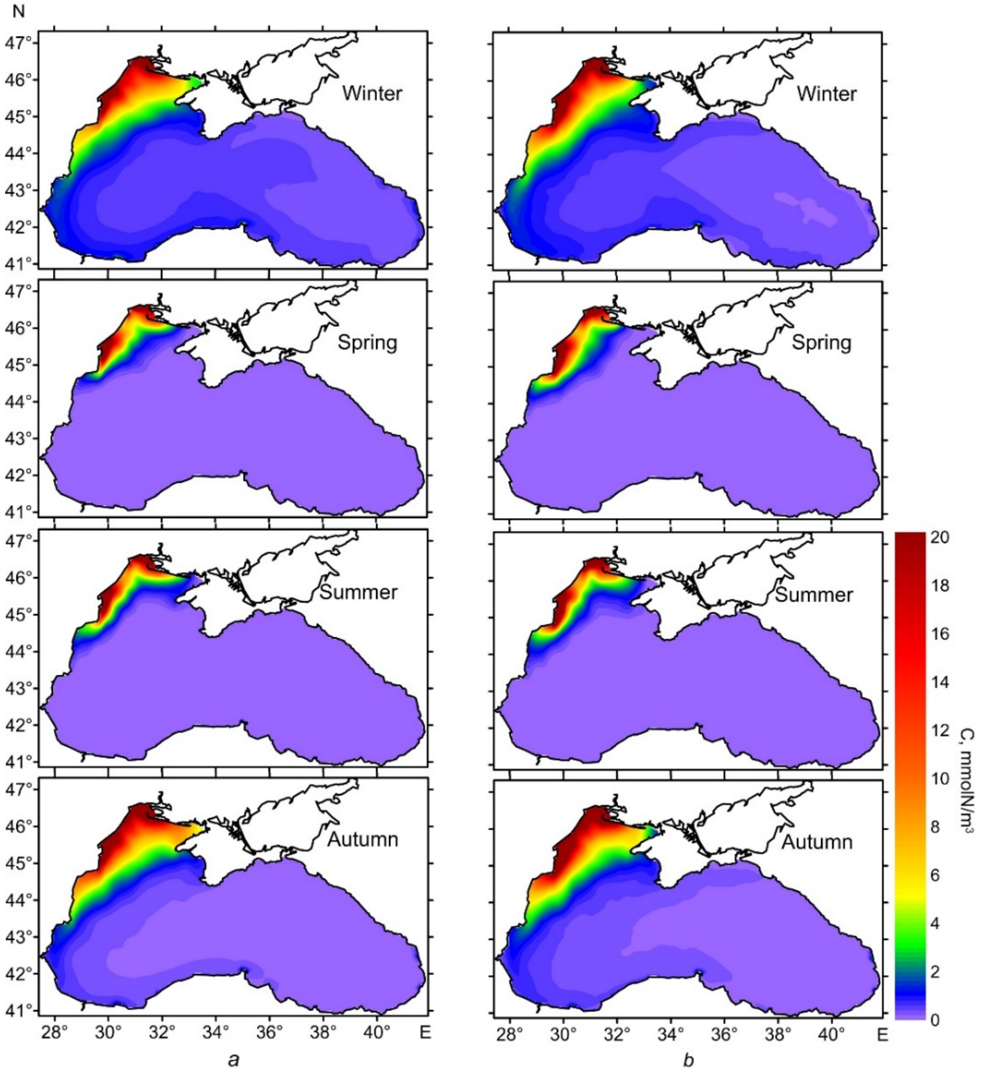
For both computation results, throughout the year, the maximum concentration of nitrates is located at a depth of about 80 m. Above (in the 40–60 m layer) and below (in the 100–120 m layer), strong gradients of nitrate concentrations (upper and lower nitroclines) are observed. In winter, the value of the concentration maximum decreases markedly in comparison with the summer and autumn seasons. At this time, the concentration in the surface layer increases, which is low in the other seasons in the deep part of the sea. This is due to intense winter mixing. The decrease in the concentration maximum is especially pronounced in February.



F i g. 1. Intra-annual variability of the nitrates (*a*, *b*) and phytoplankton (*c*, *d*) concentrations in the upper layer of the sea deep part based on the results of the first (*a*, *c*) and second (*b*, *d*) calculations

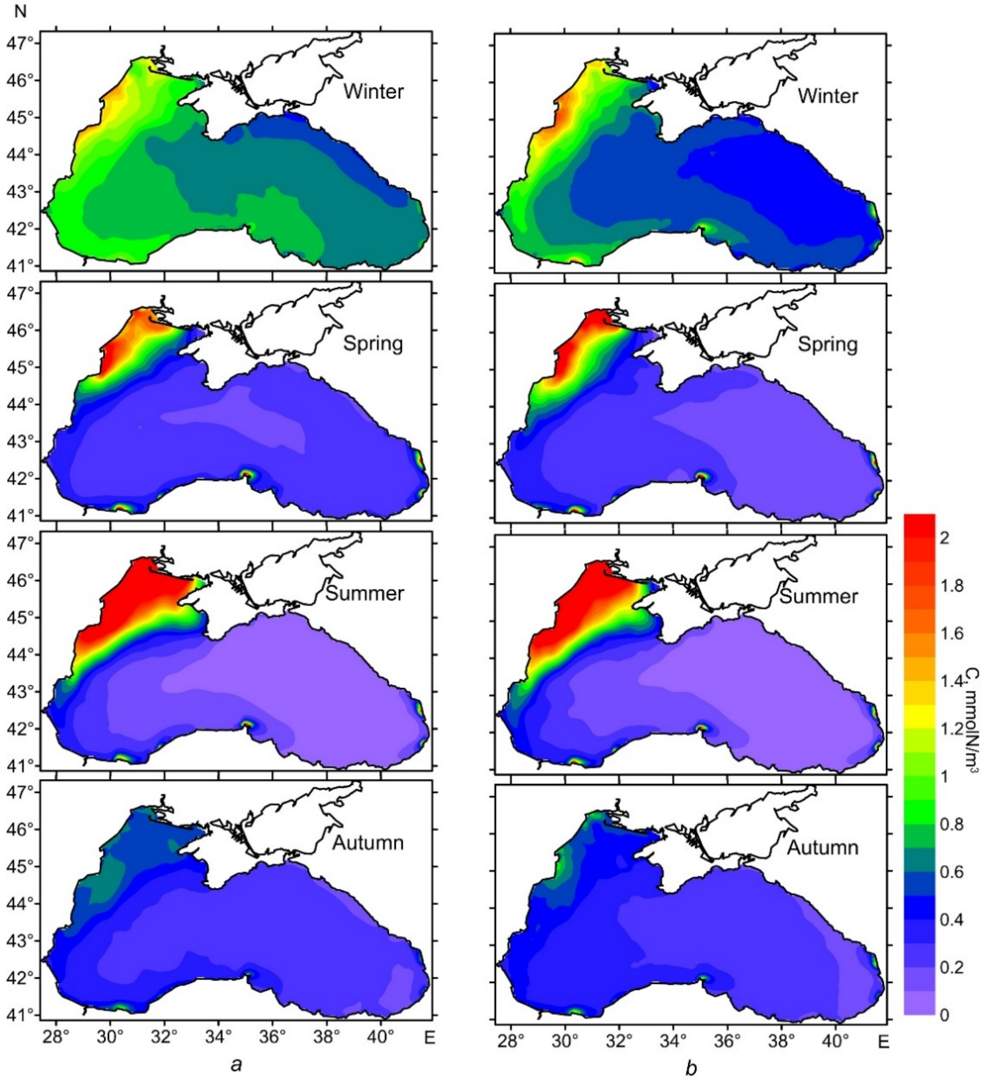
The high concentration of nutrients in the Black Sea surface layer in winter leads to an increase in the phytoplankton biomass on the sea surface, which reaches a maximum in February. Then the concentration of nitrates in the surface layer of the sea decreases. At the same time, the intensity of solar radiation on the sea surface increases, and the thickness of the photosynthesis layer increases. The maximum concentration of phytoplankton descends to a depth of approximately 25–30 m (summer subsurface maximum). At the end of the year, the maximum values of phytoplankton biomass shift towards the sea surface again. This pattern is typical for both computation results. The difference lies in the fact that for the simulation with the turbulent model, the values of the maximum concentrations of phytoplankton are lower than for the first calculation (0.65 mmolN/m^3 versus 0.76 mmolN/m^3), and the depth of occurrence is greater (32 m versus 30 m).

In both cases, the minimum values of nitrate concentration in the maximum layer are observed in February, when the processes of mixing in the Black Sea caused by storms and thermal convection are most intense. At the same time, the concentration of nitrates on the surface remains low due to their assimilation by phytoplankton, which at this time has the maximum surface concentration. In the first calculation, the minimum concentration of nitrates is observed more clearly. This is due to the fact that the February concentration of phytoplankton is higher in this calculation.



F i g. 2. Distributions of the nitrates surface concentrations (mmolN/m^3) averaged over 12 years, for four seasons based on the results of the first (*a*) and second (*b*) calculations

Seasonal climatic distributions of nitrate concentration at the Black Sea surface based on the results of two computations are given in Fig. 2. In winter, at the entire surface of the sea, including its deep-water part, the concentration values are quite large. In other seasons, they are lower, especially in spring and summer, when a high concentration is observed only on the northwestern shelf, and in the deep part of the sea it is close to zero. In autumn, an increased content of nitrates is observed not only in the NWS, but also in the western deep part of the Black Sea along the coast. This increase in nitrate content in the deep part of the sea is due to the transport of nutrient-rich waters from the NWS in the Rim Current.



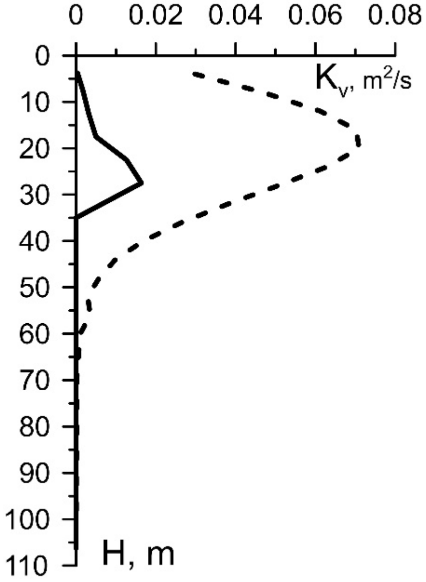
F i g. 3. Distributions of phytoplankton surface concentrations (mmolN/m^3) averaged over 12 years, for four seasons based on the results of the first (*a*) and second (*b*) calculations

In Fig. 3 the maps of the distribution of phytoplankton surface concentrations obtained from the results of two calculations for four seasons are presented. Within an annual cycle calculated over a twelve-year period, the surface concentration of phytoplankton reaches its maximum in the winter season. Sufficiently high values during this period are observed throughout the Black Sea. In the deep-water part of the basin (especially its western part), the surface concentration is slightly lower than in the NWS.

In contrast to the winter season, the concentration of phytoplankton in the surface layer in the deep part of the Black Sea in spring and especially in summer differs sharply from the concentration on the northwestern shelf, where it is an order of magnitude higher. In summer, one can also trace increased values of phytoplankton biomass along the western and Anatolian coasts of the Black Sea, where phytoplankton is carried by the cyclonic current from the NWS.

In winter, the concentration of phytoplankton in the surface layer of the deep part of the sea, obtained by calculation using the turbulent model, has lower values than in the first calculation. This can be explained by the fact that turbulent mixing in the near-surface layer is more intense due to the large values of the turbulent diffusion coefficient (Fig. 4) and, therefore, the phytoplankton concentration is more uniformly distributed with depth, but its value on the surface is less.

The vertical structure of nitrate distribution in the form of zonal sections for four seasons, obtained by averaging the results of two variants of calculations over a 12-year period, is given in Fig. 5. The main feature of the vertical distribution of nitrates is the maximum concentration at a depth of about 80 m. This maximum is present in the zonal sections for all seasons, reaching the highest value in summer, and the lowest in winter when a large number of nitrates rises to the surface due to strong mixing. Other notable features of the vertical distribution are an increased concentration of nitrates above the upper nitrocline near the western coast, caused by the export of nitrates by the Danube on the northwestern shelf, and a lowering of nitrate concentration isolines in the area of the lower nitrocline, due to the intensity of the vertical circulation cell in the Black Sea. The main difference between the two calculation options is observed in winter. In the computation using the turbulent model, the maximum value is lower – 3.8 versus 3.9 mmolN/m^3, and it is located at a shallower depth – 80 m versus 87 m in the first calculation. The mixed layer thickness in this computation reaches 40 m.



F i g. 4. Average profiles of the vertical turbulent diffusion coefficients: dashed line is for the calculation using the turbulent model and solid line is for the first calculation variant

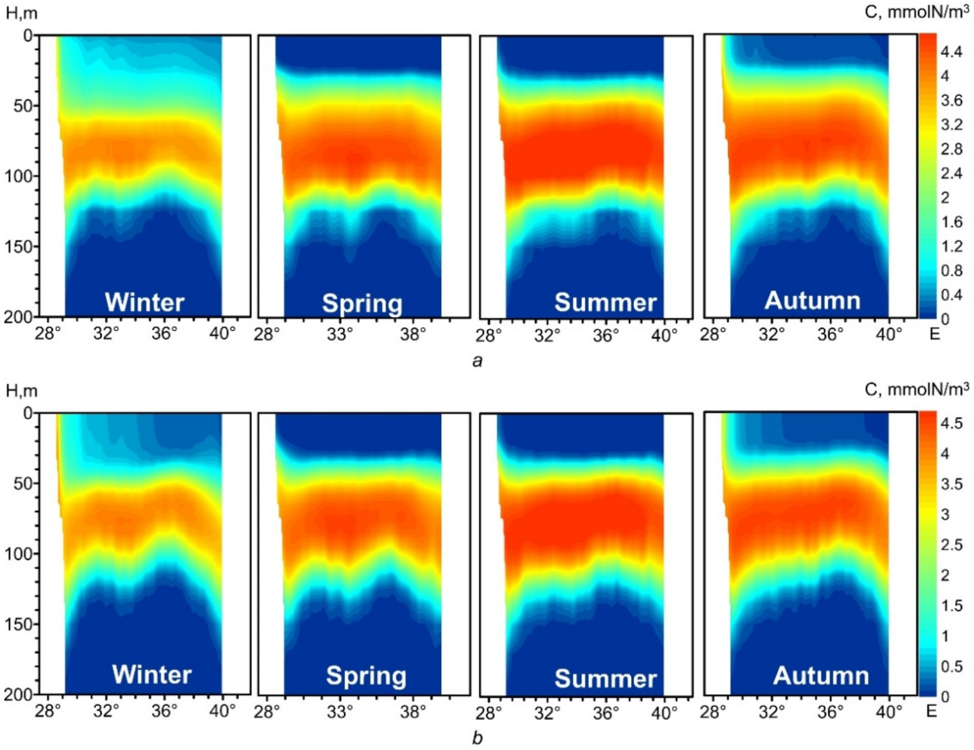
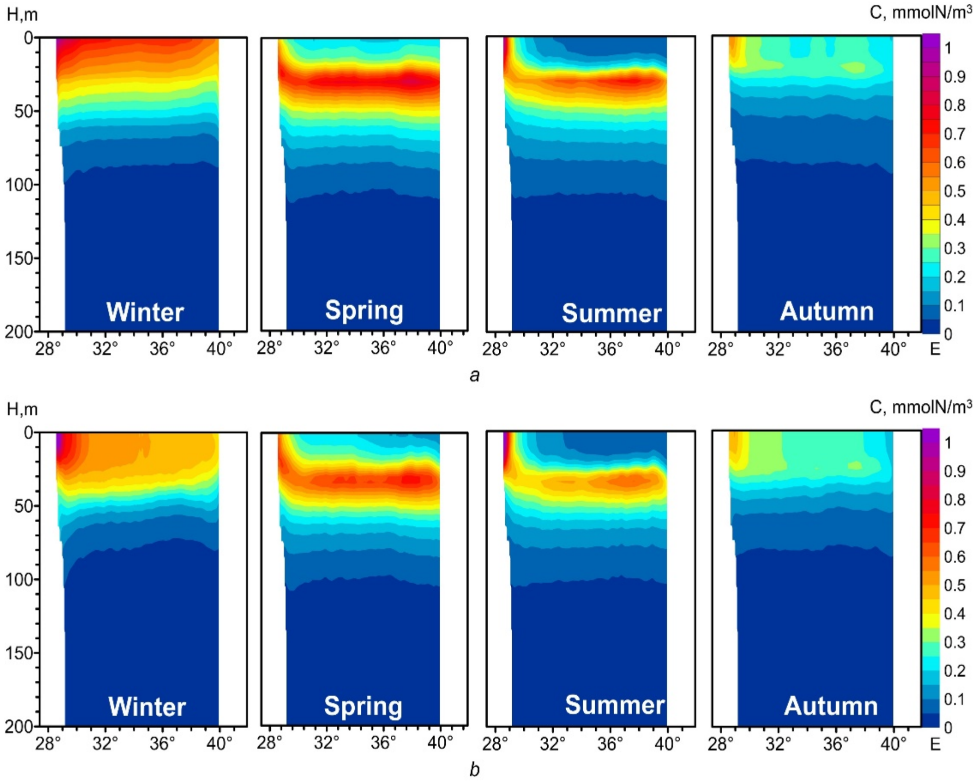


Fig. 5. Zonal sections (along latitude 43.5°N) of the nitrate concentration distributions for four seasons: a – based on the first calculation results; *b* – based on the results of calculation using the turbulent model

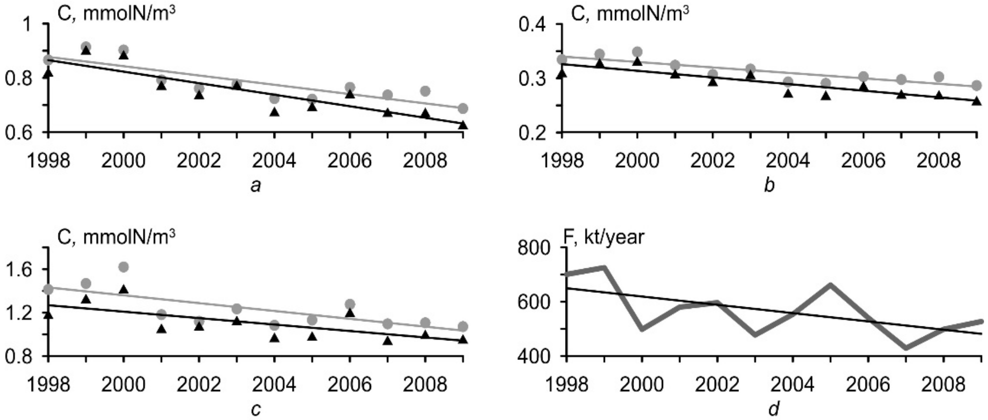
Similar zonal sections for phytoplankton are shown in Fig. 6. In winter and autumn, the phytoplankton concentration on zonal sections behaves monotonously with depth: it decreases from the sea surface. In the spring and summer seasons, the maximum phytoplankton concentration is observed at approximately 25–30 m depth, which is present along the entire length of the section from the western to the eastern coast. As noted above, this subsurface maximum is explained by an increase in the sunlight intensity during this period of the year and a very low content of nitrates in the Black Sea surface layer. As well as for the vertical distribution of nitrates, near the west coast increased concentrations of phytoplankton for all seasons due to high concentrations of nitrates took place. The greatest differences in the distribution of phytoplankton concentrations are observed in winter and autumn. In the calculation using the turbulent model, the concentration of phytoplankton in winter is almost uniform up to a depth of 40 m due to more intense turbulent mixing, while in the first calculation, a noticeable vertical concentration gradient is observed in this layer. According to the calculation with the turbulent model, in autumn the phytoplankton concentration values of 0.2 mmolN/m^3 penetrate up to 40 m, while in the first calculation – up to 30 m.



F i g. 6. Zonal sections (along latitude 43.5°N) of the phytoplankton concentration distributions for four seasons: a – based on the first calculation results; *b* – based on the results of calculation using the turbulent model

Let us consider the interannual variability of the ecosystem main parameters based on the average annual concentrations in the Black Sea euphotic zone. In Fig. 7 the evolution of the average annual concentrations of phytoplankton, total biota (that is, the sum of the biomass of all biological components of the model) and nitrates in the upper 50 m layer is demonstrated. Average annual concentrations of nitrates in the sea upper layer are higher for the first calculation. As a consequence, the concentrations of phytoplankton and total biota are higher for this calculation. A feature of the given graphs is the negative trend of all the given parameters. This is due to the negative trend in the number of nutrients inflowing with the river runoff, which was set in accordance with [14]. The graph of nitrate inflow with the river runoff by years is given in the same Figure. Similar negative trends in phytoplankton biomass were noted in [16].

A higher concentration of biochemical parameters in the euphotic zone for the first calculation seems, at first glance, illogical, because the vertical exchange in the second calculation using the turbulent model is more intense than in the first calculation. Therefore, the flow of nitrates from the upper nitrocline layer should be higher. To clarify the cause why the concentrations of ecosystem parameters in the upper layer differ, we consider the fluxes of nitrates into the euphotic zone in more detail.



F i g. 7. Annual average concentrations *C* of biota (*a*), phytoplankton (*b*) and nitrates (*c*) in the euphotic zone of the deep part of the Black Sea based on the results of the first (circles) and second (triangles) calculations; annual average nutrients inflow with river runoffs (*d*)

In Fig. 8 the average annual fluxes of nitrates into the euphotic zone of the Black Sea deep part are shown. This zone is bounded from below by a 50 m horizon and from the side by a cylindrical surface with a guide along the 200 m isobath. As follows from the graphs in Fig. 8, the total nitrate flow is always greater for the first simulation. This explains higher concentrations of biochemical parameters in this layer (see Fig. 7). Over the entire time interval, the average annual fluxes of nitrates into the euphotic zone are positive, both vertical and horizontal. This is explained by nitrate gradients in the upper nitrocline and the influx of nitrates from the NWS. Moreover, in contrast to the total, horizontal fluxes are less for the first calculation.

The values of horizontal fluxes are significantly less than vertical ones, except for 1999. Consequently, the main contribution to the influx of nitrates into the near-surface layer of the Black Sea deep-water part is made by vertical fluxes. Moreover, the main part in vertical flows is provided by advection. This can be seen in Fig. 8, where the top row represents total vertical nitrate fluxes and vertical advective fluxes. For the first computation, these values practically coincide. That is, the diffusion flux is practically equal to zero, which is consistent with Fig. 4, which shows winter mean profiles of vertical turbulent diffusion coefficients. In the first simulation, at a depth of 50 m, the diffusion coefficient is very small. In the second calculation, the diffusion flux is approximately 20% of the total vertical one. This indicates a great role of vertical movements in providing the upper layer of the sea with nutrients.

The vertical velocity fields present a rather mixed picture, with areas of rising water interspersed with the areas where the water is sinking. This vertical velocity behavior can be the result of the effect of non-stationarity and inhomogeneity of atmospheric forcing fields, inhomogeneity of the bottom relief, as well as such processes as Rossby waves and synoptic eddies. If we average the vertical velocity field over a sufficiently long period, then the vertical circulation in the upper layer will be determined by the general cyclonic vorticity of the Black Sea currents. At the same time, in the center, the water will rise to the surface and move to the periphery, and sink near the coast, forming a vertical circulation cell (see the work [1] and [17, 18]). In Fig. 9, the graphs of average annual water mass flows into the euphotic zone of the Black Sea deep part for two simulations are given. The flow of water through the lower boundary is always directed upwards, except for 1999. Accordingly, the water flow through the side surface is negative (except for 1999), i.e. it is directed out of the region. This corresponds to the regime of the vertical circulation cell for the Black Sea upper layer, due to the cyclonic (on average) vorticity of the wind stress field. Moreover, the water flows for the first calculation in absolute value exceed similar flows for the calculation with the turbulent model. That is, the circulation intensity of the vertical cell for the first variant is higher. This can also be seen on the profiles of vertical velocities averaged over the entire calculation period and for the deep-water part of the basin. Thus, due to the greater intensity of the vertical circulation cell in the first calculation, more nutrients from deeper layers enter the Black Sea upper layer, which provides a higher mass of biota in the euphotic zone for this computation, which is observed in Fig. 7.

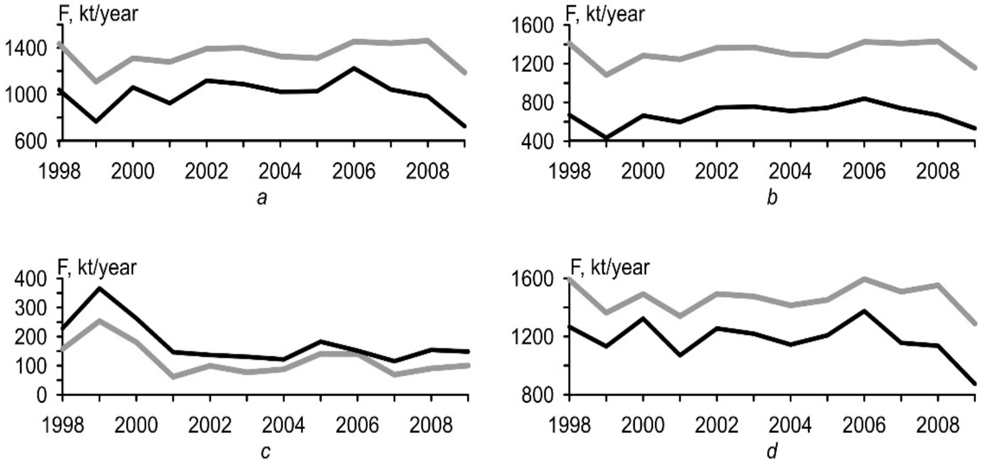
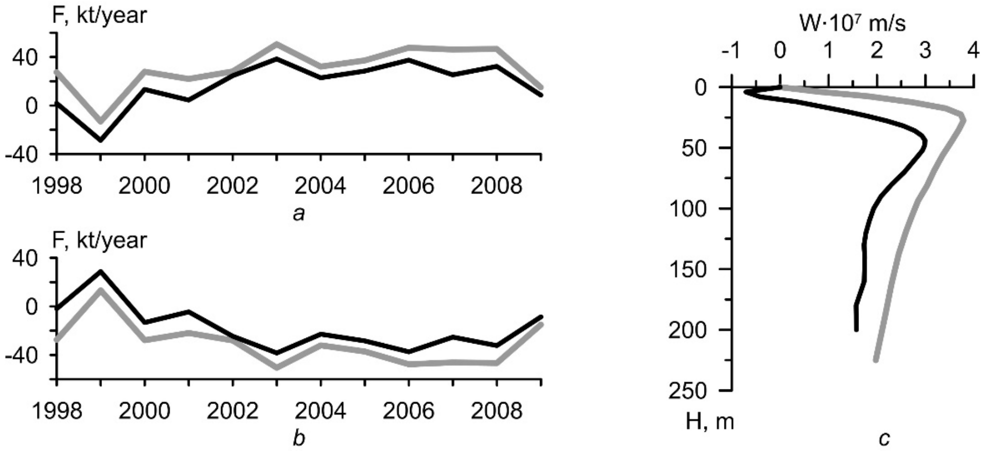


Fig. 8. Annual average nitrates flows *F* to the upper 50-m layer of the Black Sea deep part: flow through the lower boundary (*a*); advection flow through the lower boundary (*b*); flow through the lateral surface (*c*); total flow (*d*) based on the results of the first (grey line) and second (black line) calculations

---

[1] Bulgakov, S.N. and Korotaev, G.K., 1984. [Possible Mechanism of the Stationary Circulation of the Black Sea Waters]. In: *Complex Studies of the Black Sea*. Sevastopol: MHI AS Ukrainian SSR, pp. 32-40 (in Russian).



F i g. 9. Annual average values of the mass flows to the upper 50-m layer of the Black Sea deep part: through the lower boundary (*a*), through the lateral surface (*b*); the vertical velocity profiles averaged over the whole calculation period and over the deep part area of the basin (*c*) based on the results of the first (grey line) and second (black line) calculations

Comparison with observational data

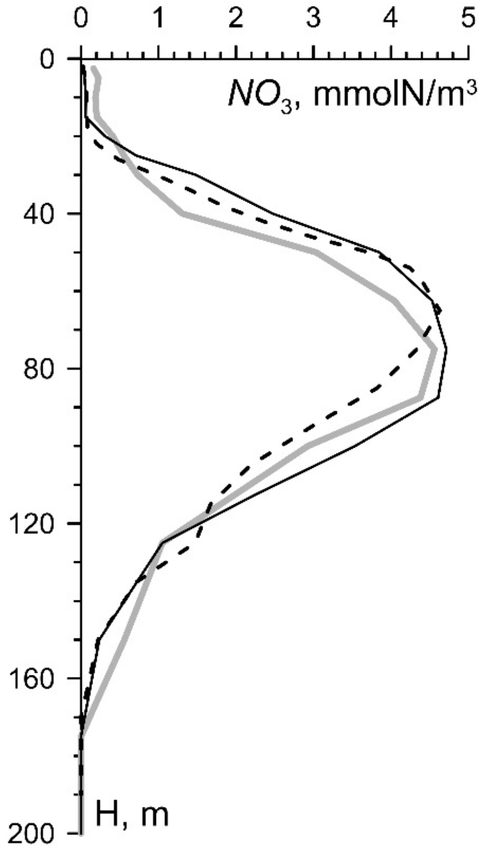
An interdisciplinary oceanographic database was applied to compare nitrate distribution modeling results with measured data. The simulation results were interpolated in space and time to those points in space and time where measurement data were available. In Fig. 10, the average depth profiles for all measurements and the corresponding simulation results are given.

According to the first simulation results, the depth of the nitrate maximum coincides with the corresponding depth from the measurement data, and for the second calculation it is higher by 10 m. The maximum values for both variants and measurement data differ within 0.1 mmolN/m^3. For the first computation, the nitrate maximum layer is wider than according to the measurement data, and for the second calculation, it is located higher. The very value of the nitrate maximum (about 5 mmolN/m^3) corresponds to what is given in [19] for the Black Sea deep part for the 2000s.

According to the first simulation results, the depth of the nitrate maximum coincides with the corresponding depth from the measurement data, and for the second calculation it is higher by 10 m. The maximum values for both computations and measurement data differ within 0.1 mmolN/m^3.

For the first variant, the nitrate maximum layer is wider than according to the measurement data, and for the second one it is located higher. The very value of the nitrate maximum (about 5 mmolN/m^3) corresponds to that given in [19] for the Black Sea deep-water part for the 2000s.

In addition, the simulation results were compared with the data on the surface concentration of chlorophyll obtained from satellite measurements. The satellite values of chlorophyll averaged over the area of the Black Sea deep-water (>200 m) part were compared with the corresponding values obtained in two versions of calculations.



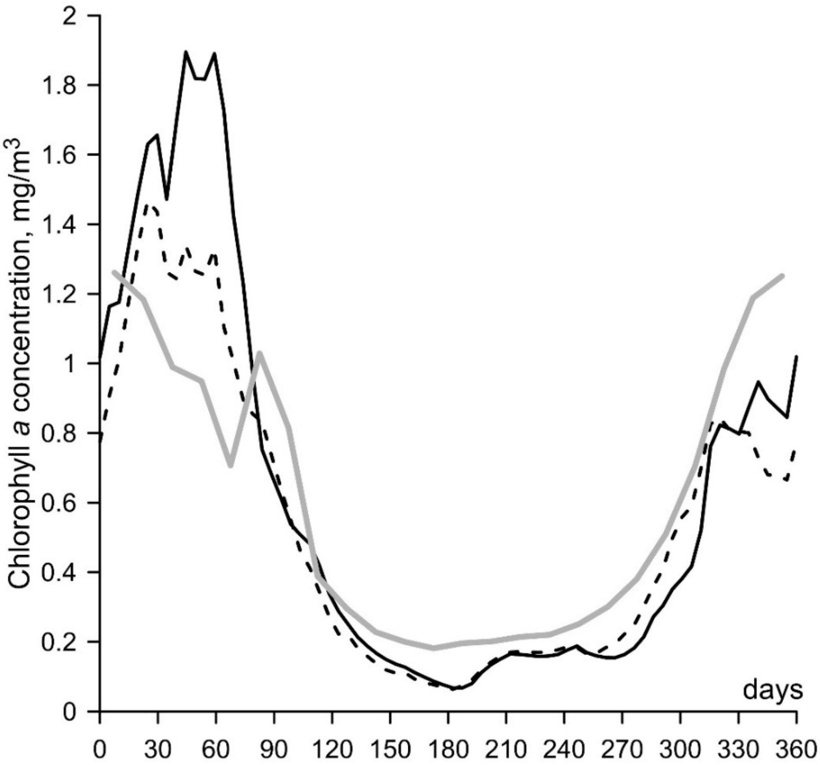
F i g. 10. Average profiles of the nitrate concentration coefficients for the Black Sea deep part based on the measurement data (grey line), and on the results of the first (solid black line) and second (dashed line) calculations

To obtain the chlorophyll concentration, the surface biomass of phytoplankton was converted from mmolN/m^3 units to mgC/m^3 using the C:N mass ratio equal to 8. Then, the chlorophyll concentration was calculated using the Chl:C ratio taken from [16]. This ratio varies significantly throughout the year. In our calculations it was approximated as follows. The first 120 days (360-day year) it falls linearly from 0.03 to 0.01. Then, for 120 days, it is assumed to be constant 0.01. For the last 120 days, it has been increasing linearly from 0.01 to 0.03.

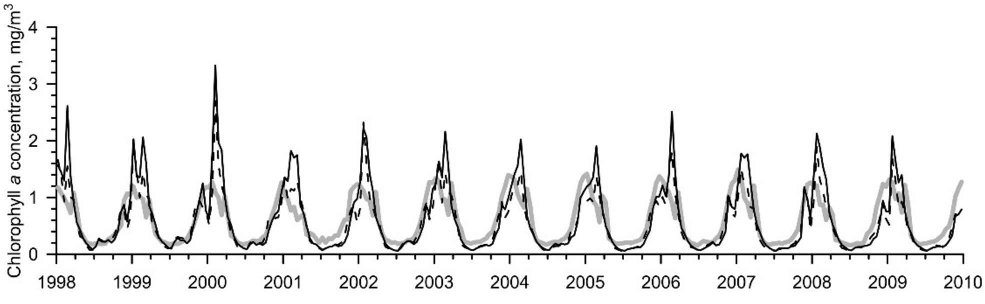
In Fig. 11, the intra-annual variation of the average chlorophyll concentration averaged over 12 years according to satellite measurements and the results of two simulations is represented.

The greatest differences between the simulation results and satellite observation data are observed in the first 90 days of the year and in the last 30 days. In the first 90 days, the chlorophyll concentration, according to the simulation results, exceeds the satellite data, especially for the first calculation. The results of computations using the turbulent model are noticeably closer to the measurement data. In the last month, on the contrary, the first computation results are closer to the satellite data. In the summer months, the chlorophyll concentration, according to the results of both calculations, is lower than the satellite data.

The temporal variation of chlorophyll concentration for the entire period under consideration (1998–2009) is shown in Fig. 12. The greatest differences in satellite chlorophyll concentration and modeling results are observed in winter seasons. Especially large differences are noticeable in the winter seasons of 1998, 2000, 2002, and 2006. In these years, nitrate flux maxima were observed in the upper 50-m layer of the Black Sea deep-water part for both versions of the model (see Fig. 8). Moreover, for the first version of the model, these fluxes are higher, respectively, the difference from satellite data is greater.



F i g. 11. Annual variation of the chlorophyll a concentration based on satellite measurements (grey line) and on the simulation results: the first (solid black line) and second (dashed line) calculations



F i g. 12. Time dynamics of the chlorophyll a concentration based on satellite measurements (grey line) and on the simulation results: the first (solid black line) and second (dashed line) calculations

Conclusions

Simulations of the twelve-year evolution of the Black Sea ecosystem were carried out using two variants of vertical exchange parameterization. Based on these computations, the average seasonal variability of ecosystem parameters was obtained. The analysis of the results revealed that the seasonal variability of the ecosystem main parameters in these simulations does not differ very much. In particular, the distribution of nitrates with depth, computed using the turbulent model, has large gradients at the upper and lower nitrocline locations. In this case, the maximum of nitrates is located higher than that obtained from the first simulation results.

For phytoplankton, the differences between the results of the two computations are manifested in the fact that the summer subsurface concentration maximum is located deeper for the computation with the turbulent model. In addition, the winter surface concentration of phytoplankton in the Black Sea deep part is higher for the first computation. This is apparently caused by more intense turbulent mixing in the near-surface layer for the second computation. In the computation using the turbulent model, the phytoplankton concentration in winter is almost uniform up to 40 m depth, and in the first computation, a noticeable concentration gradient is observed in this layer.

The interannual variability of ecosystem parameters is characterized by a decrease in biomass in the euphotic zone of the deep sea for both computations, caused by a negative trend in the number of nutrients inflowing with rivers. At the same time, the average annual concentrations corresponding to the first computation are higher than in the computation using the turbulent model. This is due to the higher values of nitrate fluxes into the sea surface layer from the upper nitrocline layer for this computation. This, in turn, is associated with a more intense vertical circulation cell obtained from the results of the first computation.

At the same time, the inflow of nitrates into the euphotic zone from the underlying layer is provided to a greater extent by advection rather than turbulent diffusion.

The surface concentration of chlorophyll calculated from the modeling results was compared with satellite data. The greatest differences are observed in the winter season, when the chlorophyll concentration, according to the simulation results for both options, exceeds the satellite data. At the same time, the difference in the results obtained using the turbulent model is less than in the first version of the model. That is, the parametrization of vertical diffusion using the turbulent model more realistically reconstructs the surface concentration of chlorophyll. The greatest differences are observed in those years when the vertical fluxes of nitrates into the upper layer of the sea, mainly advective, are maximum. From this we can conclude that, apparently, the intensity of the vertical circulation cell obtained in the first version of the circulation model is overestimated.

REFERENCES

1. Ivanov, V.A. and Belokopytov, V.N., 2011. *Oceanography of the Black Sea*. Sevastopol: ECOSI-Gidrofizika, 209 p. (in Russian).
2. Oguz, T., Ducklow, H.W., Malanotte-Rizzoli, P., Murray, J.W., Shushkina, E.A., Vedernikov, V.I. and Unluata, U., 1999. A Physical-Biochemical Model of Plankton Productivity and Nitrogen Cycling in the Black Sea. *Deep Sea Research Part I: Oceanographic Research Papers*, 46(4), pp. 597-636. doi:10.1016/S0967-0637(98)00074-0
3. Oguz, T., Ducklow, H.W. and Malanotte-Rizzoli, P., 2000. Modeling Distinct Vertical Biochemical Structure of the Black Sea: Dynamical Coupling of the Oxic, Suboxic, and Anoxic Layers. *Global Biogeochemical Cycles*, 14(4), pp. 1331-1352. doi:10.1029/1999GB001253

4. Grégoire, M., Raick, C. and Soetaert, K., 2008. Numerical Modeling of the Central Black Sea Ecosystem Functioning During the Eutrophication Phase. *Progress in Oceanography*, 76(3), pp. 286-333. doi:10.1016/j.pocean.2008.01.002

5. Oguz, T., Ducklow, H.W., Purcell, J.E. and Malanotte-Rizzoli, P., 2001. Modeling the Response of Top-Down Control Exerted by Gelatinous Carnivores on the Black Sea Pelagic Food Web. *Journal of Geophysical Research: Oceans*, 106(C3), pp. 4543-4564. doi:10.1029/1999JC000078

6. Dorofeev, V.L. and Sukhikh, L.I., 2019. Studying Long-Term Variations in Black-Sea Ecosystem Based on the Assimilation of Remote Sensing Data in a Numerical Model. *Water Resources*, 46, pp. 65-75. doi:10.1134/S0097807819010032

7. Dorofeyev, V. and Sukhikh, L., 2018. A Model for Monitoring the Evolution of the Black Sea Ecosystem on the Basis of Remote Sensing Data Assimilation. *International Journal of Remote Sensing*, 39(24), pp. 9339-9355. doi:10.1080/01431161.2018.1523589

8. Demyshev, S.G. and Korotaev, G.K., 1992. [Numerical Energy Balanced Model of Baroclinic Currents of the Ocean with an Uneven Bottom on a Grid C]. In: *Numerical Models and Results of Calibration Calculations of Currents in the Atlantic Ocean*. Moscow: INM RAS Publishing, pp. 163-231 (in Russian).

9. Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A., Balsamo, G. [et al.], 2011. The ERA-Interim Reanalysis: Configuration and Performance of the Data Assimilation System. *Quarterly Journal of the Royal Meteorological Society*, 137(656), pp. 553-597. doi:10.1002/qj.828

10. Dorofeev, V.L. and Sukhikh, L.I., 2017. Study of Long-Term Variability of Black Sea Dynamics on the Basis of Circulation Model Assimilation of Remote Measurements. *Izvestiya, Atmospheric and Oceanic Physics*, 53(2), pp. 224-232. doi:10.1134/S0001433817020025

11. Galperin, B., Kantha, L.H., Hassid, S. and Rosati, A., 1988. A Quasi-Equilibrium Turbulent Energy Model for Geophysical Flows. *Journal of the Atmospheric Sciences*, 45(1), pp. 55-62. doi:10.1175/1520-0469(1988)045<0055:AQETEM>2.0.CO;2

12. Mellor, G.L. and Yamada, T., 1982. Development of a Turbulence Closure Model for Geophysical Fluid Problems. *Reviews of Geophysics*, 20(4), pp. 851-875. doi:10.1029/RG020i004p00851

13. Dorofeyev, V.L. and Sukhikh, L.I., 2017. Modeling of Long-Term Evolution of Hydrophysical Fields of the Black Sea. *Oceanology*, 57(6), pp. 784-796. doi:10.1134/S0001437017060017

14. Ludwig, W., Dumont, E., Meybeck, M. and Heussner, S., 2009. River Discharges of Water and Nutrients to the Mediterranean and Black Sea: Major Drivers for Ecosystem Changes During Past and Future Decades? *Progress in Oceanography*, 80(3-4), pp. 199-217. doi:10.1016/j.pocean.2009.02.001

15. Suslin, V. and Churilova, T., 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

16. Finenko, Z.Z., Mansurova, I.M. and Suslin, V.V., 2022. Temporal Dynamics of Phytoplankton Biomass in the Surface Layer of the Black Sea According to Satellite Observations. *Oceanology*, 62(3), pp. 416-427 (in Russian).

17. Dorofeev, V.L. and Sukhikh, L.I., 2016. Analysis of Variability of the Black Sea Hydrophysical Fields in 1993–2012 Based on the Reanalysis Results. *Physical Oceanography*, (1), pp. 33-47. doi:10.22449/1573-160X-2016-1-33-47

18. Kubryakova, E.A. and Korotaev, G.K., 2017. Mechanism of Horizontal Mass- and Salt-Exchange between the Waters of Continental Slope and Central Part of the Black Sea. *Izvestiya, Atmospheric and Oceanic Physics*, 53(1), pp. 102-110. doi:10.1134/S0001433817010078

19. Yunev, O.A., Konovalov, S.K. and Velikova, V., 2019. *Anthropogenic Eutrophication in the Black Sea Pelagic Zone: Long-Term Trends, Mechanisms, Consequences*. Moscow: GEOS, 164 p. doi:10.34756/GEOS/2019.16.37827 (in Russian).

About the authors:

Victor L. Dorofeev, Leading Research Associate, Marine Hydrophysical Institute of RAS (2 Kapitanskaya Str., Sevastopol, 299011, Russian Federation), Ph.D. (Phys.-Math.), **ResearcherID: G-1050-2014**, viktor.dorofeev@mhi-ras.ru

Larisa I. Sukhikh, Research Associate, Marine Hydrophysical Institute of RAS (2 Kapitanskaya Str., Sevastopol, 299011, Russian Federation), **ResearcherID: M-4381-2018**, l.sukhikh@gmail.com

Contribution of the co-authors:

Victor L. Dorofeev – formulation of the problem, numerical computations, analysis of results

Larisa I. Sukhikh – numerical computations, analysis of results

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