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Winter Peak of Phytoplankton Bloom in Sevastopol Bay according to Numerical Modeling

K. A. Slepchuk *, T. V. Khmara

Marine Hydrophysical Institute of RAS, Sevastopol, Russia
* *e-mail: skira@mhi-ras.ru*

Abstract

The winter peak of phytoplankton bloom in the Sevastopol Bay is reproduced using the 3D water quality model MECCA using meteorological data for January 2003. A detailed dynamic pattern of currents' variability, temperature, salinity, concentration of phytoplankton biomass and phosphate phosphorus is reproduced. The formation of an anticyclonic eddy in the central region of the bay is demonstrated, which led to an increase in the phosphorus phosphates concentration and phytoplankton bloom. The maximum of phytoplankton bloom (0.056 gC/m^3) was observed on the 23rd model day in the central part, then the maximum concentration of biomass decreased to 0.047 gC/m^3 in the central and eastern parts of the bay. There was also a decrease in phosphorus phosphates concentration from the maximum 0.0085 gP/m^3 on January, 10 to 0.0049 gP/m^3 on January, 23 in the central part of the bay. The concentration of phytoplankton biomass increased until January, 23, and then decreased, the phosphorus phosphates concentration decreased throughout the whole calculation period. The estimates obtained in the course of numerical modelling generally agree with the observational data. The performed study can serve as a basis for the development and application of a model approach to monitoring and managing of ecosystem processes on shallow water. Using this model, it is possible to calculate various scenarios for the bay eutrophication in case nutrients are discharged.

Keywords: phytoplankton biomass, phytoplankton bloom, biogeochemical simulation, hydrodynamic model, Sevastopol Bay

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Зимний пик цветения фитопланктона в Севастопольской бухте по результатам численного моделирования

К. А. Слепчук*, Т. В. Хмара

Морской гидрофизический институт РАН, Севастополь, Россия
* *e-mail: skira@mhi-ras.ru*

Аннотация

В работе воспроизводится зимний пик цветения фитопланктона в Севастопольской бухте с помощью трехмерной модели качества вод *MECCA* с использованием метеоданных за январь 2003 г. Воспроизведена детальная динамическая картина изменчивости течений, температуры, солености, концентрации биомассы фитопланктона и фосфора фосфатов. Показано образование антициклонической вихревой ячейки в центральном районе бухты, которое привело к увеличению концентрации фосфора фосфатов и цветению фитопланктона в этом районе. Максимум цветения фитопланктона (0.056 гС/м^3) наблюдался 23 января в центральном районе, затем максимальная концентрация биомассы снизилась до 0.047 гС/м^3 в центральном и восточном районах бухты. Также прослеживается уменьшение концентрации фосфора фосфатов от максимальных 0.0085 гР/м^3 10 января до 0.0049 гР/м^3 23 января в центральном районе бухты. Концентрация биомассы фитопланктона растет до 23 января, а затем снижается, концентрация фосфора фосфатов снижается на протяжении всего расчетного периода. Оценки, полученные в ходе численного моделирования, в целом соответствуют данным наблюдений. Выполненное исследование может служить основой для развития и применения модельного подхода к мониторингу и управлению экосистемными процессами в мелководных водоемах. С помощью данной модели можно рассчитать различные сценарии эвтрофирования бухты при сбросах в нее биогенных веществ.

Ключевые слова: биомасса фитопланктона, цветение фитопланктона, биогеохимическое моделирование, гидродинамическая модель, Севастопольская бухта

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Introduction

The coastal areas of the sea, especially closed and semi-closed water areas, which include Sevastopol Bay, experience a significant man-caused load. Limited water exchange with the sea results in the pollution of the bay and prevents rapid self-purification. The stationary sources of pollution are economic and recreational facilities located on the shores of the bay, as well as ship moorings. More than thirty temporary and permanent wastewater and municipal sewage outlets, as well as

Fig. 1. Sevastopol Bay zoning according to the pollution level [2]: W – mild pollution zone; E – moderate pollution zone; C – strong pollution zone; S – very strong pollution zone

runoff from the river Chernaya transport untreated or conditionally treated waters with pollutants of various nature to the bay. The consequences of such discharges depend on a number of physical, chemical and biological processes, the result of which is the response of phytoplankton.

Depending on the localization of pollution sources, morphometric characteristics and hydrometeorological conditions, both relatively clean zones and zones of a stable high level of pollution (e.g., Yuzhnaya Bay) are formed in Sevastopol Bay [1]. According to the pollution level, the water area of Sevastopol Bay was divided into four zones (Fig. 1) [2].

When assessing the ecological state of the Sevastopol Bay ecosystems, it is also necessary to take into account the seasonality of biological processes (warm and cold periods), which determine the inclusion of nutrients in the composition of the waterbody primary production, their deposition in bottom sediments, and subsequent recycling resulted from the destruction of organic matter.

The winter period is one of the most important seasons for the shallow water ecosystems. The winter phytoplankton bloom in the bay is stipulated by an increase in the supply of nutrients resulted from the decomposition of organic matter in deeper layers with good vertical mixing throughout the entire water column of the bay.

An increase in the eutrophication level of a waterbody is one of the negative results of human impact on nature due to the saturation of the water area with nutrients, which is accompanied by an increase in phytoplankton biomass. Phytoplankton, being the initial element in the food chain of an aquatic ecosystem, produces organic matter with higher energy content from inorganic substances with low energy content. Phytoplankton can indicate the state of the ecosystem, because the state and development of zooplankton and fish depends on it.

Previously, the problem of the phytoplankton biomass modelling in Sevastopol Bay was solved using a 2D ecological model of the reaction-diffusion class [3]. In this model, the photosynthetic rate does not depend on the concentration of nutrients due to the fact that the bay is excessively enriched with them. Among other things, there is no dependence on water temperature. The only factor limiting the process in this model is light. Using a 3D physical and biochemical model [4], the concentration fields of phytoplankton biomass and nutrients in Sevastopol Bay were calculated for wind conditions prevailing in July, while in this work the photosynthetic rate depended on the concentration of nutrients and light.

The aim of this work is to study the formation of the winter peak of phytoplankton bloom in the waters of Sevastopol Bay based on mathematical modelling, taking into account the variability of temperature and water dynamics in winter, as well as to assess the effect of phytoplankton bloom on changes in the eutrophication level of the bay.

Materials and methods

Using a numerical non-stationary 3D model MECCA [1] (Model for Estuarine and Coastal Assessment) and chemical and biological module, the fields of variability of phytoplankton biomass, phosphate phosphorus, ammonium nitrogen, nitrates and nitrites, and oxygen in Sevastopol Bay in the period from January 1 to January 31 of the model year were calculated. Model days correspond to the days of the month. Previously, this model was standardized in a 1D version in order to obtain the specific rates of chemical and biological processes and coefficients reflecting the characteristics of the environment and external factors in empirical equations [5]. Using a standardized 1D version of the model, the annual variation of the phytoplankton biomass, the content of phosphorus phosphates, ammonium nitrogen, nitrite nitrogen and nitrate nitrogen, and oxygen in Sevastopol Bay was calculated. In addition, the annual variation of the E-TRIX eutrophication index was calculated both in the entire bay and in each of its zones [6, 7]. The results of calculations using the hydrodynamic module of the MECCA model 3D version are presented in [8].

The mathematical structure of the chemical and biological module of the MECCA model is based on the synthesis of known theoretical and applied water qualitymodels [9]. When constructing the module, it is taken into account that the rates of phosphatization and ammonification of organic matter can be different. Inclusion of concentrations of nitrogen and phosphorus organic and inorganic forms in the structure of the model as variables makes it possible to automatically take into account possible differences in the ratios between nitrogen and phosphorus in the composition of autochthonous and allochthonous (including those coming from anthropogenic sources) organic matter. The combination of phosphorus and nitrogen cycles in the model is based on the equation of phytoplankton dynamics, which describes the primary production of organic matter by phytoplankton in the process of photosynthesis, as well as the replenishment of inert organic matter (in units of phosphorus and nitrogen) as a result of respiration, natural death rate, and phytoplankton grazing.

The following hydrochemical and hydrobiological characteristics are considered as model variables: phytoplankton biomass B_{ph}, constant P_{rpop} and labile P_{lpop} fractions of organic phosphorus in detritus,constant P_{rdop} and labile P_{ldop} fractions of dissolved organic phosphorus, mineral dissolved phosphorus P_{dip}, constant N_{lpon} and labile N_{rpon} fractions of organic nitrogen in detritus, constant N_{rdon} and labile N_{ldon} fractions of dissolved organic nitrogen, ammonium nitrogen N_{nh4}, nitrogen of

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[1] Hess, K.W., 1989. *MECCA Programs Documentation.* Washington, D.C.: U.S. Department of Commerce, 266 p. Available at: https://repository.library.noaa.gov/view/noaa/19301/noaa_19301_DS1.pdf [Accessed: 08 June 2023].

nitrates and nitrites $N_{\text{no3+no2}}$, constant C_{rpoc} and labile C_{lpoc} fractions organic carbon in detritus, constant C_{rdoc} and labile C_{ldoc} fractions of dissolved organic carbon, dissolved organic carbon emitted by algae C_{exdoc}, dissolved oxygen O_2 [10].

The model uses the assumption of the constancy of the organic matter chemical composition in accordance with its stoichiometric model $(CH_2O)_{106}(NH_3)_{16}H_3PO_4$. Thus, the ratio between carbon, nitrogen and phosphorus in organic matter is C:N:P = 106:16:1 (µmol) [2)]. Since mineral phosphorus limits the phytoplankton bloom, we present the equations of phytoplankton biomass and phosphate phosphorus.

Phytoplankton biomass B_{ph} (gC/m^3):

$$\frac{dB_{\text{ph}}}{dt} = \left[G_{\text{B}} - k_{\text{pr}}(T) - k_{\text{grz}}(T)\right]B_{\text{ph}},$$

where t – time, day; T – water temperature, °C; G_{B} – specific gross production, 1/day; k_{pr}– specific metabolic rate (respiration), 1/day; k_{grz} – specific rate of grazing of phytoplankton by zooplankton and natural death rate of phytoplankton, 1/day, which are written as the following functional dependencies:

$$G_{\text{B}} = G_{\text{Bmax}} G_T(T) G_I(T) G_{\text{NP}}(N_{\text{din}}, P_{\text{dip}}),$$

$$G(I) = \frac{1}{\Delta Z}\int_{Z_i}^{Z_{i+1}} f_Z(I_Z)dZ = \frac{2.718 f_d}{\Delta Z \alpha}\left[\exp(-R_{Z_i}) - \exp(-R_{Z_{i+1}})\right],$$

$$R_0 = \frac{I_a}{I_{\text{opt}}}, \qquad R_{Z_i} = R_0 \exp(-\alpha Z_i), \qquad \Delta z = z_{i+1} - z_i,$$

$$f_Z(I_Z) = \frac{I_Z}{I_{\text{opt}}} \exp\left(1 - \frac{I_Z}{I_{\text{opt}}}\right), \qquad I_Z = I_a \exp(-\alpha z),$$

$$G_{\text{NP}}\left(N_{\text{din}}, P_{\text{dip}}\right) = \min\left\{\frac{N_{\text{din}}}{K_{\text{mn}} + N_{\text{din}}}, \frac{P_{\text{dip}}}{K_{\text{mp}} + P_{\text{dip}}}\right\},$$

where $N_{\text{din}} = N_{\text{nh4}} + N_{\text{no3+no2}}$;

$$G_T(T) = \begin{cases} e^{\varsigma_1 (T - T_m)^2}, & \text{если } T \le T_m, \\ e^{\varsigma_2 (T_m - T)^2}, & \text{если } T > T_m, \end{cases}$$

$$k_{\text{pr}}(T) = r_g G_{\text{B}} + r_b \theta_{\text{pr}}^{(T-20)},$$

$$k_{\text{grz}}(T) = k_{\text{grz}}(20)\theta_{\text{grz}}^{(T-20)}.$$

Here, G_{Bmax} – maximum specific gross production, 1/day; I_a – average daylight flow of photosynthetically active radiation (PAR) that penetrates the sea surface, W/m^2;

[2)] Alekin, O.A. and Lyakhin, Yu.I., 1984. *Chemistry of the Ocean*. Leningrad: Gidrometeoizdat, 343 p. (in Russian).

I_{opt} – optimal irradiance for photosynthesis, W/m^2; f_d – proportion of daylight hours per day and night period ($0 \le f_d \le 1$); I_z – irradiance at depth z, W/m^2; α – integral coefficient of PAR intensity attenuation with depth; K_{mn}, K_{mp} – half-saturation constants of the utilization rate of nitrogen and phosphorus mineral forms by phytoplankton, respectively, g/m^3; T_m – water temperature optimal for algae growth, °C; ς_1, ς_2 – coefficients that determine the nature of the temperature influence on the growth of algae in the ranges above and below T_m, 1/°C^2; r_g – proportion of algae production that is spent on the photosynthesis energy supply; r_b – specific algae metabolic rate at 20 °C, 1/day; θ_{pr} – coefficient of temperature influence on metabolic rate; $k_{\text{grz}}(20)$ – specific rate of grazing and death of phytoplankton at 20 °C, 1/day; θ_{grz} – coefficient of temperature effect on the rate of algae grazing and death.

Mineral dissolved phosphorus P_{dip} (гP/м^3):

$$\frac{dP_{\text{dip}}}{dt} = \alpha_{\text{pc}} f_{\text{dip}} \left(k_{\text{pr}}(T) + k_{\text{grz}}(T)\right) B_{\text{ph}} +$$
$$+ \left(k_{\text{mrdp}} \theta_{\text{mrdp}}^{T-20} P_{\text{rdop}} + k_{\text{mldp}} \theta_{\text{mldp}}^{T-20} P_{\text{ldop}}\right) \frac{\text{O}_2}{K_{\text{O}_2} + \text{O}_2} - \alpha_{\text{pc}} (1 - f_{\text{exB}}) G_{\text{B}} B_{\text{ph}},$$

where α_{pc} – coefficient expressing the stoichiometric ratio between carbon and phosphorus in organic matter, gP/gC; k_{mrdp} – specific rate of mineralization of dissolved organic phosphorus stable fraction at 20 °C water, 1/day; θ_{mrdp} – temperature coefficient; k_{mldp} – specific rate of mineralization of the dissolved organic phosphorus labile fraction at 20 °C water, 1/day; θ_{mldp} – temperature coefficient; K_{O_2} – process half-saturation constant in relation to available oxygen concentration, gO$_2$/m^3; f_{dip} – proportion of mineral phosphorus in the algae metabolic secretions, remains of dead and grazed algae; f_{exB} – proportion of algae primary production that is excreted as dissolved organic matter. The parameters and empirical coefficients used in the calculations are shown as follows:

G_{Bmax}	1.88 1/day	θ_{grz}	1.1
ς_1	0.006 1/°C^2	α_{pc}	0.022 gP/gC
ς_2	0.006 1/°C^2	f_{dip}	0.2
T_m	9.5 °C	k_{mrdp}	0.01
K_{mn}	0.025 gN/m^3	θ_{mrdp}	1.08
K_{mp}	0.0025 gP/m^3	k_{mldp}	0.1
r_g	0.2	θ_{mldp}	1.08
r_b	0.01	K_{O_2}	1 gC/m^3
θ_{pr}	1.067	f_{exB}	0.1
k_{gzr}	0.05 1/day		

During calculations, the water area of the bay was covered with a grid of 47 × 97 nodes with a step of 80 m and was divided into 10 model levels along the vertical in the σ-coordinate system. Data on air temperature and wind impact were estimated from measurements at the hydrometeorological station at Cape Pavlovsky on the southern shore of Sevastopol Bay. Urgent data on wind speed and direction, air temperature for 2003 with a 6-hour interval, monthly average data on humidity and cloud cover for 2003 were used for modelling.

At the boundary between the bay and the open sea, average monthly values of temperature, salinity, phytoplankton biomass, phosphorus phosphates, nitrogen nitrates, nitrites and ammonium, oxygen on the surface and at the bottom were set. At the boundary between the bay and the river, daily values of temperature, salinity, phytoplankton biomass, phosphorus phosphates, nitrogen nitrates, nitrites and ammonium, oxygen on the surface and at the bottom of the river were set. The initial fields of temperature, salinity, phytoplankton biomass, content of nutrients and oxygen were set to be horizontally homogeneous.

Results

The cumulative effect of a number of factors, among which air and water temperature, waterbody hydrodynamic regime, and concentration of nutrients (mainly inorganic phosphorus), plays a significant role in the development of phytoplankton in shallow water areas.

The air temperature in January 2003 was characterized by strong fluctuations (from –5 to 15 °C) in the first half of the month and was relatively stable (about 5 °C) in the last third of January (Fig. 2). Such changes in air temperature affected the surface water temperature in the bay. *In situ* data analysis showed that the low air temperature in January 2003 led to the upper water layer cooling [11].

In January, low salinity was noted. The main reason for its change in the study area is a salinity decrease in the surface layer caused by rains during the survey period and just before [11].

The wind regime is the main factor determining the dynamics of waters in shallow water areas. Fig. 3 shows the windroses in Sevastopol Bay in January 2003: from 1 to 19 January, from 20 to 26 January, and from 27 to 31 January.

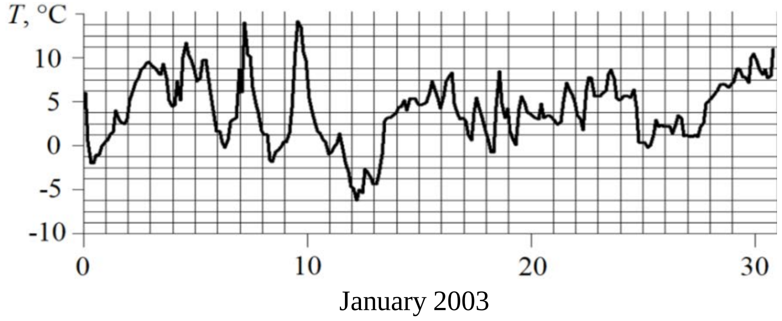

Fig. 2. Changes in air temperature in Sevastopol Bay area in January 2003

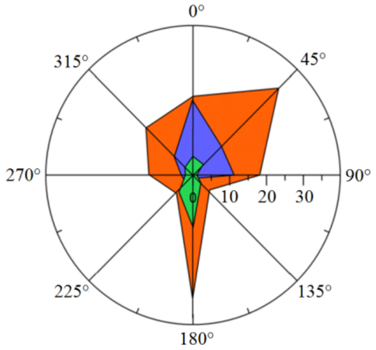

Fig. 3. Windroses from 1 to 19 January (red colour), from 20 to 26 January (blue colour) and from 27 to 31 January (green colour) 2003

In the first half of the month, the wind regime was very variable. Winds of all directions were observed with the predominance of southerly winds. From January 20, mainly northerly and northeasterly winds were observed, which from January 27 changed their direction to the south, southwest.

The structure and speed of currents in a reservoir affect production processes both directly and indirectly. The direct effect is manifested in the mechanical effect on the growth and development of phytoplankton, and the indirect effect is shown through the change in the physical and chemical conditions of algae vegetation.

The distribution of currents and water temperature in the Sevastopol Bay was obtained using a 3D hydrothermodynamic model. The pattern of currents in the bay is influenced by shallow depths, as well as by the large length and indentation of the coastline. The structure of the currents corresponds to the average climate for the winter period, obtained in [12] with an easterly wind. According to the calculation results, the current is directed from the bay to the open sea, while the highest vorticity is typical for the eastern part of the bay (Fig. 4).

Wind direction and bottom topography have the main effect on the formation of currents in the central region of the bay. In winter, there is almost no fresh water inflow from the river Chernaya. During the period of winter cooling, a sharp cooling of surface waters and activation of convective mixing lead to the appearance of many irregular structures in the overall flow pattern. One of the eddies is observed in the central region.

Figures 5 and 6 show the dynamics of phytoplankton biomass, phosphate phosphorus for the 10th, 17th, 23rd, and 29th model days. The table shows the values

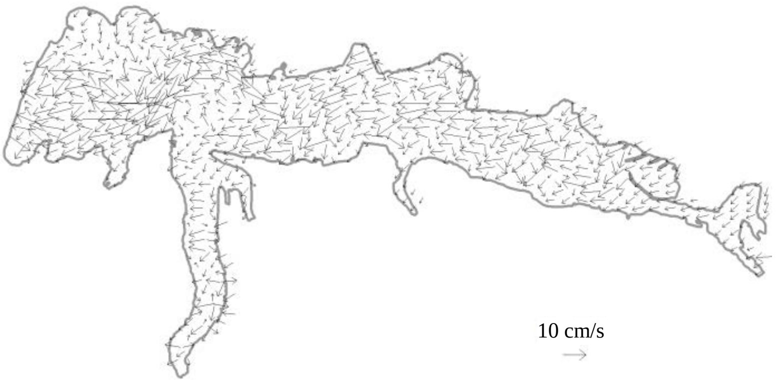

Fig. 4. Map of currents on the bay water surface on the 23rd model day

Variability range (above the line) and average values (under the line) of the phytoplankton biomass concentration B_{Ph}, gC/m^3, and phosphate phosphorus PO$_4$, gP/m^3, in the Sevastopol Bay areas

Model day	Area	Concentration	
		B_{Ph}	PO$_4$
10	W	0.0222–0.0355 0.0307	0.0011–0.0069 0.0059
	S	0.0272–0.0385 0.0332	0.0032–0.0078 0.0064
	C	0.0325–0.0444 0.0404	0.00590.0094 0.0086
	E	0.0238–0.0432 0.0383	0.0009–0.0094 0.0085
17	W	0.0235–0.035 0.0306	0.0014–0.0041 0.0033
	S	0.0306–0.0387 0.0343	0.0025–0.0048 0.004
	C	0.0401–0.0526 0.047	0.0053–0.0067 0.0061
	E	0.0282–0.0525 0.0488	0.0007–0.0068 0.0061
23	W	0.0242–0.0472 0.0416	0.0012–0.0038 0.0032
	S	0.0301–0.051 0.0411	0.0022–0.0042 0.0034
	C	0.0455–0.056 0.0537	0.0045–0.0053 0.0049
	E	0.0294–0.0553 0.0504	0.0006–0.0053 0.0048
29	W	0.0221–0.0343 0.0291	0.0009–0.0021 0.0016
	S	0.0294–0.036 0.0332	0.0009–0.0021 0.0016
	C	0.0377–0.0472 0.0429	0.0027–0.0041 0.0033
	E	0.029–0.0474 0.0436	0.0006–0.0043 0.0039

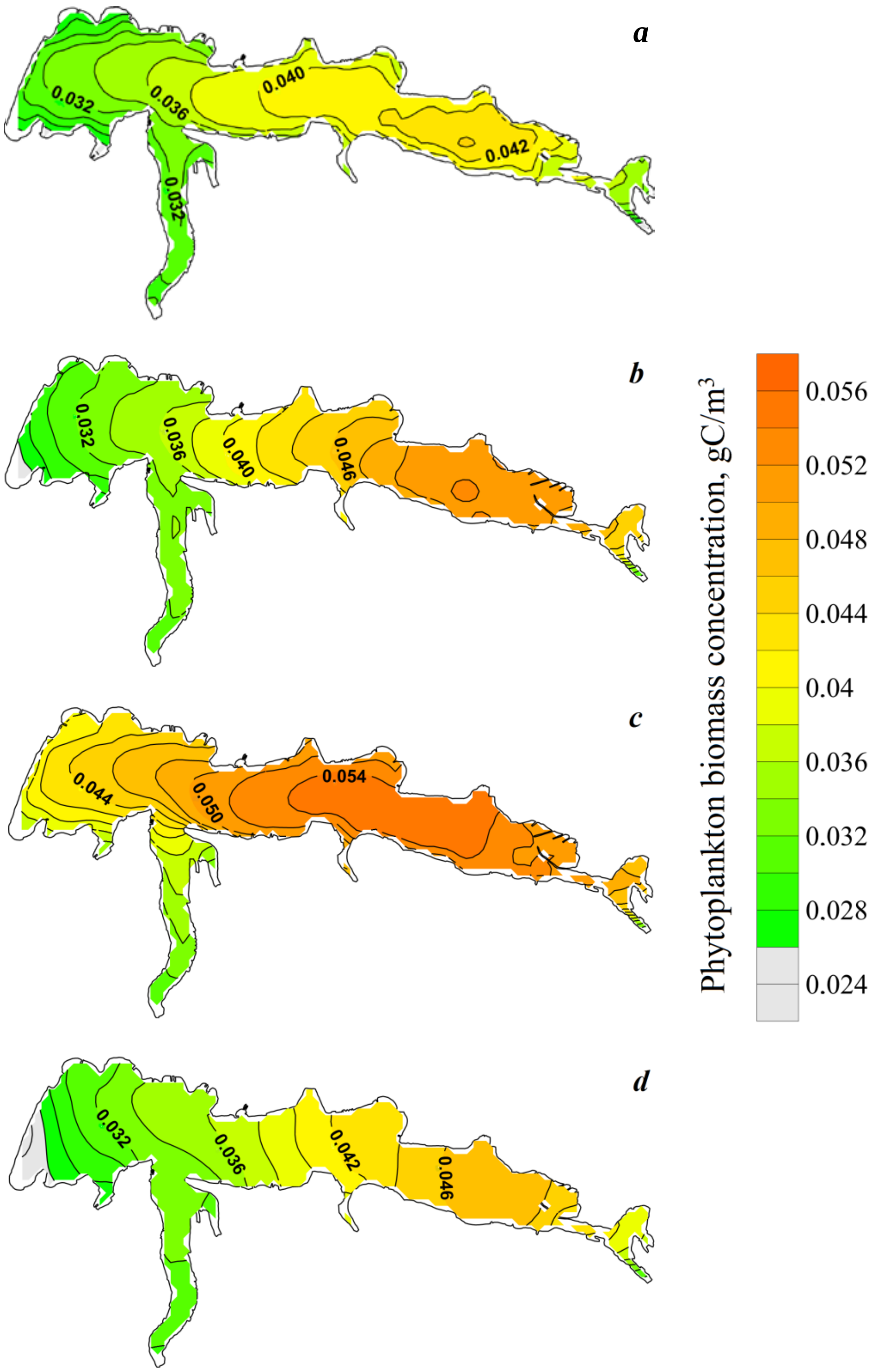

Fig. 5. Phytoplankton biomass concentration, gC/m^3, on the 10th (*a*), 17th (*b*), 23rd (*c*) and 29th (*d*) model days in Sevastopol Bay

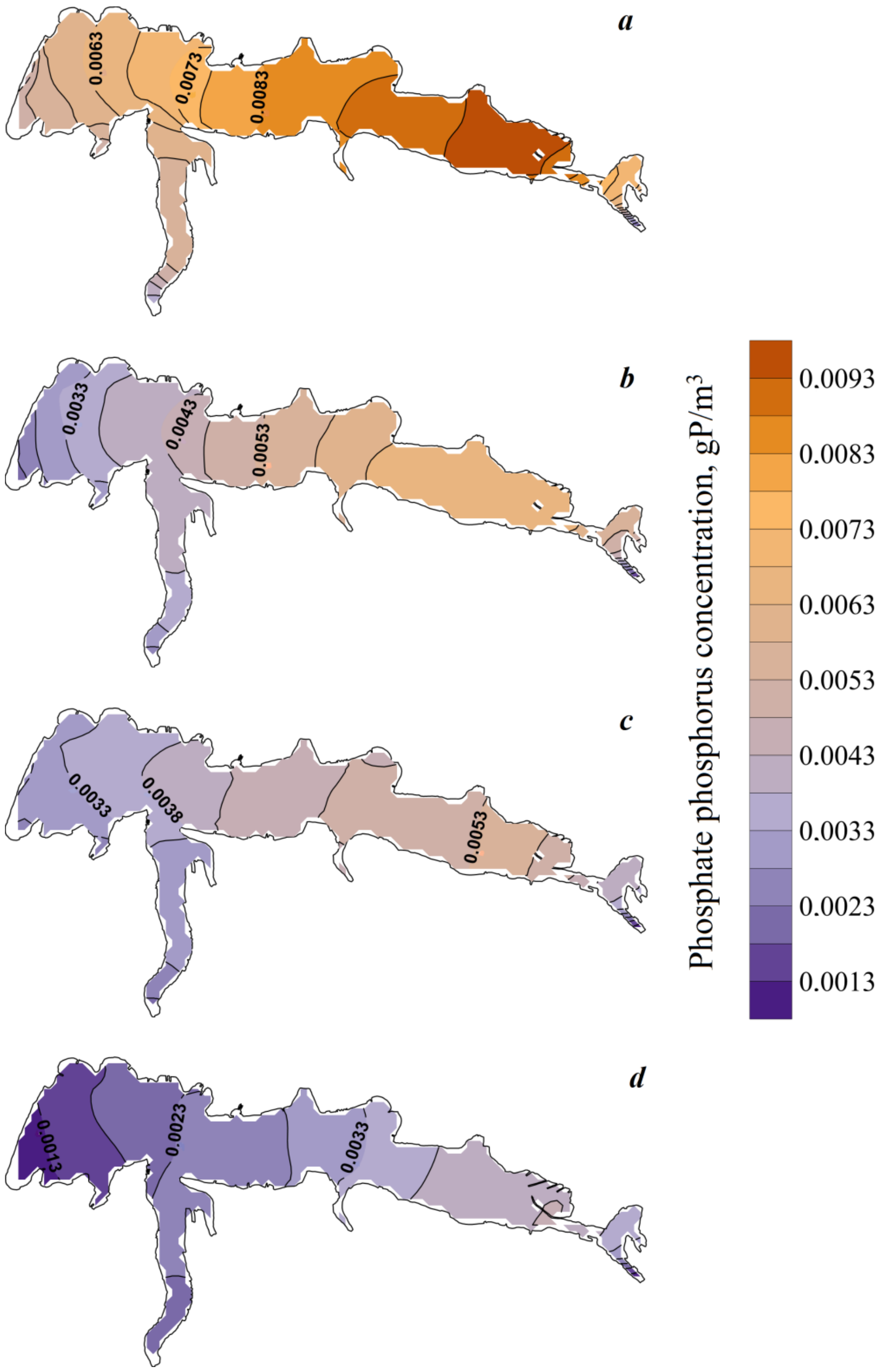

Fig. 6. Phosphate phosphorus concentration, gP/m^3, on the 10th (*a*), 17th (*b*), 23rd (*c*) and 29th (*d*) model days in Sevastopol Bay

of these indicators on average, as well as their range of variability in the western (W), southern (S), central (C), eastern (E) areas of the bay according to zoning in [2] (see Fig. 1). The highest concentrations of phytoplankton biomass and phosphorus phosphates over the entire model period are observed in the eastern and central regions. The maximum phytoplankton bloom is observed on the 23rd model day – 0.056 gC/m^3 in the central region, then the maximum biomass concentration decreases to 0.047 gC/m^3 in the central and eastern regions. In addition, in the central region of the bay, a decrease in the concentration of phosphorus phosphates is observed from the maximum 0.0085 gP/m^3 on the 10th model day to 0.0049 gP/m^3 on the 23rd model day. This confirms the fact that phosphorus, being the limiting element, is consumed by phytoplankton.

The blooming area in the central region can be explained by the formed eddy, due to which an area with an increased concentration of phosphorus phosphates, as well as an increased temperature, compared to other areas of the bay, appeared, which is a favourable factor for the development of algae. If the phytoplankton biomass concentration increases on average in the bay from 0.0357 gC/m^3 on the 10th model day to 0.0467 gC/m^3 on the 23rd model day, and then decreases to 0.0372 gC/m^3 on the 29th model day, then the concentration of phosphorus phosphates during the entire model period decreases from 0.0074 gP/m^3 on the 10th model day to 0.0028 gP/m^3 on the 29th model day. This fact also indicates the consumption of phosphorus phosphates by phytoplankton and, due to its shortage by the end of the model period, a decrease in the concentration of phytoplankton biomass. The results obtained are in good agreement with the experimental data described in [11, 13, 14].

Conclusion

The performed numerical modelling of the winter phytoplankton bloom in the Sevastopol Bay under the meteorological conditions of January 2003 makes it possible to trace the dynamics of phytoplankton and phosphorus phosphates in different regions of the bay. The peak of phytoplankton bloom is observed on the 23rd model day in the central region of the bay, while the concentration of phosphorus phosphates decreases throughout the model period. The maximum values of the concentrations of these parameters in the central region of the bay are stipulated by the formed eddy and increased water temperature. The estimates obtained in the course of numerical simulation generally agree with the observational data.

Despite the fact that, in the absence of observational data, the results of modelling serve only as an indirect estimate, their use will help advance the understanding of the mechanisms of ecological processes and outline the direction of future clarifying studies. Through modelling, it is also possible to calculate various scenarios for the bay eutrophication with an increase in the volume of nutrients discharged into it.

The performed study can serve as a basis for further development of the model approach and its application to the monitoring and management of ecosystem processes in shallow waterbodies.

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About the authors:

Kira A. Slepchuk, Junior Research Associate, Marine Hydrophysical Institute of RAS (2 Kapitanskaya St., Sevastopol, 299011, Russian Federation), **ORCID ID: 0000-0001-5437-4866, ResearcherID: H-9366-2017**, *skira@mhi-ras.ru*

Tatyana V. Khmara, Research Associate, Marine Hydrophysical Institute of RAS (2 Kapitanskaya St., Sevastopol, 299011, Russian Federation), **Scopus Author ID: 6506060413**, **ResearcherID: C-2358-2016**, *xmara@mhi-ras.ru*

Contribution of the authors:

Kira A. Slepchuk – problem statement, performance of numerical calculations, processing and interpretation of modelling results, preparation of the article text and graphic materials

Tatyana V. Khmara – performance of numerical calculations, analysis and description of the study results, text preparation

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