Mathematical modeling of zooplankton productivity in the Azov Sea in summer on a high-performance computer system

Sukhinov A I¹, Belova Y V¹, Lyapunova I A² and Nikitina A V²,³

¹ Don State Technical University, 1, Gagarin Square, Rostov-on-Don, 344000, Russia
² Southern Federal University, 105/42, Bolshaya Sadovaya Str., Rostov-on-Don, 344006, Russia
³ Supercomputers and Neurocomputers Research Center, 106, Italyansky lane, 347900, Taganrog, Russia

E-mail: nikitina.vm@gmail.com

Abstract. The work is devoted to modeling of eurythermal and stenothermal zooplankton populations productivity in the Azov Sea in summer. The discretization of the problem was carried out using difference schemes of a higher order of accuracy, taking into account the filling of the calculated cells. The grid equations obtained as a result of the proposed mathematical model of biological kinetics discretization were solved by a modified adaptive variable-triangular method, which has a higher convergence rate in comparison with the existing methods of the variational type. A parallel algorithm for solving the problem on a high-performance computing system was developed, which made it possible to significantly reduce the time of the numerical solution of the problem. With the help of mathematical modeling, the analysis of various ways of development of the Azov Sea ecosystem was carried out, the influence of the gelatinous invasive on the production and de-struction processes of phyto- and zooplankton was researched. The developed software module, oriented to a multiprocessor computing system, can be effectively used for predictive modeling of interrelated hydrodynamic and biogeochemical processes in a shallow water body in summer.

1. Introduction

The geographical position and relatively small size of shallow water bodies, like the Azov Sea, determine the high spatio-temporal variability of the main abiotic factors of the sea ecosystem, especially salinity, which determines the significant, compared to the volume of the sea, river runoff, water exchange with the Black Sea and fluctuations of the general moisture of the water body. Violation of the natural habitat of aquatic organisms in water bodies entails changes in their production parameters and structural changes. One of the most important groups in the aquatic animal community is zooplankton, which in the ecosystem performs the function of an energy transformer in the food chain from producers to secondary consumers, in particular fish. Zooplankton makes up the food supply for planktrophagous fish and juveniles of other valuable commercial species, which is one of the most important factors that determine the fish productivity of water bodies [1, 2]. The first works devoted to the researching of zooplankton under the conditions of a changing sea regime appeared in the mid-1950s XX century. They reflect the influence of hydro construction and reduction of the Don River flow for reproduction, development and distribution of various species of zooplankton. Based on these data, an attempt was made to predict changes in the zooplankton of the
Azov Sea under conditions of regulated river flow, the response of certain species to changes in salinity was studied, faunistic lists of zooplankton in the Azov Sea were compiled, and the first reviews of studies of plankton communities were summed up. Many Russian and foreign scientists, such as Mordukhai-Boltovskiy F.D. [3], Kryuchkova N.M. [4], Odum Y., Vinberg G.G. [5], Petzold T. [6], Cheriton O.M. [7], Richards Sh.A., etc., have studied the factors affecting the heterogeneity of the distribution of species, among which temperature, illumination, diffusion processes, interactions between species, as well as daily vertical migrations of some species of zooplankton are mainly distinguished. Tables of average weights of zooplankton organisms used today for calculating the biomass of populations in the Azov-Black Sea region make it possible to obtain overestimated values of the communities biomass. During the period of increasing sea salinity, which averaged 13.8‰, in the late 70s XX century, the zooplankton community underwent significant structural and functional changes associated with the displacement of native species by invaders from the Black Sea. As a result of such a change in the composition of communities, not only the diversity, but also the productivity of zooplankton decreased: in the Taganrog Bay, it decreased by 1.5 times, in the main water area – by 1.2 times. Researches have shown that the invasion of the predatory zooplanktophage ctenophagus Mnemiopsis leidyi (M. leidyi) and its active development in the spring-summer period contributes to a significant redistribution of matter and energy flows in the pelagial food chain: Mnemiopsis enters the Azov Sea from the Black Sea, actively develops, feeding on mainly zooplankton, as well as larvae of fish and molluscs. As a result, the biomass of zooplankton from the second half of summer to autumn decreases to significantly small values (in the sea – up to 5–10 mg/m³, which is on average two orders of magnitude lower than the values in the period before the introduction of Mnemiopsis), the structure of communities in towards the prevalence of meroplankton, while the fish productivity of the reservoir decreases.

In order to quantify the role of zooplankton in the cycle of organic matter in water body, it is necessary to know not only the number and biomass of individual populations, but also the rate of production of organic matter by them, the degree of use of this production by predatory zooplankton species and fish, the contribution of each population to total zooplankton production. In this case, it is necessary to take into account the changes in these production characteristics during the year, depending on specific conditions. It is impossible to carry out a comprehensive study of zooplankton development based only on the results of processing standard samples. In this situation, the methods of mathematical modeling turn out to be the only opportunity for analysis and an attempt to find answers to many important questions of hydrobiology. The most common models of the dynamics of zooplankton communities take into account the food pyramid of water bodies "phytoplankton – zooplankton – fish – animals". Figure 1 shows the habitats of various species of zooplankton in the Azov Sea in summer [2]. In figure 1 Copepoda represented by Acartia tonsa, Centropages ponticus and Calanipeda aquae dulcis; Cladocera represented by Pleopis polyphemoides and Podonevadne trigona. Table 1 shows data on the composition of the Azov Sea zooplankton by the number of species [8]. According to expeditionary data, ecological atlases, literary sources, copepods and rotifers are most common in the Azov Sea in summer.

| Group     | Number of species |
|-----------|-------------------|
| Rotifera  | 37                |
| Copepoda  | 27                |
| Cladocera | 12                |
| Other     | 12                |
| Total     | 88                |

Table 1. The composition of the Azov zooplankton by the number of species.
Figure 1. Species composition of zooplankton in the Azov Sea in summer.

The currently available data on the production characteristics of plankton require clarification in connection with changes in the species composition of zooplankton as a result of fluctuations in climatic and oceanographic factors in the studied water area. When constructing forecasts of changes in hydrobiological processes in such complex natural systems as the Azov Sea, based on mathematical modeling methods, it becomes necessary to solve grid equations with a non-self-adjoint operator of large dimension (from $10^8$ to $10^{11}$ at each time layer). Solutions to such computationally laborious problems can be obtained using high-performance cluster-type systems.

2. Materials and methods

2.1. Zooplankton interaction mathematical model

Spatial three-dimensional mathematical model used to describe the ecological-biological process of interaction of eurythermal (resistant to fluctuations in water temperature) and stenothermal zooplankton species (sensitive to fluctuations in water temperature) and a gelatinous invasive limiting the development of zooplanckton in summer is based on a system of non-stationary equations of convection-diffusion-reaction parabolic type with nonlinear functions of sources and lower derivatives and has the form [9]:

$$\frac{\partial P_i}{\partial t} + \text{div}(UP_i) = \mu \Delta P_i + \frac{\partial}{\partial z} \left( \nu_i \frac{\partial P_i}{\partial z} \right) + \psi_i, \ i \in 1,9.$$

$$\psi_1(P_1, P_2, P_3) = \left\{ \alpha_1 z_1^2 P_4 \right\} P_1,$$

$$\psi_2(P_2, P_1, P_3) = \left\{ \alpha_2 z_2^2 \xi_2^2 P_4 - \delta_2 P_2 - \varepsilon_2 \right\} P_2,$$

$$\psi_3(P_1, P_2, P_3) = \left\{ \alpha_3 z_3^2 \xi_3^2 (P_1 + P_2) - \delta_3 - \varepsilon_3 \right\} P_3,$$
\[ \psi_i \left( P_1, P_2, P_3, P_5 \right) = \left( \alpha_{i4} + \gamma_i M_4 \right), \]
\[ \psi_s \left( P_1, P_2, \ldots, P_9 \right) = \sum_{i=1}^{4} \varepsilon_i P_i - \delta_i P_i + B \left( \bar{P}_i - P_i \right) + f, \]
\[ \psi_m \left( P_1, P_2, P_3, P_5, P_6, \ldots, P_9 \right) = \sum_{i=1}^{4} k_i P_i - \varepsilon_m P_m, m \in 6,9, \]

where \( P_i, i \in 1,9 \) – concentration values of: 1 – eurythermal zooplankton (Copepoda); 2 – stenothermal zooplankton (Rotifera and Cladocera); 3 – gelatinous plankton-comb jelly (Mnemiopsis leidyi); 4 – phytoplankton; 5 – nutrient; 6, 7, 8, 9 - metabolites of zooplankton 1 and 2, comb jelly, phytoplankton, respectively; \( \psi_i \) – functions of trophic interactions; \( \alpha_i \) – growth function of plankton (phyto-, zooplankton) and comb jelly, \( l = 1,4 \); \( \alpha_{i4}, \gamma_i \) – phytoplankton growth rate in the absence of metabolite and metabolite effect parameters; \( B \) – nutrient intake rate \( P_i \) (compounds of nitrogen, phosphorus, silicon); \( \bar{P}_i \) – maximum possible concentration of nutrients; \( \varepsilon_i \) – coefficient taking into account the mortality of the \( l \)-th type; \( \varepsilon_m \) – metabolite decomposition coefficients, \( m = 6,9, \); \( k_i \) – excretion coefficients of the \( l \)-th species (zooplankton, \( l = 1,2 \)), comb jelly (\( l = 3 \)), phytoplankton (\( l = 4 \)); \( \delta_i \) – loss rates on account of grazing, \( l = 1,4 \); \( f = f(x, y, z, t) \) – source function \( P_5 \) (pollution); \( u \) – flow velocity field; \( U = u + u_n, U = \left( U_1, U_2, U_3 \right) \) – convective transfer rate; \( u_{0i} \) – sedimentation rate of the \( i \)-th substance; \( \mu_i, \nu_i \) – diffusion coefficients in the horizontal and vertical directions of the \( i \)-th substance.

Functions of the dependence of the growth rate of aquatic organisms on temperature and salinity:

\[ \xi^T \left( T \right) = \exp \left( -a_i \left( T - T_{opt} \right) / T_{opt} \right)^2, l = 2,4; \]
\[ \xi^S \left( S \right) = \exp \left( -b_i \left( S - S_{opt} \right) / S_{opt} \right)^2, l = 1,4, \]

where \( T_{opt} \), \( S_{opt} \) – temperature and salinity optimal for a given type of aquatic organisms; \( a_i > 0 \), \( b_i > 0 \) – coefficients of the width of the range of aquatic organisms tolerance to temperature and salinity, respectively.

The functions of grazing phytoplankton by two species of zooplankton and zooplankton by the comb jelly have the following form:

\[ \delta_i = \sum_{n=1}^{2} r_n \Lambda P P_n \left( 1 - \exp \left( -\Lambda P_n \right) \right) \]
\[ \delta_n = r_n \Lambda P P_n \left( 1 - \exp \left( -\Lambda P_n \right) \right), n = 1,2, \]

where \( r_n \) – maximum intensity of grazing by a predator, \( \Lambda \) – Ivlev constant for grazing.

The computational domain \( G \) is a closed basin bounded by the undisturbed surface of the reservoir \( \Sigma_b \), the bottom \( \Sigma_0 = \Sigma(x, y) \), and the cylindrical surface \( \sigma \) for \( 0 < t \leq T_0 \). \( \Sigma = \Sigma_0 \cup \Sigma_0 \cup \sigma \) – piecewise-smooth boundary of the domain \( G \).

Add the boundary conditions to system (1):

\[ P_i = 0 \text{ on } \sigma, U_n < 0; \frac{\partial P}{\partial n} = \varphi_i \left( P_i \right) \text{ on } \sigma, U_n \geq 0; \frac{\partial P}{\partial n} = 0 \text{ on } \Sigma_0; \frac{\partial P}{\partial n} = -\beta_i P_i \text{ on } \Sigma_0, \]

where \( \beta_i \) – absorption coefficient of the \( i \)-th component by bottom sediments; \( \varphi_i \) – preset functions; \( n \) – outward normal vector to the surface \( \Sigma \).

It is also necessary to add the initial conditions:

\[ P_i \mid_{t=0} = P_{0i}(x, y, z), i = 1,9, \]

where \( P_{0i} \) – initial concentration of the \( i \)-th substance.
where \( P_{i0}(x, y, z) \) – preset functions.

### 2.2. Numerical solution of the diffusion-convection problem

Problem (1) – (3) for the two-dimensional case can be represented by the diffusion-convection-reaction equation, in the three-dimensional case, discretization is performed similarly:

\[
c_i' + u \frac{c_i'}{x} + v \frac{c_i'}{y} = \left( \mu c_i' \right)_x + \left( \mu c_i' \right)_y + f
\]

with boundary conditions:

\[
c_i'(x, y, t) = \alpha u + \beta_n,
\]

where \( u, v \) – velocity vector components, \( \mu \) – turbulent exchange coefficient, \( f \) – function describing the intensity and distribution of sources, \( \alpha_n, \beta_n \) – given coefficients.

For the numerical implementation of the problem discrete mathematical model, a uniform grid is introduced:

\[
w_h = \left\{ t^n = n\tau, x_i = ih_x, y_j = jh_y; \ n = 0, N_x, i = 0, N_x, j = 0, N_y; \ N_x, N_y, \tau = T, N_xh_x = l_x, N_yh_y = l_y \right\},
\]

where \( \tau \) – time step, \( h_x, h_y \) – space steps, \( N_x, N_y \) – upper time limit, \( l_x, l_y \) – characteristic dimensions of the computational grid.

Discrete analogues of convective operators \( uc_i' \) and diffusion transfer \( (\mu c_i')_x \) in the case of partial filling of the cells can be written in the following form:

\[
(q_0)_{i,j}uc_i' = \left( q_1 \right)_{i,j}u_{i+1/2,j} \frac{c_{i+1,j} - c_{i,j}}{2h_x} + \left( q_2 \right)_{i,j}u_{i-1/2,j} \frac{c_{i,j} - c_{i-1,j}}{2h_x},
\]

\[
(q_0)_{i,j}(\mu c_i')_x = \left( q_1 \right)_{i,j}u_{i+1/2,j} \frac{c_{i+1,j} - c_{i,j}}{h_x^2} + \left( q_2 \right)_{i,j}u_{i-1/2,j} \frac{c_{i,j} - c_{i-1,j}}{h_x^2} - \left( q_1 \right)_{i,j} - \left( q_2 \right)_{i,j} \mu_{i,j} \frac{\alpha x_{i,j} + \beta_x}{h_x}.
\]

To approximate the convective transfer operator by a difference scheme with the fourth order of accuracy, it is necessary to approximate the operator \( uc_i' - c_i' \frac{h_x^2}{4} - \frac{h_y^2}{4} \) by scheme of the second order of accuracy. To approximate the diffusion transfer operator by a difference scheme having the fourth order of accuracy, it is necessary to approximate the operator \( (\mu c_i')_x - \mu c_i' \frac{h_x^2}{12} - \frac{h_y^2}{6} \) by scheme of the second order of accuracy.

Grid equations obtained as a result of discretization of hydrophysics and biological kinetics mathematical models were solved by a modified adaptive alternating triangular method (MATM) [10].

### 3. Results and discussion

#### 3.1. Parallel implementation on a supercomputer

Parallel algorithms for MATM have been implemented at the MCS of the Southern Federal University (SFedU). MCS technical parameters: maximum productivity is 18.8 TFlops; 8 computing racks; the MCS computing field is based on the HP BladeSystem c-class infrastructure with integrated communication modules, power supply and cooling systems. 512 identical 16-core HP ProLiant BL685c Blade servers are used as computational nodes, each of which is equipped with four 4-core AMD Opteron 8356 2.3 GHz processors and 32 GB of RAM; the total number of computing nodes is 2048; the total amount of RAM is 4 TB.
With the parallel implementation of the developed numerical algorithms for solving the problem of interaction of zooplankton populations in the Azov Sea, methods of decomposition of computational domains were used for various computationally laborious problems of hydrodynamics and biological kinetics, taking into account the architecture and parameters of the supercomputer. The maximum acceleration was achieved on 512 processors and amounted to 63 times (table 2).

Figure 2 shows the graphs of the dependence of acceleration and efficiency on the number of processors for the developed parallel MATM algorithm for solving the problem of transporting pollutants in the Azov Sea [11].

To model the dynamics of the Azov Sea hydrobionts, a software package has been developed that makes it possible to calculate the concentrations of the main hydrobionts, including phyto- and zooplankton, gelatinous macroplankton (invading species - comb jellies) in areas of complex shape, implemented on a multiprocessor computing system (MCS) of Southern Federal University. The software complex allows for: improvement and implementation of a system of integrated fishery monitoring in water bodies (observation, assessment and forecast of the state of the state of the ecosystems regime, food base and stocks of commercial objects); development of the methodology of nature conservation research, creation of new, approbation and implementation of promising methods for researching the state of aquatic ecosystems and individual components; development and improvement of diagnostic methods for the toxic effects of polluting nutrients entering the reservoir with river flows and by sedimentation from the air on hydrobionts, including early and differential diagnosis of eutrophication, as well as the search for antidote protection of aquatic ecosystems; development of proposals and measures to reduce and prevent atural and anthropogenic impacts.

Table 2. Acceleration and efficiency of the parallel MATM algorithm.

| Number of processors | Time, s  | Acceleration (practical) | Efficiency | Acceleration (theoretical) |
|----------------------|---------|--------------------------|------------|---------------------------|
| 1                    | 3.700073| 1                        | 1          | 1                         |
| 2                    | 1.880677| 1.967                    | 0.984      | 1.803                     |
| 4                    | 1.2655  | 2.924                    | 0.944      | 3.241                     |
| 8                    | 0.489768| 7.555                    | 0.731      | 7.841                     |
| 16                   | 0.472151| 7.837                    | 0.49       | 9.837                     |
| 32                   | 0.318709| 11.61                    | 0.378      | 14.252                    |
| 64                   | 0.182296| 20.297                   | 0.363      | 26.894                    |
| 128                  | 0.076545| 48.338                   | 0.317      | 55.458                    |
| 256                  | 0.06318 | 58.563                   | 0.229      | 65.563                    |
| 512                  | 0.058805| 62.921                   | 0.123      | 72.921                    |

Figure 2. Graphs of the dependence of acceleration (a) and efficiency (b) on the number of processors for the developed parallel adaptive MATM algorithm.
To simulate hydrobiological and hydrodynamic processes in a three-dimensional area of complex shape (the Azov Sea and the Taganrog Bay), successively refined rectangular grids with dimensions: \(251 \times 351 \times 15\), \(502 \times 702 \times 30\), \(1004 \times 1404 \times 60\), etc. computing nodes. The water flow velocity, solinity and temperature fields [12] refer to the input data for the model (1) – (3). The initial distribution of polluting nutrients, phytoplankton, zooplankton, and comb jelly was taken into account in the form corresponding to the spatio-temporal scales of the simulated processes. Note that the algorithm for the numerical solution of the posed problem of the multi-species model of biological kinetics (1) – (3), implemented on the MCS, makes it possible to vary the form of boundary conditions, control functions and check the sensitivity of the input parameters for various scenarios of changes in the ecological situation of a shallow water body.

3.2. Results of numerical experiments
When modeling the development of hydrobionts, it is important to take into account the influence of abiotic factors on their growth, such as salinity and temperature. The Azov Sea is an estuarine-type reservoir; therefore, it is characterized by a large difference in the salinity level during the transition from fresh river waters to salty sea waters. During the year, changes in the average salinity of the sea without Taganrog Bay reach 1 ‰. The optimum temperature for *Copepoda* zooplankton is 20–24 °C, this species can withstand a wide range of salinity. For the phytoplankton of the Azov Sea, the optimum temperature is 24–25 °C and salinity up to 9–10 ‰.

As a rule, monthly average salinity and temperature values are presented on maps at separate points or field isolines (isohaline and isotherm) (figure 3). It is undesirable to use such maps as there are computational errors. Thus, the problem arises of processing hydrological information. An image recognition algorithm was used to obtain salinity and temperature isolines from hydrographic maps and satellite images. Figure 4 shows the salinity and temperature fields reconstructed from the cartographic information for the Azov Sea in the summer on the basis of high-order approximation schemes [13].

**Figure 3.** Initial images of distributions of salinity (a) and temperature (b) of the Azov Sea according to long-term observations and satellite images.
When modeling spatially inhomogeneous processes of interaction of the main hydrobionts of the Azov Sea \((1) – (3)\), the external periodicity was taken into account, leading to the complication of the system. The results of modeling the dynamics of polluting nutrients at different points in time in the Azov Sea are shown in figure 5 a) \((It)\) is the number of the iteration, the initial distribution of the fields of currents of the water flow at the northerly wind direction). The results of modeling the dynamics of phytoplankton in the Azov Sea are shown in figure 5 b). The distribution of the concentration of stenothermal zooplankton \((P_2)\) at different times is shown in figure 6.

According to data from expeditions carried out in the Azov Sea in the summer (late July and early August) by the staff of the SSC RAS in 2017 and 2019, the zooplankton biomass was in the range of 48.63 – 0.551 mg/m³ (on average, 13.4 mg/m³) [14]. The biomass of zooplankton in the Taganrog Bay
reaches 358 mg/m³, in the eastern part, in some cases, it exceeds 1500 mg/m³ [15]. A decreased concentration of zooplankton in July–August was observed in the areas where the comb jelly *Mnemiopsis leidyi* developed. The dominant group of zooplankton in the Azov Sea were *Copepoda* – 80% of the total number of zooplankton, the share of *Cladocera* in the total number of zooplankton was 18%, *Rotifers* in the Azov Sea had very low values of abundance and biomass, while they accounted for about 2% of the total zooplankton. When modeling the processes of biological kinetics, the vegetation period of phytoplankton, as well as allelopathic interaction of plankton, were taken into account. The maximum values of the concentrations of nutrients and phytoplankton are highlighted in white, and the minimum are in black. The stable heterogeneity of the spatial distribution of the polluting nutrient and phytoplankton is also due to diffusion processes and the presence of an ectocrine regulation mechanism in phytoplankton, i.e., regulation of the growth rate through the release of biologically active metabolites into the environment. Diffuse processes in the reservoir act in the direction of smoothing the spatial distribution and dispersion of phytoplankton "spots", indicating the active movement of heterotrophic organisms (zooplankton and fish) in the direction of the "food" gradient, which ensures the consolidation of the spatial heterogeneity of nutrients in the aquatic environment. The results obtained in the course of the numerical experiment agree with the data of long-term observations.

4. Conclusion
According to the performed numerical experiments, a significant influence of abiotic factors, including temperature and salinity, on the growth and mortality of phyto-, eurythermal and stenothermal species of zooplankton and comb jellies was revealed. When studying the mechanisms of interaction between plankton and comb jellies, on the basis of the developed software package, the optimal modes were identified under which the ecosystem is in a stable state. When modeling spatially inhomogeneous processes of interaction of the main hydrobionts of the Azov Sea, the external periodicity was taken into account, the summer period was considered. In parallel implementation of the developed numerical algorithms for solving the problem of interaction of zooplankton populations in the Azov Sea, methods of decomposition of the computational domain were used for various computationally laborious problems of hydrodynamics and biological kinetics, taking into account the architecture and parameters of the supercomputer. It was found that the maximum acceleration was 63 times was achieved on 512 processors. Data of the current level of development of zooplankton, its seasonal dynamics and productivity, can be effectively used in assessing fish productivity and predicting the dynamics of valuable commercial fish species, the distribution of invasive species, including comb jellies, the development of rational nature management schemes and the protection of natural resources of aquatic ecosystems.

Acknowledgment
The reported study was funded by RFBR, project number 20-01-00421.

References
[1] Berdnikov S V 2019 Expeditionary studies of the Southern Scientific Center of the Russian Academy of Sciences in 2018. Results of expeditionary studies in 2018 in the World Ocean, inland waters and on the Spitsbergen archipelago Conference proceedings: electronic resource 12–27 (In Russian)
[2] Matishov G G 2011 *Ecological atlas of the Azov Sea*, ed Golubeva N I and Sorokin V V (Rostov-on-Don: Publishing house of the SSC RAS) p 328 (In Russian)
[3] Mordukhai-Boltovskoy F D 1960 *Caspian fauna in the Azov-Black Sea basin* (Leningrad: I D Papanin Institute for biology of inland waters) (In Russian)
[4] Kryuchkova N M 1987 The structure of zooplankton communities in water bodies of different trophic types *Production hydrobiological studies of aquatic ecosystems* 184–198 (In Russian)
[5] Vinberg G G 1962 Energy principle of studying trophic connections and productivity of ecological systems *Zoological journal* **41** 1618–1630 (In Russian)

[6] Petzold T et al. 2009 Effects of zooplankton diel vertical migration on a phytoplankton community: a scenario analysis of the underlying mechanisms *Ecological Modelling* **220** 1358–1368

[7] McManus M, Cheriton O, Drake P, Holliday D, Storlazzi C, Donaghy P and Greenlaw C 2005 Effects of physical processes on structure and transport of thin zooplankton layers in the coastal ocean *Marine Ecology Progress Series* **301** 199–215

[8] Afanasyev D F, Mirzoyan Z A, Martynyuk M L, Khrenkin D V, Shlyakhova N A, Bychkova M V, Zhukova S V 2019 Early summer zooplankton of the Sea of Azov during the period of salinization *Biology of Inland Waters* **2** 51–60. (In Russian)

[9] Tyutyunov Yu, Senina I and Arditi R 2004 Clustering due to acceleration in the response to population gradient: a simple self-organization model *The American Naturalist* **164** 722–735

[10] Sukhinov A I, Chistyakov A E, Nikitina A V, Belova Y V, Sumbaev V V and Semenyakina A A 2018 Supercomputer modeling of hydrochemical condition of shallow waters in summer taking into account the influence of the environment *Communications in Computer and Information Science* **910** 336–351

[11] Voevodin V V and Voevodin VI V 2002 *The Parallel Computing* (St. Petersburg: BHV–Petersburg) (in Russian)

[12] Sukhinov A I, Chistyakov A E and Alekseenko E V 2011 Numerical realization of the three-dimensional model of hydrodynamics for shallow water basins on a high-performance system *Mathematical Models and Computer Simulations* **3** 562–574

[13] Nikitina A, Belova Y and Atayan A 2019 Mathematical modeling of the distribution of nutrients and the dynamics of phytoplankton populations in the Azov Sea, taking into account the influence of salinity and temperature *AIP Conference Proceedings* **2188** 050027

[14] Svistunova L D 2020 Zooplankton of the Azov Sea and the Taganrog Bay of the full-water 2019 in summer *Patterns of formation and impact of marine, atmospheric hazards and disasters on the coastal zone of the Russian Federation in the context of global climatic and industrial challenges ("Hazardous phenomena - II")* 128–131 (in Russian)

[15] Povazhny V V 2009 Features of the zooplankton community dynamics of the Taganrog Bay *Bulletin of the SSC RAS* **5** 94–101 (in Russian)