Modeling of the Sea Upper Layer Ecosystem Fields by the Adaptive Balance of Causes Method

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A method for constructing the sea upper layer ecosystem fields, based on negative feedbacks in the ecosystem model, which provide mutual adaptation of biochemical processes taking into account resource limitations and external influences, is considered. This method allows us to construct cause-and-effect dependencies between the processes in complex ecosystems using negative feedbacks between the ecosystem model variables and rates of their change. It is shown that such an approach retains material balances of biochemical reactions in the ecosystem and increases sensitivity of adaptive models to the data of observations assimilated in them. A method for assimilation of calculated data on marine environment dynamics in adaptive models of marine ecosystems consisting in simultaneous adjustment of biochemical process values to the data of satellite observations and previously obtained assessments of marine environment advection and diffusion is proposed. The method is illustrated by the examples of constructing the charts of phytoplankton, zooplankton, bio-resource and oxygen concentrations for the shelf regions of the north-western Black Sea. Satellite observation data on the sea surface temperature and chlorophyll-a concentration as well as the assessments of the substance simulated advection and diffusion resulted from the hydrodynamic model are used as the external sources of influences. The coefficients of intra-system influences in ecosystem are assessed by the data of long-term observations carried out in this area. The charts of spatial-temporal fields of biochemical processes in the upper sea layer, coordinated with the charts of horizontal currents and satellite observations of chlorophyll-a concentrations are constructed. The conclusion that the ecosystem adaptive models should be advisably applied for obtaining the assessments of spatial distribution of the bio-chemical substance concentrations in the sea upper layer ecosystem is drawn.

Keywords: Adaptive Balance of Causes method, marine ecosystem.

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Introduction. The studies of ecosystem fields of the sea upper layer are both of scientific and practical interest due to dynamical activity and high biological productivity of marine environment of this layer. High resolution numerical models (in which the concentrations of biological objects and chemical substances are calculated by partial differential equations describing diffusion and transfer of substances into the sea) are usually used to construct the field charts of ecosystem biochemical characteristics [1]. Satellite data is assimilated by these equations and, in particular, by the adaptive statistics method [2]. Due to the possibility of satellite monitoring of certain sea upper layer characteristics, the informative results on the ecosystem fields mapping (by this method) are obtained in the works on the Black Sea operative oceanography [3].

Along with the calculation of biochemical fields in numerical dynamical models of marine environment, two-stage method of these sea upper layer fields chart constructing is possible [4]. At the first stage the calculations of currents according to the hydrodynamical model (which allow us to construct the assessments of advection and diffusion in the nodes of the grid domain covering the area under study) are performed. At the second stage these assessments and also the satellite monitoring data are used as sources of external effect in the special ecosystem model, which has a property of local adaptation to the abovementioned assessments and satellite data. Local adaptation means an automatic adjustment of ecosystem model variables to the assimilating data. This adaptation takes place due to negative feedbacks between the ecosystem model variables and change rates of these variables. This fact gives reason to call this type of ecosystem models the adaptive ones [5]. Particularly, the assimilation of simulated data on transport and diffusion in marine ecosystem adaptive model, which describes the scenarios of biochemical processes in a single point of the upper sea layer, was considered in [4].

The purpose of this study is to represent the possibilities of two-stage mapping of biochemical fields by the method of local adaptation of ecosystem model variables. We don't set ourselves a task to describe in details of the biochemical processes of the upper sea layer. Therefore, the simplest scheme of cause-effect relationship, which includes the concentrations of phytoplankton, zooplankton, bioresource and dissolved oxygen, was chosen as a conceptual model. The model, in addition to these main structural elements, includes the agents of limitation of aquatic organism concentration increase and abovementioned sources of external effects.

General equations of ecosystem adaptive model and computational algorithms. Marine ecosystem adaptive model represents a set of interrelated processes $\{u_i\}$ satisfying the dynamical balance condition of intersystem and external influences [6]. Dynamical balance is based on the tendency of living organisms to adapt to changing environmental conditions. We call "reactions" any interactions of processes in the ecosystem, which result in changes of variable values u_i in the ecosystem model. Realization of such reactions assumes the presence of all required components, i.e. resources, and their volumes are always limited. We will call this limiting property of environment its "resource capacity" in relation to the ecosystem model variable, which represents the product of reaction.

Variables of ecosystem model should have nonnegative values because all the biochemical processes in ecosystems are represented by concentrations of substances in the marine environment. This means that, as a result of reactions, takes place the deviation of variable values from some average values C_i characterizing the stationary state of the system. Therefore, the variables u_i have variation intervals $(0;\ 2C_i)$ and their resource capacities are $2C_i$ values. It is natural to assume that the models of natural ecosystems, which are in static equilibrium with the environment, have a set of average values $\{C_i\}$ as a stationary state and the changes in environment lead to the deviation from this state.

We call the ecosystem models adaptive if at the presence of external influences a model tends to the state of dynamical equilibrium with them. A mutual adaptation of the model values to each other and to the external influences occurs in the adaptive models, and a set of equations of the model "monitors" varying external influences keeping a state of dynamic balance with them.

An *Adaptive Balance of Causes* method (*ABC*-method), which provides a construction of ecosystem model equation system possessing a property of dynamic adaptation to the varying external influences, is proposed in [5]. An adaptive system mathematical model consists of ordinary differential equations of a special form, and rates of change of their variables are related by negative feedbacks with the squares of variables (second order feedbacks).

We will represent the ecosystem reactions in the form of transformations (not necessarily linear) of resources u_j into the products u_i with the presence of external influences A_i :

$$u_i = \sum_{j \neq i} a_{ij} u_j + A_i + C_i \qquad (i = 1, \ldots, n), \tag{1}$$

where a_{ij} are the coefficients of intersystem influences. These transformations express the mass balances of substances involved in the reactions. The system of *ABC*-method modular equations is constructed in such a way as to satisfy the balance relations (1) simultaneously for all of u_i variables in a model [5]:

$$\frac{du_i}{dt} = 2 r_i u_i [C_i - (u_i - \sum_{j \neq i} a_{ij} u_j - A_i)], \tag{2}$$

here r_i are specific rates of u_i functions change.

It follows from the system of equations (2) that its stationary solution is reached at

$$u_i - \sum_{j \neq i} a_{ij} u_j - A_i = C_i \tag{3}$$

and it satisfies the condition of keeping the balance of influences (1). This means that during the adaptation the variables of ecosystem model take on the values that complement the algebraic sum of intersystem $\sum_{j \neq i} a_{ij} u_j$ and external A_i influences up to the values which are equal to the halves of $2C_i$ resource capacity values. Under the effect of external influence variables a deviation of u_i values from their stationary C_i values takes place. This results in formation of steady states of dynamic balance of influences (1). This conclusion is confirmed by the computational experiments with the equations (2) which had been carried out in [5 – 7].

General equations of *ABC*-method (2) are complemented with logical conditions (management agents) in which the resource limitations of reaction proceeding are taken into account. One of these limitations prevents the solutions of equations from falling outside the scope of specified process variability intervals described by the following ecosystem model:

$$u_i = IF[u_i < 0; 0; IF(u_i > 2C_i; 2C_i; u_i)]. \tag{4}$$

Another limitation takes into account those cases when the formation of reaction product occurs at the simultaneous use of several types of resources. For instance, for the increase of zooplankton concentration in marine environment a simultaneous consumption of phytoplankton, oxygen, nitrogen compounds and other substances by zooplankton is needed. At each moment of time the stocks of one type of these resources are minimal against other types of resources. This minimal resource type will limit a zooplankton concentration increase.

In order to consider this fact the management agents $AG_i \arg\min(a_{ik}u_k, \ldots, a_{in}u_n)$ are included in the *ABC*-ecosystem model equations:

$$\frac{du_i}{dt} = 2r_i u_i \left\{ C_i - \left[u_i - \sum_{j \neq i} a_{ij} u_j - AG_i \arg\min(a_{ik}u_k, \ldots, a_{in}u_n) - A_i \right] \right\}, \qquad (5)$$

$$AG_i \arg\min = IF(a_{il}u_l = M_l; a_{il}u_l; 0), \; M = \min(a_{ik}u_k, \ldots, a_{il}u_l, \ldots, a_{in}u_n). \quad (6)$$

The experience of *ABC*-method use for constructing of marine ecosystem adaptive models [7] showed that the equation solutions (5) with the limitations (4) rapidly converge to the stable values on the condition that influence coefficients a_{ij} are selected properly. These coefficients take into account an amount of u_j resource necessary for increment of u_i product amount by one. It is necessary to keep in mind that increments can be both positive and negative. Negative increments mean a decrease of u_i product when the resource u_j consumes (absorbs) the product.

There are several ways to assess the influence coefficients in marine ecosystem adaptive models. All of them are based on aprioristic information on the functional relations between the ecosystem processes involved in the reactions. If $u_i = u_i(u_j) = a_{ij}u_j$, then

$$a_{ij} = \frac{\partial u_i}{\partial u_j}. \qquad (7)$$

If there are time series of observations u_i and u_j the assessments of influence coefficients can be obtained using a regression analysis. In paper [6] it is shown that influence coefficients connected by the balance relations (1) form a system of cause-effect relationships where they serve as variables connected to each other by correlation dependences. This gives ground to consider $\{a_{ij}\}$ coefficients as a stationary state of *ABC*-model of influence coefficient system of the following form:

$$\frac{da_{ij}}{dt} = a_{ij}\{1 - 2[a_{ij} - R_{jj}^{-1}(R_{ij} - \sum_{k=1}^{n} a_{ik}R_{ki} - \sum_{l=1}^{n} a_{il}G_{lj})]\} \quad (i, j = 1, 2, \ldots, n), (i \neq j), \; (8)$$

Where cross correlation functions of u_i, u_j and A_i processes are used

$$R_{ij} = E\{u_i u_j\}, \; G_{ij} = E\{u_i A_j\}.$$

If there is enough observational data to construct the system of equations (8), the influence coefficients evolve in time in parallel with the observed correlation dependences. This increases the model sensitivity to external influences and also potentially increases its adequacy to real ecosystem processes.

Minimum amount of aprioristic information necessary for assessment of influence coefficients is contained in average values of *ABC*-model C_i variables. As much as the balance relations (1) in the equations (2) are satisfied, the sums of positive and negative influences should not violate the limits of $(-C_i; C_i)$ intervals. This means that the sums of both positive and negative coefficients in modulus can not be greater than 0.5. In this case, the assessment of values of the influence coefficients for the limiting resource could be found from the following normalization requirement

$$a_{ij} = \frac{1}{2C_j \sum_{k=1}^{m} \frac{1}{C_k}}, \tag{9}$$

where m is a number of influences with the same sign in the equation of the system (2).

Computational algorithm of solution of the equations system (2) can be easily implemented according to the Euler scheme. For example, if we assume $2C_i r_i \Delta t = 1$ as an additional condition (where Δt is a step of calculation by the time), the finite difference variant of equations (2) can be written in the following form:

$$u_i^{k+1} = 2u_i^k [1 - 0.1(u_i^k - \sum_{j \neq i} a_{ij} u_j^k - A_i^k)]. \tag{10}$$

The equations (10) represent the scenarios of u_i processes on the interval of dimensionless values (0; 10). For returning to the dimensional values the solutions of these equations should be multiplying by 0.2 C_i .

An adaptive model of a sea upper layer ecosystem. It is natural to begin the model construction from balance relations (1) making. The task of this study is to verify the two-stage method of the chart constructing of the sea upper layer fields. Therefore, from the set of biochemical reactions there was selected their minimum amount that is sufficient to explain the idea of field mapping. The concentrations of phytoplankton *PP*, zooplankton *ZP*, bioresource *BR* and oxygen *OX* in marine environment are used as the components of u_i and u_j relations (1). What is more, the bioresource concentration means all the living objects above the zooplankton in the food chain. The assessments of advection and diffusion obtained from the calculations of current velocity components *u*, *v* and *w* by the hydrodynamic model and also the satellite observations data on sea surface temperature *TW* and chlorophyll-a concentration *CH* are used as the external influences A_i . The scheme of intersystem and external influences (conceptual model) of ecosystem is represented in Fig. 1.

The ecosystem model contains resource limitation agents (6) of aquatic organism concentration in the food chain $AG_{ZP}(OX, PP)$ and $AG_{BR}(OX, ZP)$, concentration change monitoring agents of oxygen $AG_{\text{dyn}}(OX)$, zooplankton $AG_{\text{dyn}}(ZP)$ and bioresource $AG_{\text{dyn}}(BR)$ (the concentrations change due to advection and diffusion of these substances) and also the agents that consider the effect of seasonal temperature variation of the sea upper layer on zooplankton $AG_{ZP}(TW)$ and bioresource $AG_{BR}(TW)$ concentrations.

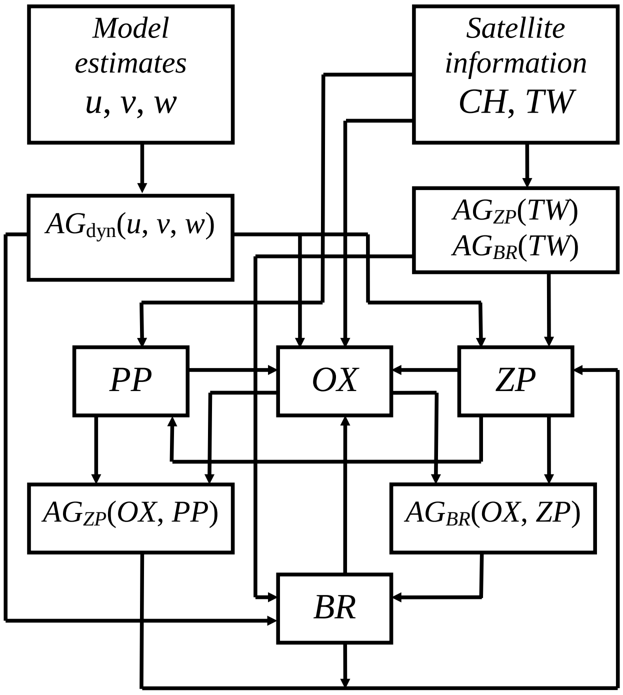


Fig. 1. Conceptual model of the sea upper layer ecosystem

To construct the system of equations of ecosystem adaptive model, corresponding to conceptual model (Fig. 1), the common *ABC*-method equations are used. For the comparison of scenarios to be easier, model variables were represented in dimensionless form and were reduced to the common interval of variability (0; 10). At the same time, average values of all variables became equal $(C_i = 5)$, and specific rates of variable change were taken to be equal to $1\,(r_i = 1)$. The equations of adaptive ecosystem model take on the following form:

$$\frac{dPP}{dt} = 2PP[5-(PP - a_{PP/CH}CH + a_{PP/ZP}ZP)], \quad (11)$$

$$\frac{dOX}{dt} = 2OX\{5-[OX - AG_{\text{dyn}}(OX) + a_{OX/BR}BR + a_{OX/ZP}ZP -$$
$$- a_{OX/PP}PP + a_{OX/TW}TW]\}, \quad (12)$$

$$AG_{\text{dyn}}(OX) = a_{\text{adv}}OX_{\text{adv}} + a_{\text{dif}}OX_{\text{dif}}, \quad (13)$$

$$\frac{dZP}{dt} = 2ZP\{5-[ZP - AG_{\text{dyn}}(ZP) + a_{ZP/BR}BR - AG_{ZP}(OX, PP) - AG_{ZP}(TW)]\}, \quad (14)$$

$$AG_{\text{dyn}}(ZP) = a_{\text{adv}}ZP_{\text{adv}} + a_{\text{dif}}ZP_{\text{dif}}, \quad (15)$$

$$AG_{ZP}(OX, PP) = IF[M_{ZP} = a_{ZP/OX}OX; a_{ZP/OX}OX; 0] +$$
$$+ IF[M_{ZP} = a_{ZP/PP}PP; a_{ZP/PP}PP; 0], \quad (16)$$

$$M_{ZP} = \arg\min[a_{ZP/OX} OX(t); a_{ZP/PP} PP(t)],$$

$$AG_{ZP}(TW) = a_{ZP/TW} \exp[-\alpha_{ZP}(TW - TW_{ZP}^{*})^2], \quad (17)$$

$$\frac{dBR}{dt} = 2BR\{5 - [BR - AG_{\text{dyn}}(BR) - AG_{BR}(OX, ZP) - AG_{BR}(TW)]\}, \quad (18)$$

$$AG_{\text{dyn}}(BR) = a_{\text{adv}} BR_{\text{adv}} + a_{\text{dif}} BR_{\text{dif}}, \quad (19)$$

$$AG_{BR}(OX, ZP) = IF[M_{BR} = a_{BR/OX} OX; a_{BR/OX} OX; 0] + \\ + IF[M_{BR} = a_{BR/ZP} ZP; a_{BR/ZP} ZP; 0], \quad (20)$$

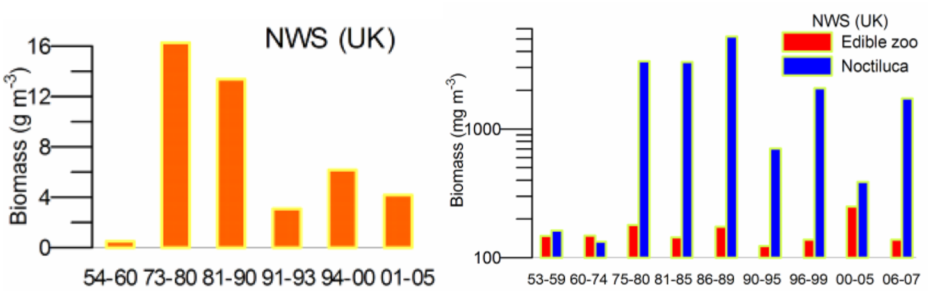
$$AG_{BR}(TW) = a_{BR/TW} \exp[-\alpha_{BR}(TW - TW_{BR}^{*})^2]. \quad (21)$$

In the equations (11) – (21) the agents $AG_{\text{dyn}}(OX)$, $AG_{\text{dyn}}(ZP)$ and $AG_{\text{dyn}}(BR)$ consider the changes of oxygen, zooplankton and bioresource concentrations, respectively, which takes place in marine environment unit volume due to advection and diffusion of substances in this volume. $AG_{ZP}(TW)$ and $AG_{BR}(TW)$ agents control the degree of the sea upper layer temperature effect on the change of zooplankton and bioresource concentrations, respectively. At the values of $TW_{ZP}^{*} = TW_{BR}^{*} = 26$ °C the most favorable conditions for the increase of these concentrations are set.

It should be noted that phytoplankton advection and diffusion are indirectly taken into consideration in the equation (11), because the satellite measurement data on *CH* chlorophyll-*a* concentration, formed under effect of advection and diffusion, had been used as an external influence source in this equation. Through system of equations of the model this influence is also extended to other model variables. However, it is insignificant due to the fact that the influence of previous resource factors decreases with each transition to the new reaction. This is the cause of diffusion and advection inclusion in all other model equations. Current velocities and turbulent exchange coefficients, taken from the calculations by the hydrodynamic model, introduce an additional data on environment dynamics to the ecosystem model because during the calculation of currents the observational data on temperature and salinity fields, shear stress of wind friction and heat flows on the sea surface and also boundary conditions etc. are used. Therefore the management agents $AG_{\text{dyn}}(OX)$ and $AG_{\text{dyn}}(BR)$ are the additional sources of influences on the substance concentration changes in the equations (12), (14) and (18).

Implementation of ecosystem model for the mapping of upper layer fields in the area of the Black Sea north-western shelf. The adaptive ecosystem model considered above is implemented to the calculation of field charts of phytoplankton, zooplankton, bioresource and oxygen concentrations for the area of the Black Sea North-Western shelf (BS NWS). To initialize the model the data of literary sources, which give approximate estimations of C_{PP}, C_{ZP}, C_{BR}, C_{OX} average values of corresponding concentration fields, are used. Fig. 2 represents the observational data characterizing phytoplankton and edible zooplankton biomass dynamics in

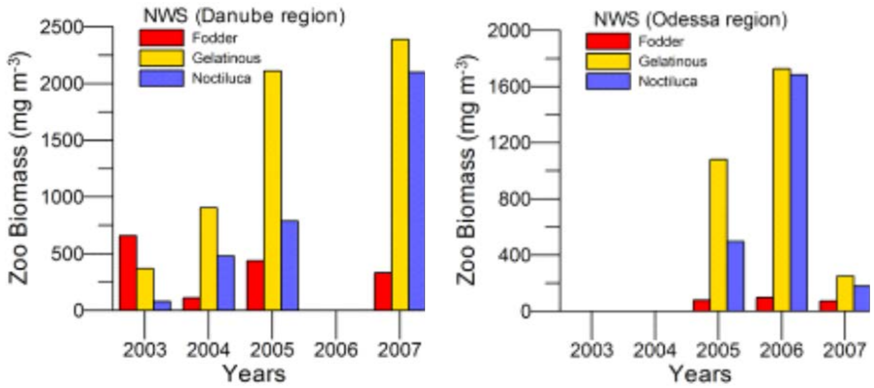
1954 – 2007. These data allow us to adopt the following concentration values as estimations of field average values: C_{PP} = 6 g/m^3 and C_{ZP} = 0.2 g/m^3.



a *b*

Fig. 2. The change of phytoplankton biomass (g/m^3) in 1954 – 2005 [8] (*a*) and biomasses (mg/m^3) of edible zooplankton and *Noctiluca scintillans* in 1953 – 2007 [9] (*b*) at the BS NWS

The data on bioresource concentration monitoring are quite scattered and belong, in general, to the Dnieper and the Danube estuarine regions. For an approximate estimation of C_{BR} value the results of edible and gelatinous zooplankton biomass monitoring in these regions (given in Fig. 3) are used. Relying on these data and also on the materials of [10], the value C_{BR} = 0.1 g/m^3 was adopted as an estimation of bioresource concentration average value.



a ***b***

Fig. 3. Biomass (mg/m^3) of edible and gelatinous zooplankton and *Noctiluca scintillans* in the Danube (*a*) and Odessa (*b*) regions during 2003 – 2007 [9]

Literary sources contain a great number of data on oxygen concentration for the BS NWS region. It is noted that summer is a period of the lowest absolute oxygen content in the entire water column and water area of the region, which is due to increase of temperature and, consequently, rates of biochemical processes. At the same time, oxygen concentrations decrease (even on the surface) approximately by 2 ml/l in the estuarine regions and by ~1 ml/l in the seaward regions making up, on average, 5.94 and 6.15 ml/l. The most probable oxygen concentration variability range in the estuarine regions makes up 5.6 – 7.0 ml/l. In winter period the maximum concentration values 8.2 – 8.8 ml/l had been observed in the estuarine regions of the rivers. Therefore the value equivalent to C_{OX} = 7 ml/l [11, 12] was adopted as an estimation of average annual oxygen concentration.

The obtained approximate estimates of average values of concentrations allowed us to calculate the coefficients of intersystem influences in the ecosystem model using the formula (10). The coefficients of *CH* chlorophyll-*a* and *TW* water temperature are selected from considerations of computational stability. Their absolute values are represented in the table.

The values of coefficients of intersystem and external influences

$a_{MM/NN}$	*PP*	*OX*	*ZP*	*BR*	*CH*	*TW*
PP	1	0	0	0	0.8	0
OX	0.5	1	0.3	0.2	0	0.9
ZP	0.27	0.23	1	0.5	0	0.6
BR	0	0.14	0.49	1	0	0.6

To construct the charts of the sea upper layer ecosystem fields in the BS NWS region there were used the scenarios of inter annual variability concentrations of chlorophyll-*a*, temperature and horizontal velocities of currents, calculated for each node of a square grid (which covered this region) with 5 km step according to the data of satellite observations for 2012 posted on a web-site http://www.myocean.eu/ [13]. Grid domain included 4004 nodes. The calculations of ecosystem fields were performed for 366 calculation time steps (days).

Calculations of ecosystem variables were carried out in two stages. Initially, the model equations (11) – (21) were solved in each nod of the grid domain with no regard for advection and diffusion. As a result, the scenarios of within-year variation of all ecosystem parameters, by which the charts of substance concentration spatial distributions for each day were constructed subsequently, had been calculated. These data, alongside with the calculations of horizontal currents, were used to obtain the advection and diffusion assessments in each node of grid domain for each day of experiment. Advection and diffusion were calculated by standard finite-difference formulas.

At the second stage the local adaptation of model variables to the obtained advection and diffusion assessments was performed by means of model (11) – (21). These assessments were included into the management agents (13), (15) and (19), and influence coefficients in management agents AG_{dyn} had the meaning of time intervals during which the advective and diffusive supplements to the concentrations of substances. Thus, the assessments of advection and diffusion have served as additional sources of external influences in the ecosystem model equations.

The influence of external factors on ecosystem variables is observed in temporal scenarios in all the nodes of the grid domain. As an example, temporal scenarios of processes in ecosystem, constructed for the point with 45° 22' N and 30° 22' E, are shown in Fig 4.

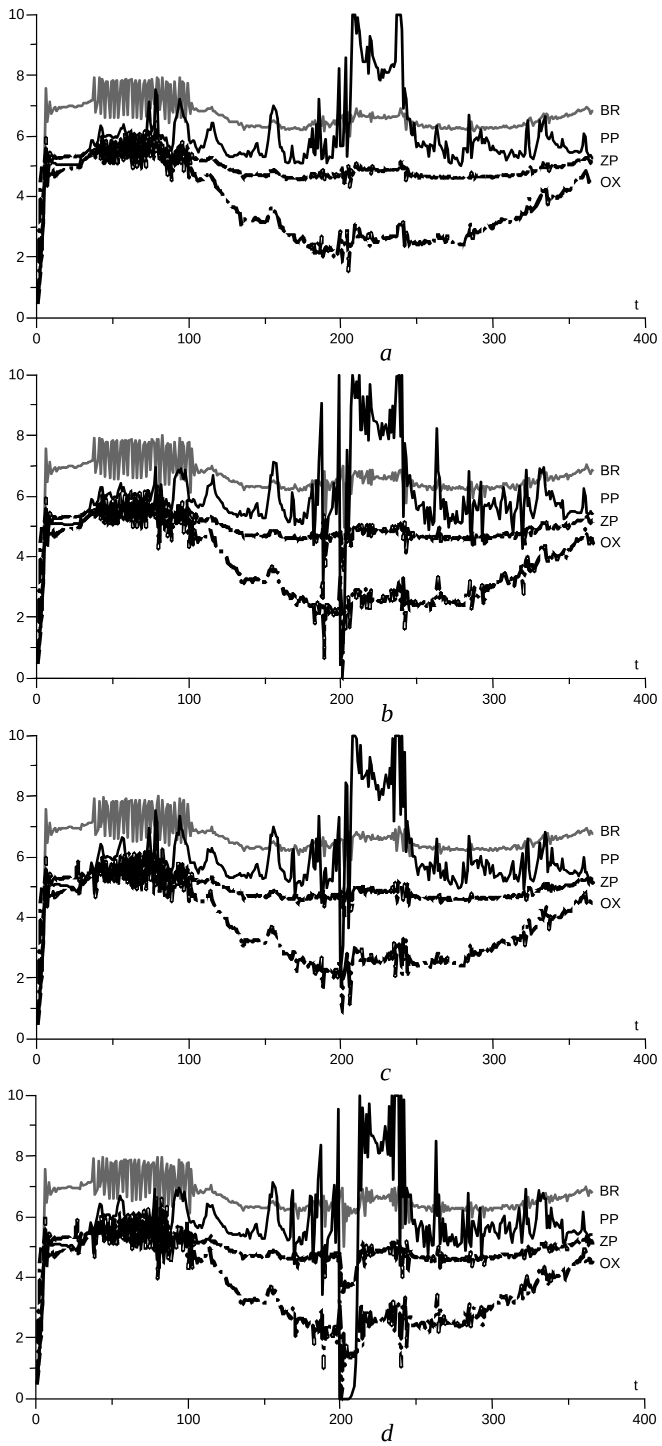


Fig. 4. Scenarios of processes in the ecosystem during the year calculated in dimensionless units for the point with 45° 22' N and 30°22' E coordinates: *a* – excluding advection and diffusion, *b* – taking into account the diffusion, *c* – taking into account the advection, *d* – taking into account advection and diffusion

From the analysis of the graphs represented in Fig. 4, *a* it follows that the main contribution to the biochemical process variability was made by the data on chlorophyll-*a* concentration and seasonal sea temperature variation. As expected, the scenario of phytoplankton concentration *PP* appeared to be the most sensitive one. Summer temperature maximum sufficiently affected the scenario of oxygen concentration *OX*. At the same time, this maximum did not affect zooplankton *ZP* and bioresource *BR* scenarios due to resource limitations of concentration increase, which were performed by $AG_{ZP}(OX, PP)$ and $AG_{BR}(OX, ZP)$ management agents. The scenarios of *ZP* and *BR* concentrations were affected by oxygen concentration *OX* because of minimum values of oxygen concentration which had been observed in this nod of grid domain almost all year long.

The advection influence on the scenarios excluding the diffusion is represented in Fig. 4, *b*. This influence appeared to be rather weak. It manifested itself in the increase of phytoplankton and oxygen concentration variability. The diffusion influence excluding the advection (represented in Fig. 4, *c*) had a bit stronger effect. In both cases the changes have affected phytoplankton and oxygen scenarios.

Scenarios shown in Fig. 4, *d* demonstrate a joint effect of taking into account advection and diffusion. The feature of these scenarios is a sharp minimum of phytoplankton concentration occurred on the 210th day of computation. In Fig. 4, *a* this minimum is absent, and this fact confirms its dependence on the dynamic processes in the sea. Resource limitation agents transformed the minimum of phytoplankton concentration *PP* into the minima of zooplankton *ZP* and bioresorce *BR* concentrations.

The analysis of ecosystem variable temporal scenarios confirmed the model sensitivity to the satellite data and information on marine environment dynamics obtained from the calculations performed by hydrodynamical model. The coefficients of influences, applied in computational experiments, were used at the second stage of calculations during the computation of scenarios in all nodes of grid domain to construct the charts of ecosystem fields.

Four time points (45th, 65th, 210th and 325th days of computation) were selected to analyze the spatial distributions of concentrations. Due to the registered anomaly of phytoplankton scenario falling on 210th day of computation, the field charts constructed for this time point are represented below. In Fig. 5 *a*, *b* the charts of surface temperature and chlorophyll-a concentration fields, constructed for the 210th day of the year according to the data of satellite observations in the BS NWS region for this time period, are represented. The chart of horizontal current field in the sea upper layer, constructed according to the data of the region hydrodynamic modeling [13], is shown in Fig. 5, *c*.

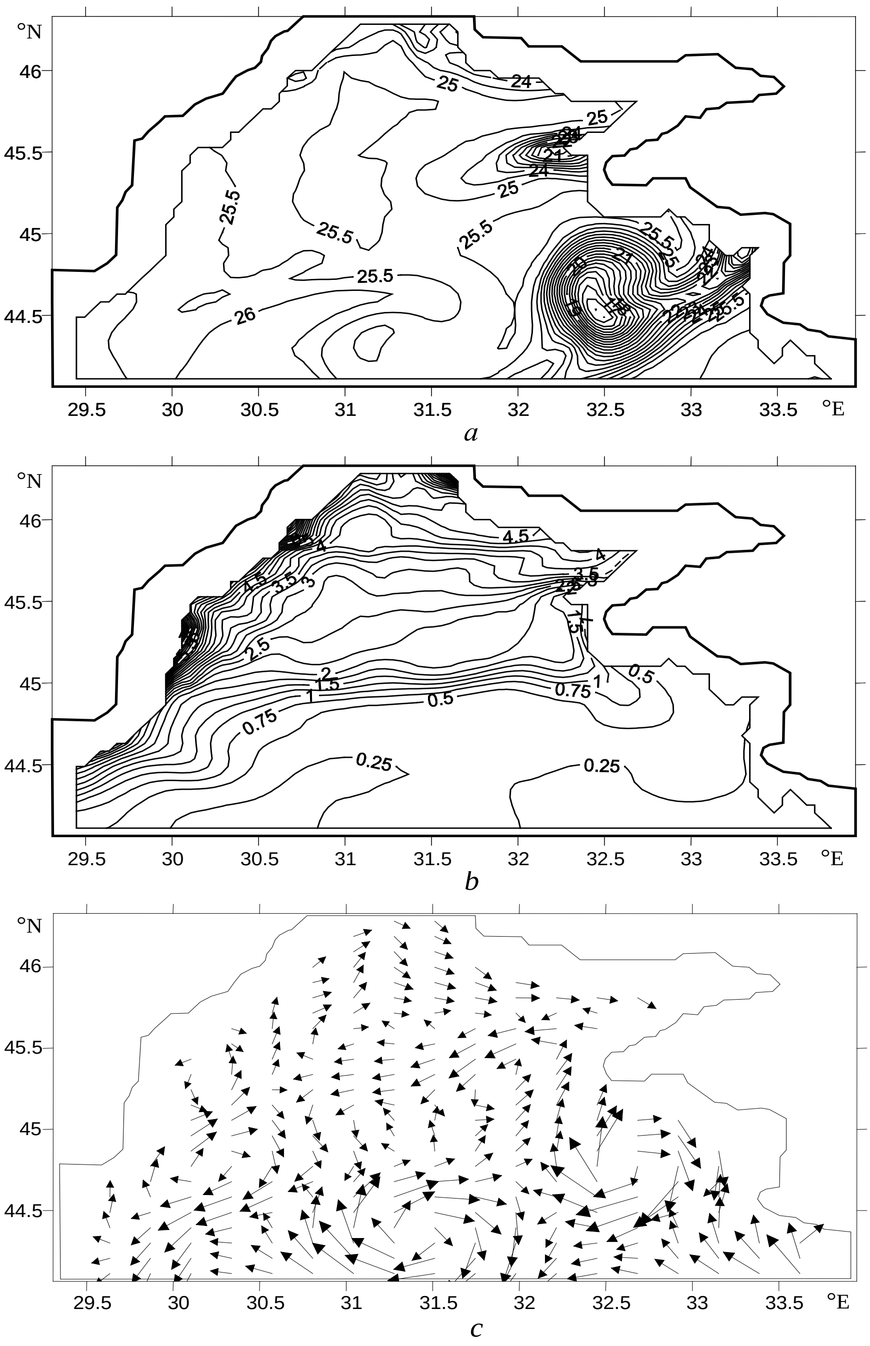


Fig. 5. Charts of surface temperature fields °C (*a*) and chlorophyll-*a* concentrations, mg/m^3 (*b*) in the sea upper layer constructed on the 210th day of the year according to the data of satellite monitoring for the BS NWS area, and a chart of the field of horizontal currents in the sea upper layer constructed according to numerical modeling data (*c*) (the longest arrow corresponds to 30 cm/s velocity)

In Fig. 6, *a* chart of phytoplankton concentration field, constructed without taking into account the marine environment dynamics by the temporal scenarios calculated in the nods of grid domain, is given. The structure of isolines on this chart basically follows the one from Fig. 5, *b* (the chart of chlorophyll-*a* concentration fields constructed according to the satellite data).

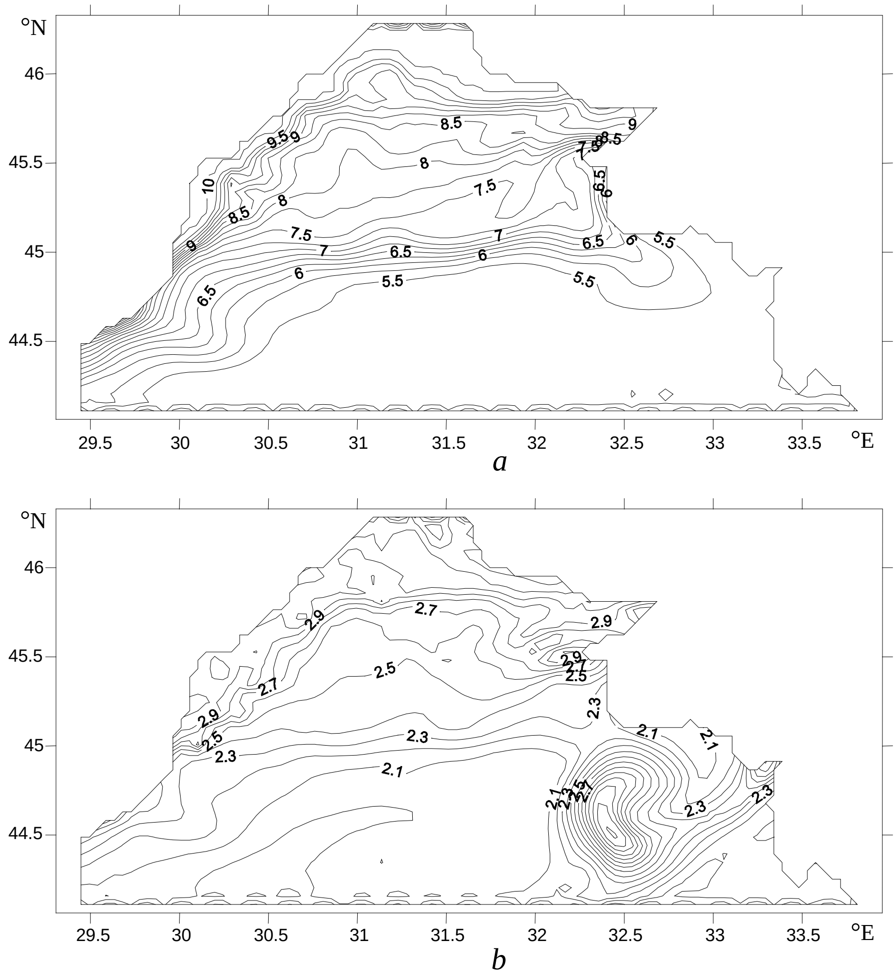


Fig. 6. Charts of phytoplankton (a) and oxygen (b) concentrations calculated in dimensionless units on the 210th day of computations excluding marine environment dynamics

The chart of oxygen concentration field represented in Fig. 6, *b* demonstrates that it was sufficiently affected by satellite data on sea surface temperature. The chart of temperature field, (Fig. 5, *a*) constructed by satellite data, contains a notable anomaly in the area of south-western coast of the Crimea, and this anomaly is due to anticyclonic gyres. This anomaly clearly manifested itself in the oxygen concentration field (Fig. 6, *b*).

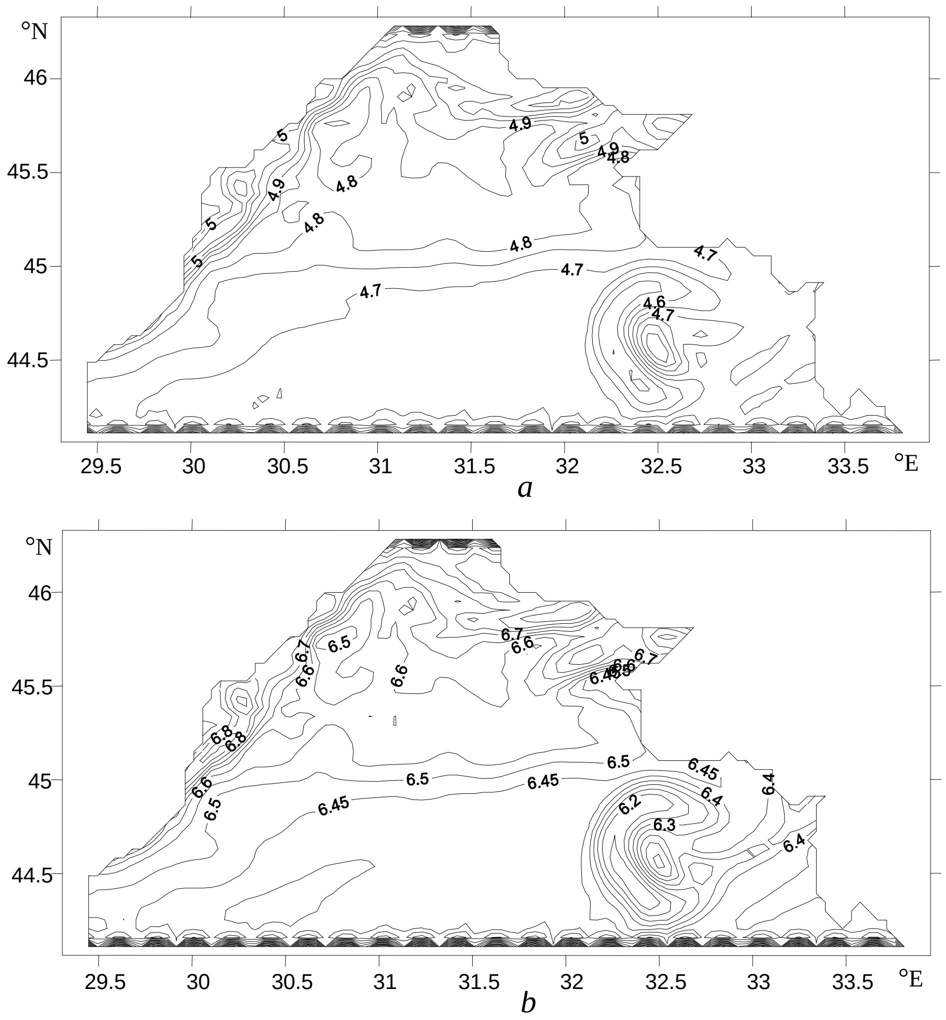


Fig. 7. Charts of zooplankton (a) and bioresource (b) calculated in dimensionless units on 210th day of computation excluding the marine environment dynamics

Considering the influence of resource limitation agents on scenarios of processes shown in Fig. 4, *a* it was pointed out that oxygen concentration minima play a key role in formation of scenarios of zooplankton and bioresource concentrations. Therefore, it should be expected that the oxygen field anomaly will manifest itself in the fields of zooplankton and bioresource as well. The charts of these fields, represented in Fig. 7, *a*, *b*, confirm this statement. The greatest zooplankton and bioresource concentrations are observed in the Danube estuary coastal regions and the lowest concentrations – in the area of oxygen field anomaly near the southwestern coast of the Crimea.

The chart of phytoplankton concentration field, which was calculated taking into account the marine environment dynamics on the 210th day of computations, is represented in Fig. 8, *a*. This field appeared to be more changeable in comparison with the one given in Fig. 6, *a*, which was obtained at the first stage. Local inhomogeneities of chlorophyll-*a* field, which had been observed on the chart of its concentrations in Fig. 5, *b* near the north-western coast of the BS NWS water area, were not visible in the chart of phytoplankton concentration (Fig. 6, a) constructed excluding the water dynamics. Taking into account the dynamics, they explicitly manifested themselves in Fig. 8, *a*.

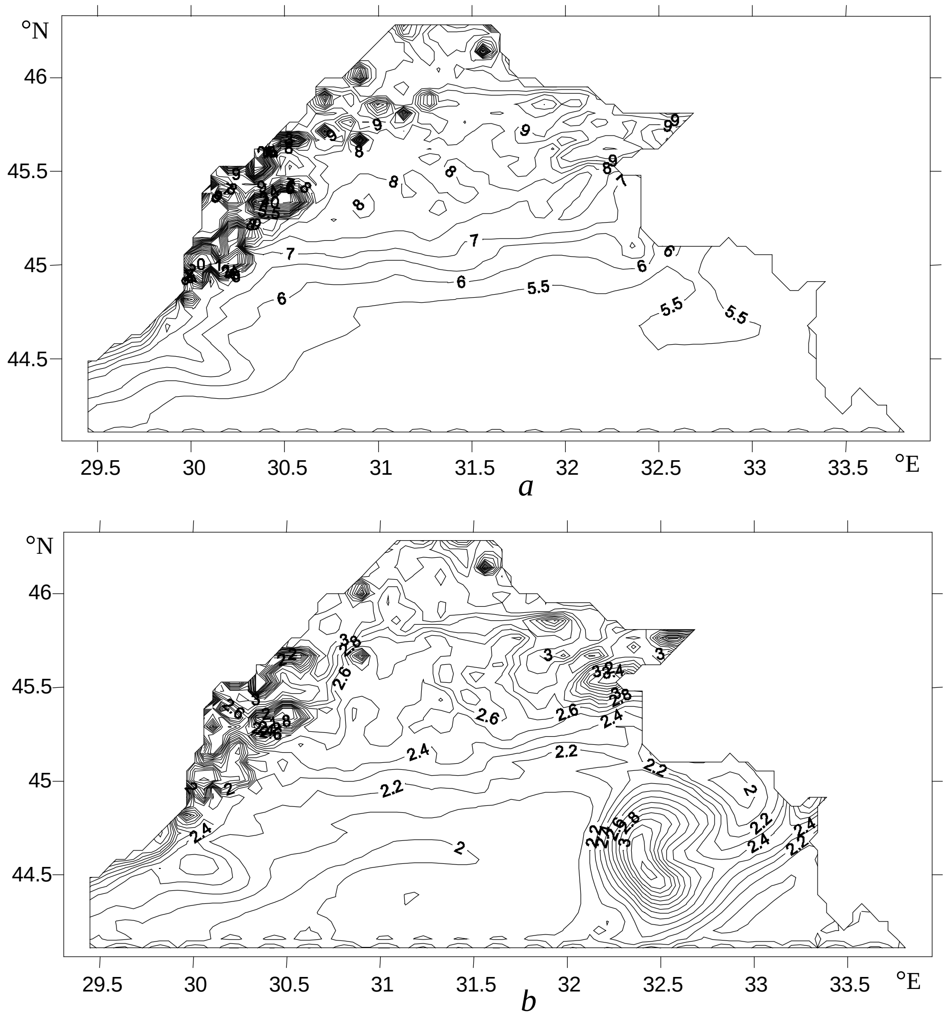
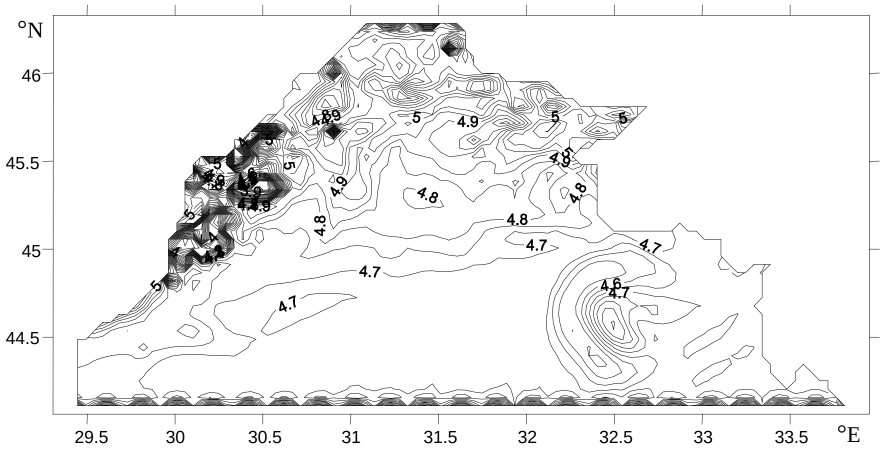
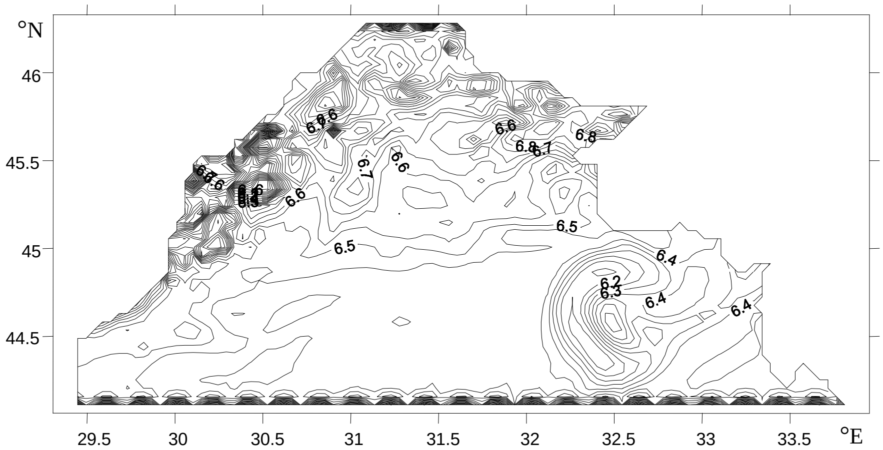


Fig. 8. The charts of phytoplankton (a) and oxygen (b) concentrations calculated in dimensionless units on the 210th day of computations taking into account advection and diffusion

This conclusion also extends to other ecosystem fields constructed with regard to advection and diffusion. This is evidenced by the results of the comparison of appropriate oxygen (Fig. 6, *b* and 8, *b*), zooplankton (Fig. 7, *a* and 9, *a*) and bioresource (Fig. 7, *b* and 9, *b*) concentrations. Thus, marine environment dynamics sufficiently affects the results of ecosystem field modeling using the Adaptive Balance of Causes method.



a



b

Fig. 9. The charts of zooplankton (*a*) and bioresource (*b*) concentrations calculated in dimensionless units on the 210th day of computations taking into account advection and diffusion

Conclusion. The Adaptive Balance of Causes method applied in the present paper is based on an important principle of negative feedback between the rate of process change and its values, which are forming by external influences. Second order feedbacks (contained in each equation of adaptive ecosystem model) automatically maintain the dynamic balances of model variables with the functions of intersystem and external influences. This property of adaptive ecosystem models simplifies the task of data assimilation in them, and this is essential because these data are additional sources of external influences. The proposed two-stage method of the sea upper layer ecosystem model constructing allows to specify the complicated calculations of substance transport and advection processes (carried out by hydrodynamic models) in a separate stage and to use their results as the sources of external influences in adaptive ecosystem model. This principle is implemented in a relatively simple sea upper layer adaptive ecosystem model for the BS NWS region. The equations of Adaptive Balance of Causes method provided the adjustment of phytoplankton, zooplankton, bioresource and oxygen concentration fields to the data of satellite observations and assessments of advection and diffusion (calculated according to marine environment numerical modeling data). It is shown that the fact of taking into account the marine environment dynamics and resource limitation agents in the ecosystem adaptive model makes possible the charts of biochemical fields to be presented in more details. The proposed method in its further development may provide an alternative to the method of biochemical field calculation using the complex partial differential equations of “reaction – advection – diffusion” type in numerical modeling of marine ecosystem dynamics.

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