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SIMULATION MODEL OF OKHOTSK SEA ECOSYSTEM

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Abstracts. *There are many examples of effective marine models giving the possibility to study the sea ecosystem dynamics. However, the sea ecosystem modeling is run into the difficulties the removal of which requires the developent of new modeling methods. Namely, the sea ecosystem is complex system fuctioning into the unstable conditions of environment. These conditions are defined both measured and undefined parameters. Therefore the sea ecosystems are studied with expeditional measurements, mathematical models and space observations. A combination of these approaches gives the useful results (Berdnikov et al. 1989; Krapivin 1996). The main difficulties on this way are arisen because of information incompleteness.*

Keywords: *ecosystems, mathematical model, simulations*

Introduction

Recently several investigators (Kelley et al. 1992; Krapivin and Shutko 1989) have reported a variety of problems in monitoring complex systems for meaningful collection and synthesis of environmental information concerning the Okhotsk Sea. In response to these difficulties, a method was devised to integrate a Geographical Inforation System (GIS) with models and field measurements. The newly developed Geo-Information Monitoring Systems (*GIMS =GIS + Model*) is focused on the systematic observation and evaluation of the environment related to changes attributable to human impact on the marine system. One of the important functional aspects of the integrated systems is the possibility of forecasting capability to warm of undesirable changes in the environment. Application of mathematical modeling to the monitoring effort greatly improves simulation of the natural processes in the environmental complex under observation.

Simulation Models

Development of models based on biogeochemical, biocenotic, demographic, and socioeconomic information, including consideration of environmental dynamics of biospherical and climatic processes on the overall system, necessitates formulation of requirements imposed on the *GIMS* structure and its database. According to guidelines proposed in the paper of Kelley et al. (1992), simulation of biosphere dynamics is one of the important functions of *GIMS*. Accordingly, growing importance has been attached to the value of this new monitoring approach which integrates assessment of the status of the biosphere. The basic objective of all investigations in the development of *GIMS*-technology is to describe the regional biogeosystem as a biosphere sub-system. The Okhotsk Sea comprises such sub-system. Therefore, application of *GIMS* technology to the study of the Okhotsk Sea Environment (*OSE*) entails synthesis of a Simulation Model of the Okhotsk Sea Environment (SMOSE) to describe the associated ecosystem dynamics. Preliminary results in this direction have been published by Aota et al. (1993). It is just what helps to describe the spatial dynamics of *OSE* and to optimize the monitoring regime.

The *OSE* keeps a significant position in global natural system. At present time it has low level of pollution but the fishering is main antropogenic influence. A correlation between the *OSE* state and global changes is one of problems which is discussed both in the framework of regional investigations and in global studies of environment. The *OSE* interacts with biosphere processes via the influence on global climate and on the Pacific

Ocean. This influence is reciprocal. This paper gives some approach to the estimation of this influence. The common concept of coplex system survivability is interpreted for the ecological system of Okhotsk Sea and criteria of survivability is defined.

A survivability of complex system is its ability to resist to the influence of external impacts and to reserve the structure and effectiveness under the realization of its aim. The *OSE* is more than energy and nutrient flows, trophic webs, and competition communities. It is the full interrelations among coexisting living organisms, and its nonliving elements. In this study the definition problem of ecosystem '*aim*' and '*behaviour*' are not discussed. These categories are deterined by Krapivin (1968). It is postulated that *OSE* has aim to maximize the biomass of living elements on high trophic levels and its behaviour in the adaptive change of food chains. The model developed by Aota et al.(1993) is considered as the *OSE* prototype. The final realization of all dynamic levels describing the interaction of ecological factors in the sea leads to a set of model units shown in Fig.1.

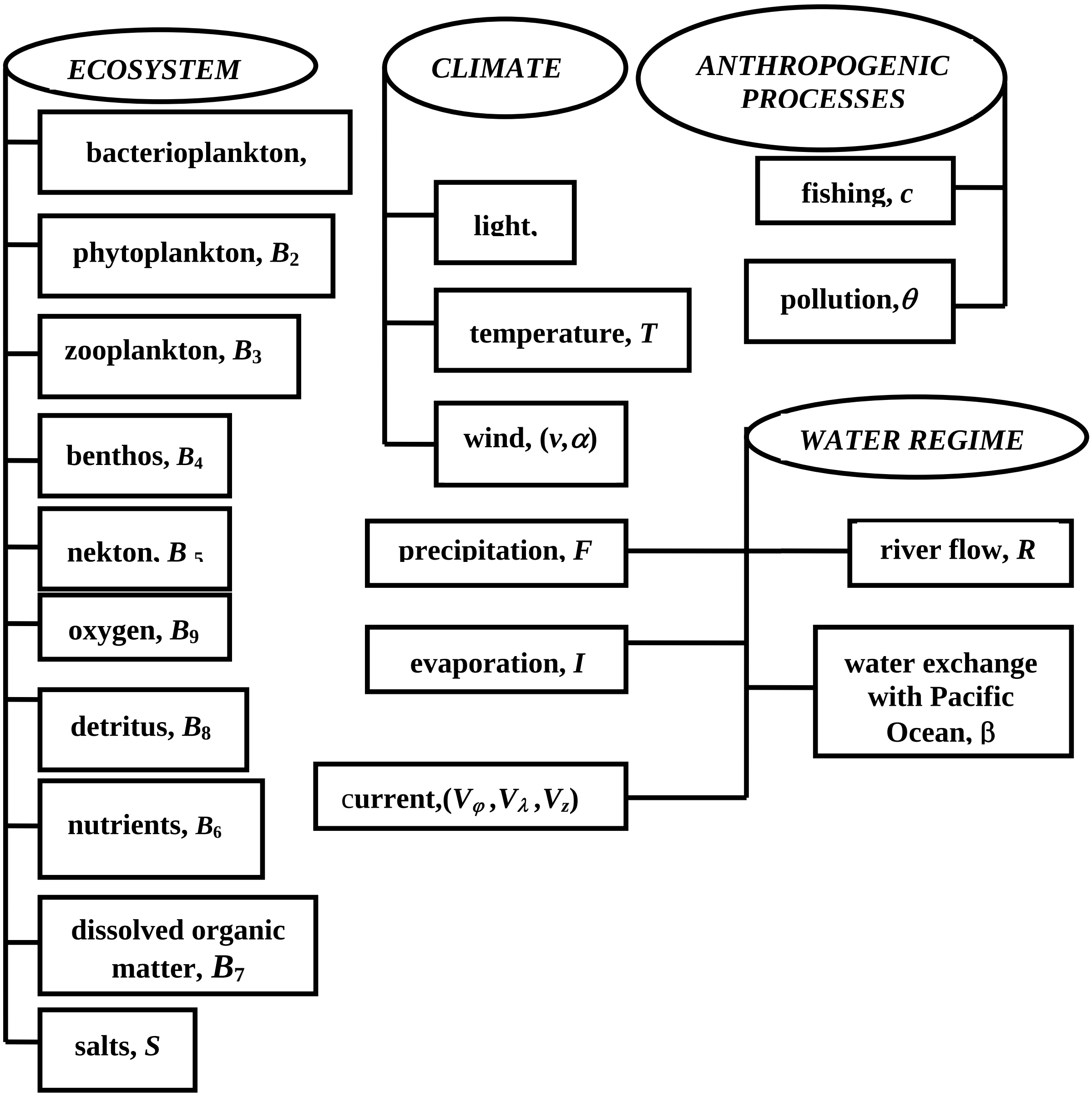

Fig. 1. The *SMOSE* structure

Let us designate the Okhotsk Sea oceanic environment as $\Omega=\{(\varphi,\lambda)\}$, where φ and λ are latitude and longitude, respectively. Spatial in-homogeneity of the Okhotsk Sea basin model is provided for by representing Ω as spatially discrete on the set of cells Ω_{ij} with latitude and longitude steps of $\Delta\varphi_i$ and $\Delta\lambda_j$, respectively. Each of Ω_{ij} has square $\sigma_{ij} = \Delta\varphi_i \cdot \Delta\lambda_j$. According to this, Okhotsk Sea is considered to consist of $N = i_{max} \cdot j_{max}$ waterbodies Ξ_m ($m= j+(i-1)j_{\max}$. These cells are the basic spatial structure of Ω for the purpose of developing computer algorithms. The water in the sea flows between Ξ_m (Kawasaki and Kono 1993). Each of Ξ_m has a vertical structure with original discretization in the depth z by steps Δz_m. Every now and then with step Δt a vertical structure is fixed on base of remote information about the sea surface state and temperature. A scheme of vertical structure developed by Legendre and Krapivin (1992) is taken into consideration.

The cells Ω_{ij} are heterogeneous as to their parameters and function. There is a set of cells adjacent to the river mouths (Ω_R) and to the ports (Ω_P), bordering on the land (Ω_Γ), in the Kuril - Kamchatka Straits (Ω_B) and on the boundary with Japan Sea (Tartar and Soya Straits, Ω_N). Distribution of depths is given as the matrix $||h_{ij}||$ where $h_{ij} = h(\varphi_i, \lambda_j)$, $(\varphi_i, \lambda_j) \in \Omega_{ij}$. As a result, the full water volume of Ω is divided into volumetric compartments $\Xi_{ijk} = \{(\varphi,\lambda,z) / \varphi_i \le \varphi \le \varphi_{i+1}; \lambda_j \le \lambda \le \lambda_{j+1}; z_k \le z \le z_{k+1})$ with volume equaled $\sigma_{ijk} = \Delta\varphi_i \Delta\lambda_j \Delta z_k$. Within compartment Ξ_{ijk}, the water body is considered as a homogeneous structure. Water temperature, salinity, density, and biomass of Ξ_{ijk} are described by point in the models at a given location. The four seasons are used to represent the effect of anthropogenic processes on the oceanic environment Ω: τ_w - winter, τ_s - spring, τ_u -summer, τ_a - autumn.

Simulation procedure realization is defined by the structure of the *OSE* oceaniv environment discretization. When

$$\Delta z_{ij} = h_{ij} \ (i=1,...,i_{max}; j= 1,...,j_{max}),$$

vertical mixing processes interior Ξ_m are identified with uniform vertical distribution of all model parameters. In the case of $\Delta z_{ij} < h_{ij}$ compartment Ξ_m is considered as vertical structure with based characteristics.

A conceptual diagram identifying the components of the *SMOSE* are shown in Fig. 1. Dynamics of the *SMOSE* is supported in turn by a global biosphere model. *SMOSE* input data are from pollutant sources indicated in the near-shore Okhotsk Sea and sea ice areas, as referenced current maps. The set of *SMOSE* components is divided into three types of information sources: mathematical models of the natural ecological and hydrophysical processes, service software, and the scenarios generator.

The *OSE* functions in such climatic conditions when greater part of sea surface is covered with ice during several months. Therefore the vertical structure is represented by three-layer block-diagram.

Complete system of ecosystem dynamics equations is formed from the set of traditional balance, hydrodynamical and biogeochemical equations. These equations have a set of coefficients $X = X_1 \cup X_2 \cup X_3$, where sub-set X_1 contains the coefficients values of which are determined with the high precision, sub-set X_2 consists of the coefficients determined by inaccuracy, and sub-set $X_3 = X \setminus (X_2 \cup X_1)$ has the coefficients which are inestimated. Simulation procedure foresees two-tier process of model adaptation. At the first tier the model adaptation process is realized at the expense of sub-set X_3 coefficients determination. This process consists in the variation of coefficient values in the ranges fixed by the *SMOSE* user. The quality criterion is formulated by the user also proceeding from the existing experimental data or from the other consideration. Service block of the *SMOSE* has a set of such possibilities. The user can demand to minimize the divergence between his data about some paraeter of *OSE* and its model estimation. Spectrum of such parameters spreads to main individual and integral elements of *OSE*.

At the second tier the model adaptation process is continued by the making more precision of sub-set X_2. The quality criterion of this process is based on the improvement of model quality reached during the first stage of adaptation process. Thus the simulation procedure of the *SMOSE* is continuous process of model adaptation via the coefficient changes or trophical graph modification. Really there is a set of models $\{A_i\}$. This set is fored with the sorting out of model parameters. Every model A_i is characterized by the quality level Q_i .Complete model A^* is formed as the limit of above models set. The finishing of adaptation procedure depends on the user's definition of quality criterion Q^* and on the values $|Q^* - Q_i|$. Model A^* ensures the $\min_i |Q^* - Q_i|$. In this paper it is believed that

$$Q_i = \frac{1}{h_1\sigma} \int_{(\varphi,\lambda,z)\in\Omega} B_2(t,\varphi,\lambda,z)\,d\varphi d\lambda dz .$$

Value of Q^* (= 20 g/m^3) is estimated at the time t_* (middle of summer) as average concentration of phytoplankton biomass at the top layer with depth of h_1 (= 100 *m*).

Simulations of the *OSE* offer the possibility for studying various aspects of how the *OSE* functions. Below there are some simulation results received under the values of *OSE* parameters given by Kondratyev et al. (2002). Specifically, the present status of the *OSE* is of great interest in order to understand the role of anthropogenic influence on it. According to the common theory of complex systems, a dynamic system is in the 'living state' at the time interval $[t_0,t_1]$ if the biomass of its elements is within limits $B_i \geq B_{i,min}$. Correlations between the trophic levels and nonliving elements give summary conditions for survivability criteria: $B_{min} \leq \Sigma B_i$. Finally, survivability criteria for the *OSE* can be written in the form: $J(t) \geq \alpha J(t_0)$, where

$$J = U(t)/U(t_0),\ U(t)=\sum_{k=1}^{9} \int_{(\varphi,\lambda,z)} B_k(t,\varphi,\lambda,x)\,dx\ ;\ t_0$$

is a moment of time when value of function $A(t)$ is considered as known; $\alpha < 1$ is the level of survivability. Really we consider the *OSE* to be in a living state if the condition $J(t) > \alpha J(t_0)$ is carried out for $t>t_0$. Calculations of $J(t)$ for $t > t_0$ demonstrate how the *OSE* reaction depends on the variability of various environmental conditions. For example, fluctuations in the oxygen saturation of water may be of anthropogenic origin (oil pollution, large discharge of sewage waters, temperature increase, etc.). The $J(t)$ shows that the *OSE* displays a high degree of stability with respect to the initial saturation of water with oxygen, then how the *OSE* proceeds rapidly to a quasi-stationary regime of functioning at $B_9(t_0,\varphi,\lambda,z) \geq$ 1.8 *ml/l* and how long it takes to overcome the initial shortage of oxygen in the case of $B_9(t_0,\varphi,\lambda,z)$ = 1.1*ml/l. For* $B_9(t_0,\varphi,\lambda,z) \leq$ 0.8 *ml/l*, the *OSE* is unable to proceed to the stationary regime of functioning. The OSE is observed to be more sensitive to a dynamic effects when the water is saturated with oxygen. A reduction of the oxygen production by 12 % does not influence the *OSE* dynamics. However, the *OSE* does not survive when the oxygen production is decreased as much as 20%.

Calculations of J(t) offer possibility for detection capability in searching zones at risk for survivability in Ω. For instance, one of particularly dangerous anthropogenic influences is change in nutrient concentration. Simulation experiments enable us to determine variations in the vertical uprising velocity of water within the some range .

To estimate turbulent escape of nutrients into layers overlying the maximal depth of photosynthetic layer ($z \leq h_*$) it is assumed in the *SMOSE* that the velocity of water uprise is equal to 10^{-3}*cm/s*. The obtained data point to the fact that, on the average, the integrated pattern of the distribution of community elements is not subject to any significant variations within the velocity range from $3.5\cdot 10^{-4}$ to 10^{-2} and even 10^{-1} *cm/s*, but is observed to be drastically distorted under a higher and what is the most important under a lower (< 10^{-4}*cm/s*) vertical advection of water.

Marine environmental research methods include the mathematical models as main component giving the possibility to reconstruct the spatial image of sea ecosystem on the base of fragmentary information. The findings from this study show that the *SMOSE* can be considered as such unit under the synthesis of Okhotsk Sea environment monitoring system. It is obviously the *SMOSE* is simple realization of a set of parametrical descriptions of *OSE* functions. There are many problems for study in the future. We can mentioned about the following problems which could solve in framework of joint efforts undertaken by American, Japanese and Russian scientists. This paper is example of the first step in this direction.

Conclusions

The first problem for the future modernization of the *SMOSE* is the extension of parametrical description of energy and heat exchange between *OSE* and atmospfere to increase the model validaty and to establish the dependence between model parameters and satellite measurements.
The second problem of the *SMOSE* to be greater accuracy consists in the detailed elaboration of *OSE* elements to extend its applied significance to the fishering. Description in the more details of *OSE* biological balance with the formation of industrial fishes has a priority for future investigations. Finally, the third problem to improve the *SMOSE* touches upon the synthesis of expert system in structure of which the *SMOSE* will be main unit.

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