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Mathematical Modelling of Marine Systems

Simulation model of basic components of the Okhotsk Sea ecosystem*

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Abstract—A simulation system which models the dynamics of major groups of plankton in the Okhotsk Sea, taking into account the most important abiotic environmental factors and the complex of external influence, is devised. A model study of the seasonal variability and spatial distribution of these groups has been carried out. The simulation complex consists of blocks which represent complete program algorithms of separate processes: the large-scale water circulation in the Okhotsk Sea, the formation of salinity, temperature conditions, spatial–temporal dynamics of phytoplankton, and the dynamics of macroplankton and mesoplankton.

There are enormous biological resources in the Okhotsk Sea including such valuable fishing objectives as pollack, salmon, herring, flat-fish, navaga, bullheads, halibut, Japanese crab, shrimps, molluscs, trepangs, seals, white whales, laminaria, etc. This fact is supported by research in the north region of the Okhotsk Sea shelf made by the Pacific Ocean Institute for Fishery and Oceanography (POIFO) and its branches. At the same time, at the end of the 1950–1960s the population of flat-fish, Japanese crab, and herring had almost been exhausted. As a result of efforts directed to regulate fishing, the stock of the Pacific ocean herring has been restored and at present its commercial fishing is permitted in the north region of the sea. Thus, in spite of a highly productive sea, intense exploitation of its bioresources in the interests of national economy required a scientifically grounded strategy.

Estimation of the productivity of separate regions and the sea as a whole is a crucial problem. Considerable efforts of the POIFO staff are concentrated just in this direction. In this connection, there are a series of problems which can be solved effectively under the condition of wide employment of modern methods of system analysis, simulation modelling in particular. The positive experience obtained in the solution of such problems is well known [1]. The problem which was solved in cooperation with researchers from the Institute for Mechanics and Applied Mathematics of the Rostov State University consisted in the elaboration of the simulation system which models the dynamics of major groups of plankton in the Okhotsk Sea, taking into account the most significant abiotic factors of the environment and the complex of external force, and a model study of their seasonal variability and spatial distribution.

The interpretation of the simulation system as an element of the man–computer

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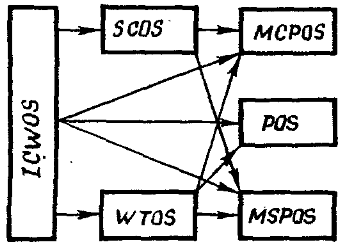

Figure 1. Block diagram of the simulation model of the Okhotsk Sea.

system of rather complex structure which allows us to perform a wide range of experiments serves as the basis for the development of a model for the lower trophic levels in the ecosystem of the Okhotsk Sea. In reality, the elements of such a structure (blocks) are completed program algorithms of separate processes.

While the construction of the models of biological subsystems we proceeded from the fundamental notion about the interaction between the object and the habitat [2] and the importance of variations of external abiotic factors which determines the population kinetics. The operation of the whole simulation complex, with a structure correspondent to the general principles of constructing a model of the spatial–temporal dynamics of hydrobionts [3], represents the sequential computation of the large-scale circulation of waters in the Okhotsk Sea (LCWOS model), salinity conditions (SCOS model), water temperature (WTOS model), and then (based on them) the computation of biological subsystems: phytoplankton (POS), mesoplankton (MSPOS), and macroplankton (MCPOS). Figure 1 shows a block diagram of simulation system.

MODEL OF THE CIRCULATION

The aperiodic circulation of water masses in the Okhotsk Sea represents a complex system of circular motions of various scales and signs inside a cyclonic macro-ring consisting of a chain of long-shore flows: the West Kamchatka flow, the North Branch, the Penzhinsky flow, the Yamskoy flow, the North Okhotsk flow, the Amur flow, the East Sakhalin flow, which together with the Soya flow discharges its waters into the ocean, and the North-East flow which closes the macrosystem in the south region of the sea [4]. The mass balance approach [5] was chosen to simulate the large-scale circulation. A compartment model is developed which contains the following hypotheses:

(1) The Okhotsk Sea is divided into 26 segments (Fig. 2). Within these segments all the characteristics are considered to be homogeneous and averaged over a segment.
(2) The sea is divided vertically into two layers: from the surface down to the 30-m layer and deeper to 200 m (or to the bottom of the shelf).
(3) Volumes of segments are considered to be constant with time.
(4) The external boundaries are the 'air–sea' interface, the coastline, the 200-m level, the bottom, the Kurilsky straits, and the La Perouse straits (the Soya Strait).

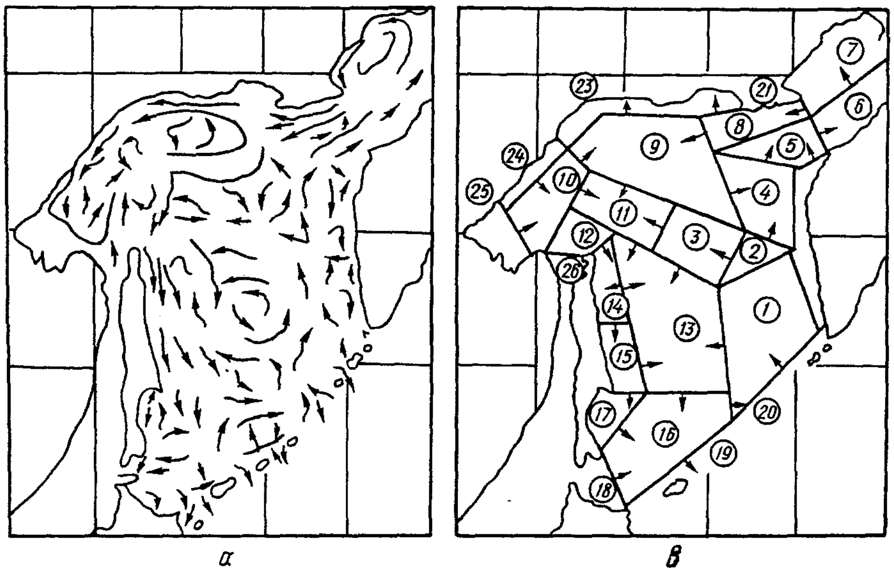

Figure 2. Scheme of the division of the Okhotsk Sea water table into segments and the structure of circulation assumed in the model.

(5) The circulation structure (the directions of motions of water masses from one segment to another), which consists of all the steady circulation systems of the 200 km spatial scale, is considered to be known in the model and constant during the year. It is the same for both layers.
(6) All the periodic or short-term motions of water masses with a spatial scale less than 200 m are considered as random and they are simulated in the same way as the mechanism of turbulent diffusion.
(7) The following components of the water balance are taken into account for the Okhotsk Sea: the river run-off, precipitation, evaporation, the water exchange through the Kurilsky straits and the La Perouse straits, the addition of water masses due to ice melting, and the exchange with deep-water layers. A linear common differential equation of the water balance with the corresponding terms in its right-hand part is valid for the volume of every segment.

The problem concerning the simulation of the circulation in the Okhotsk Sea is associated with a correct choice of its spatial structure and it is solved with the help of models of the salinity and temperature conditions (Fig. 1). The blocks SCOS and WTOS are also independent in the prediction of thermohaline conditions of the sea. From the results of a large series of simulation experiments the model of circulation is identified and its parameters are calibrated on the basis of an iteration procedure for the comparison of the estimated and field data (using the systematized data of background surveys made by the Magadan branch of the POIFO). In addition, we employed computational data obtained using a hydrodynamic approach, which is an alternative to a certain degree [6].

We obtained values for the directed and 'diffusion' exchange between the segments selected, being typical for three types of year: normal, warm, and cold [7].

SPATIAL AND SEASONAL DYNAMICS OF SALINITY

The dynamics of salinity in every region is described by the following balance ratio:

$$V_i \frac{dC_i}{dt} = \sum_{\substack{j=1 \\ j \geqq i}}^{N} [\alpha_{ij} R_j C_j + E_{ij}(C_j - C_i)] - R_i C_i + F_i; \quad i = \overline{1, N}. \tag{1}$$

Here C_i is the concentration of salts in the i-th segment of volume V_i; E_{ij} is the 'diffusion' volume coefficient, which is equal to $D_{ij}A_{ij}/\bar{L}_i$, where $\bar{L}_i$ is the mean length of the adjacent boundary of the i-th segment; A_{ij} is the area of contact between segments i and j; D_{ij} is the turbulent diffusivity; F_i is the source function which describes the external input of salts into the i-th segment (the influx from the ocean, ice melting, salts rising from the deep sea); R_i is the total water flux from the i-th segment α_{ij} is its portion directed into the j-th segment, β_i is the portion of flow R_i towards the environment;

$$\sum_{j=1}^{N} \alpha_{ji} + \beta_i = 1; \quad \alpha_{ii} = 0$$

for non-adjacent segments. Model (1) does not take into account the degree of mineralization of the river water or the precipitation as well as the salt loss due to evaporation. The values α_{ij} describe the structure of water exchange and E_{ij}, being analogues of the diffusion terms in hydrodynamics, are the calibration parameters of the model.

The seasonal variation of salinity as a whole, computed using the models LCWOS and SCOS, corresponds to the virtual dynamics of this environmental feature in summer. It provides the basis for assuming that the character of the variability in the rest seasons corresponds to reality also (Fig. 3).

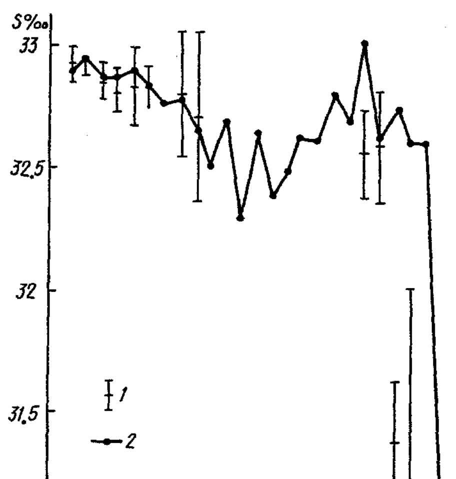

Figure 3. Spatial distribution of the salinity (comparison between estimated data and the actual data in June 1970). (1) Real salinity (average ± dispersion); (2) estimated salinity.

TEMPERATURE MODEL FOR THE OKHOTSK SEA

The water temperature in the Okhotsk Sea as well as the salinity is taken as a tracing characteristic to calibrate the circulation parameters. We describe its variation in every segment by the heat balance equation.

$$\rho C V_i \frac{\mathrm{d}T_i}{\mathrm{d}t} = \sum_j W_{ij}^{\mathrm{A}} + \sum_j W_{ij}^{\mathrm{D}} - W_i + \Omega_i^1 + \Omega_i^2, \tag{2}$$

where T_i is the water temperature in the i-th segment (in K), W_{ij}^{A} is the flux of heat with water flow from the j-th segment into the i-th one, W_{ij}^{D} is the heat exchange between the i-th and j-th segments as a result of 'turbulent' motion of water masses, W_i is the total outflow of heat from the j-th segment, Ω_i^1 is the inflow of heat with water through the external boundary, Ω_i^2 is the heat exchange through the outer boundaries which is not associated with water flows, ρ is the seawater density (in g/cm^3), and C is the heat capacity (cal/g deg).

At present, climatic models employ a multitude of various semi-empirical schemes which describe the interaction between the atmosphere and the underlying surface through relatively simple ratios. In the present work, preference is given to semi-empirical dependences accepted in ref. [8].

We calculated the water temperature values for every segment in the layers 0–30 and 30–200 m. Figure 4 shows the distribution of the estimated temperature in the lower layer in August and the location of cold cores (steady zones with extremely low temperatures which are bonded by the isotherm $-1 \cdot 0^{\circ}$C). In the north Okhotsk Sea, this corresponds, as a whole, to data obtained by V. I. Chernyavsky (1984), who singled out the thickness (intensity) of cold cores in the Okhotsk Sea as an indicator related to sea thermics as well as the basis for the classification of years by the heat content of waters. The results obtained support the adequate nature of the scheme adopted for modelling the currents.

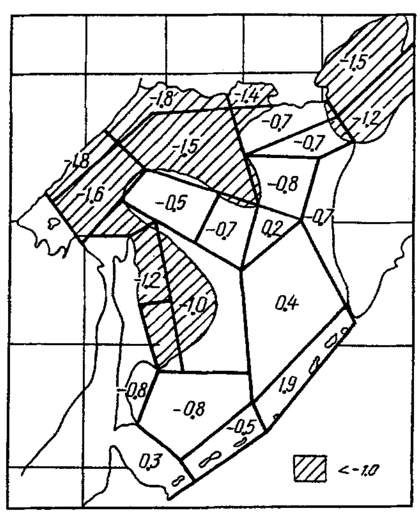

Figure 4. Spatial distribution of the estimated temperature of the lower layer in August and the location of cold cores.

BIOLOGICAL SUBSYSTEMS OF THE MODEL

The approach to modelling the dynamics of planktonic communities employed in the present work corresponds, as a whole, to traditional methods of the model description of these links in water ecosystems. But the analysis of the data on phytocoenosis collected during field hydrobiological surveys showed that it is impossible to apply adequately even the simplest model which is based on the circulation of biogeneous elements limiting the growth of phytoplankton. That is why we employed the simpler mathematical model. Attention was concentrated on the effects of external factors (temperature, water mass transport, etc.) on the population kinetics. However, this does not hamper further structural–parametric extension of base models for biological subsystems [taking account of other (biogeneous) factors of regulations, the description of the processes of spore formation for phytoplankton, passive stages, age classes, nourishment, etc., for crustaceans].

More detailed consideration will be given to the approach to modelling the macrozooplankton of Okhotsk Sea which includes organisms of large enough dimensions measured in cm (euphausiids, hyperiids, sagitta, etc.) exemplified by euphausiids, which play a determinant role in the biotic circulation of aquacoenosis in the Okhotsk Sea and have maximum total biomass among the major taxonomic groups of invertebrates (up to 82%) of the total biomass [9, 10]). The neritically cold-water *Thysanoessa raschii* and moderately cold-water *Th. longipes* and *Euphausia pacifica* (according to the data of complex expeditions of MB POIFO during 1974–1980 [10]) among 95 species of macroplankton have occurrence frequencies of 84, 49, and 13%, respectively. They are the basis of the food of such game fish as herring, pollack, and salmon [11].

The mechanisms which form the spatial–temporal dynamics of euphausiids are of considerable interest. The areas of high biomasses of the species under consideration are located on the shelf, central deep sea, and south regions, respectively. Typical interannual variability exists [9, 12] due to different thermohaline conditions of the years which differ as to their heat content. While modelling, it is usual to divide the population into two age groups—mature and immature individuals. The seasonal temperature variation produces an essential influence on the readiness of crustaceans for spawning and their mortality. The viability of larvae depends on the intensity of intraspecific competition between mature crustaceans. In the spatial aspect, it is assumed that a population consists of 52 subpopulations and each of them occupies its own spatial habitat (segment) according to the two-layer division of the sea into 26 regions accepted in the development of the simulation system. The relation between subpopulations is provided through modelling of the passive transport of crustaceans according to the matrix of circulation, which is the result of the operation of the hydrological block. The dynamics of each point-like subpopulation is described by a set of common differential equations with the parameters chosen according to the biological characteristics of the modelled species and their ecological requirement to physico-chemical factors of habitat [9, 10, 12–16].

The analogue of the splitting method is employed during computation. It is shown that the temperature factor has a determinant role in the formation of spatial inhomogeneity typical of the euphausiid species under consideration. The species with an optimum temperature of 6°C (*Th. raschii*) is consolidated and reproduced more effectively in the northern and shelf regions; crustaceans with an optimum temperature of 10°C (*Th. longipes*) 'prefer' central and southern (the deepest water) regions of the sea. In the seasonal aspect, the spatial distribution of euphausiids varies considerably. The patchy structure is most pronounced in the warm months of the year; in winter, when the thermal conditions of the sea become equal the distribution of crustaceans is more uniform.

The seasonal variation and spatial dynamics of phase variables obtained as a result of computation agree satisfactorily with ideas about the behaviour of biological components of lower trophic levels in the Okhotsk Sea ecosystem in the years which differ by their heat content and with the hydrobiological survey data as well.

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