Remote sensing radiometry technology for the Okhotsk Sea ecosystem biocomplexity assessment

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Abstract

Biocomplexity of the Okhotsk Sea ecosystem (OSE) and its synthesis using a simulation model of the OSE, allowing us to assess conditions in the ecosystem, depending on global and regional changes in an environment, poses a difficult problem. By using this model it may be possible to establish some laws of dynamics of a trophic pyramid of the sea, and also to understand the mechanisms regulating the community of the sea due to external influences. This paper is oriented to the development of biocomplexity indices based on remotely measured environmental characteristics. Microwave radiometry is used as an effective technique to assess sea water parameters. Other ranges help to provide input information for the Okhotsk Sea Biocomplexity Model that will be developed in the framework of this work.

Introduction

Biocomplexity refers to phenomena that result from dynamic interactions between the physical, biological and social components of the *Nature/ Society System* (NSS). The investigations of the processes of interaction between the *Society* and *Biosphere* are, as a rule, targeted at understanding and estimating the consequences of such interactions. The reliability and precision of these estimations depend on criteria founded on conclusions, expertise and recommendations. At present, there is no unified methodology for selecting criteria due to the absence of a common science-based approach to the ecological standardization of anthropogenic impacts on the natural environment. After all, the precision of ecological expertise for the planning and functioning of anthropogenic systems, as well as the quality of the global geoinformation monitoring data, depend on these criteria.

The processes that have their origin in the environment can be presented as a combination of interactions between its subsystems. The human subsystem is a part of the environment and it is impossible to divide the environment into separate subsystems such as Biosphere and Society. The task is to search for methodologies to describe existing feedbacks between Nature and Humanity and to simulate reliably the dynamic tendencies in the NSS. Unfortunately, the part of the NSS that is responsible for the quality of modeling the climatic processes introduces instability in the modeling results. That is why it is supposed that the NSS climatic component is replaced by a scenario describing stable climatic trends during the time interval of investigation. What is actually studied is the NSS.

We introduce a scale of biocomplexity ranging from the state where all interactions between the environmental subsystems are broken down to the state level where they correspond to natural evolution. In this case, we have an integrated indicator of the environmental state including bioavailability, biodiversity and survivability. It reflects the level of all types of interactions among the environmental subsystems. In reality, specific conditions exist where these interactions are changed and transformed. For example, under the biological interaction of the *consumer/producer* or *competition-for-energy-resources* type there exists some minimal level of food concentration where contacts between interacting components cease. In the common case, physical, chemical and other types of interactions in the environment depend upon specific critical parameters. Environmental dynamics is regulated by these parameters and the main task is in the parametrical description of it. Biocomplexity reflects these dynamics.

Biocomplexity Model

The NSS consists of subsystems $B_i(i = 1,\ldots, m)$, the interactions of which are formed during time as functions of many factors. The NSS biocomplexity reflects the structural and dynamic complexity of its components. In other words, the NSS biocomplexiry is formed under the interaction of its subsystems $\{B_i\}$. In due course the subsystems B_i can change their state and, consequently, change the topology of the relations between them. The evolutionary mechanism of adaptation of the subsystem B_i to the environment allows the hypothesis that each subsystem B_I, independent from its type, has the structure $B_{i,S}$, behaviour $B_{i,B}$ and goal $B_{i,G}$, so that $B_i = \{B_{i,S}, B_{i,B}, B_{i,G}\}$. The strivings of subsystem B_i to achieve certain preferable conditions are represented by its goal $\hat{A}_{i,G}$. The expedience of the structure $B_{i,S}$ and the purposefulness of the behaviour $B_{i,B}$ for subsystem B_i are estimated by the effectiveness with which the goal $B_{i,G}$ is achieved.

As an example, we consider the process of fish migration. The investigations of many authors revealed that this process is accompanied by an external appearance of purposeful behaviour. From these investigations it follows that fish migrations are subbordinated to the principle of complex maximization of effective nutritive ration, given the preservation of favourable environmental conditions (temperature, salinity, dissolved oxygen, pollution level, depth). In other words, the travel of migrating species takes place at characteristic velocities in the direction of the maximum gradient of effective food, given adherence to ecological restrictions. That is why we can formulate that the goal $B_{i,G}$ of the fish subsystem is toward the increase of their ration, and the behaviour $B_{i,B}$ consists in the definition of the moving trajectory securing the attainability of the goal $B_{i,G}$.

Since the interactions of the subsystems B_i ($i = 1, \ldots, m$) are connected with chemical and energetic cycles, it is natural to suppose that each subsystem B_i realizes the geochemical and geophysical transformation of matter and energy to remain in a stable state. The formalism of approach to this process consists in the supposition that the interactions between the NSS subsystems are represented as a process whereby the systems exchange a certain quantity V of resources spent in exchange for a certain quantity W of resources consumed. We represent this process by the name (V,W)-exchange.

The goal of the subsystem is the most advantageous (V,W)-exchange, *i.e.*, it tries to get maximum W in exchange for minimum V. The quantity W is a complex function of the structure and behaviour of interacting subsystems, $W = W(V,B_i,\{B_k, k\in K\})$, where K is the space of subsystem numbers interacting with the subsystem B_i .

We designate $B_K = \{B_k, k \in K\}$. Then the following (V,W)-exchange is the result of interactions between the subsystem B_i and its environment B_K:

$$W_{i,0} = \max_{B_{ii}} \min_{B_K} W_i\left(V_i, B_{i,opt}, B_{K,opt}\right);$$

$$W_{K,0} = \max_{B_K} \min_{B_i} W_k\left(V_K, B_{i,opt}, B_{K,opt}\right).$$

Figure 1 represents a block-scheme for the global model of the NSS (GMNSS). The synthesis of the GMNSS is based on its consideration as a self-organizing and self-structuring system, in which the elements are coordinated in time and space by the process of natural evolution. The anthropogenic constituent in this process breaks this integrity. Attempts to parameterize, on a formal level, the process of co-evolution of nature and humans, as elements of the biosphere, are connected with the search of a single description of all processes in the NSS, which would combine all spheres of knowledge in perceiving the laws of the environment. Such a synergetic approach forms the basis of numerous studies in the field of global modeling (Kondratyev *et al.*, 2002; Kondratyev *et al.*, 2004).

All of this corroborates the fact that biocomplexity is related to categories which are difficult to measure empirically and to express by quantitative values. However, we will try to transfer the truly verbal tautological reasoning to formalized quantitative definitions. For the transition to gradations of the scale Ξ with quantitative positions it is necessary to postulate that relationships between two values of Ξ are of the type $\Xi_1 < \Xi_2$, $\Xi_1 > \Xi_2$ or $\Xi_1 \equiv \Xi_2$. In other words, there always exists a value of the scale ρ that defines a biocomplexity level $\Xi \to \rho = f(\Xi)$, where f is a certain transformation of the bio-complexity concept to a number. Let us attempt to search for a satisfactory model with which to reflect the verbal biocomplexity image onto the field of conceptions and signs, subordinating to the formal description and transformation. With this purpose m subsystems of the NSS are selected. The correlations between these subsystems are defined by the binary matrix function: $X = ||x_{ij}||$, where $x_{ij} = 0$, if subsystems B_i and B_j do not interact and $x_{ij} = 1$, if subsystems B_i and B_j are interacting. Then any one point $\xi \in \Xi$ is defined as the sum

$$\xi = \sum_{i=1}^{m} \sum_{j>i}^{m} x_{ij}.$$

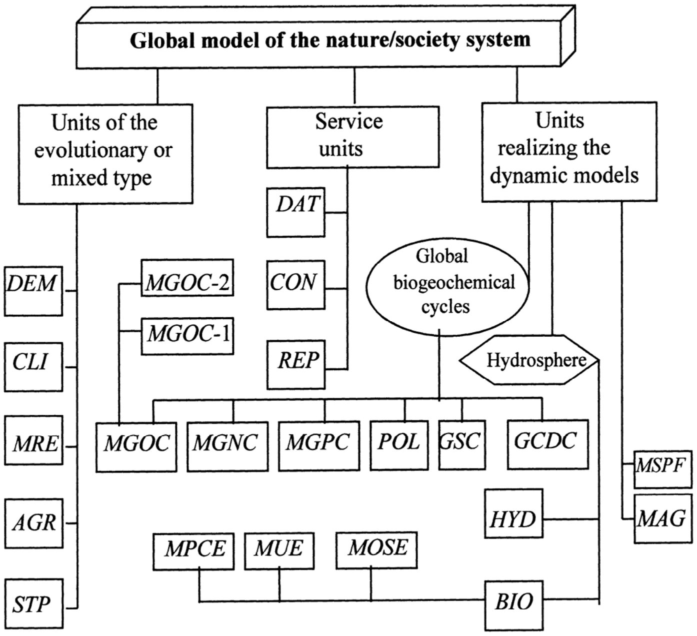

Fig. 1 Structure and items of the GMNSS. List of items is given in Table 1.

Table 1 A description of the items used in Figure 1.

Item	Item description
DEM	A set of demographic models that parameterize the population dynamics with the consideration of age structure
CLI	A set of climate models with various spatial resolutions
MRE	Model for the control of mineral resources
AGR	Model of agriculture production
STP	Model of science-technical progress
DAT	Controlling procedure of interface between the MGNSS items and database
REP	Reporting and visualization procedure
GSC	Model of global sulphur cycle
POL	A set of models parameterizing the pollutant kinetics within different medias
BIO	A set of models parameterizing the aquatic ecosystems in different climatic zones
HYD	Model of global hydrodynamic processes and the biosphere water balance
MAG	Model of the magnetosphere processes related to the global biogeochemical cycles
MUE	Typical model of the upwelling ecosystem of the World Ocean
MOSE	Model of the Okhotsk Sea Ecosystem

Certainly there arises the need to overcome uncertainty for which it is necessary to complicate the scale Ξ, for example, to introduce weight coefficients for all NSS subsystems. The origin of these coefficients depends on the type of subsystem. That is why three basic subsystem types are selected: living and nonliving subsystems and vegetation. Living subsystems are characterized by their density, estimated by numbers of elements or by biomass value per unit area or volume. Vegetation is characterized by the type and portion of occupied territory. Nonliving subsystems are measured by their concentration per unit square or volume of the environment. In the common case, certain characteristics $\{k_i\}$, corresponding to the significance of the subsystems $\{B_i\}$, are assigned to every subsystem B_i (i = 1,..., m). As a result, we obtain more closely the definition of the formula to move from the biocomplexity concept to the scale Ξ of its indicator:

$$\xi = \sum_{i=1}^{m} \sum_{j>i}^{m} k_j \, x_{ij}.$$

It is clear that $\xi = \xi(\varphi,\lambda,t)$, where φ and λ are geographical latitude and longitude, respectively, and t is the current time. For the territory Ω, the biocomplexity indicator is defined as mean value

$$\xi_\Omega(t) = (1/\sigma) \int\limits_{(\varphi,\lambda)\in\Omega} \xi(\varphi,\lambda,t)\, d\varphi\, d\lambda,$$

where σ is the area of Ω. Thus the indicator $\xi_\Omega(t)$ is the integrated NSS complexity characterization reflecting the individuality of its structure and the behaviour at each time t in the space Ω. According to natural evolution laws, a decrease (increase) in ξ_Ω will correspond to an increase (decrease) of biocomplexity and the survivability of the nature–anthropogenic systems. Since a decrease of biocomplexity disturbs the exclusiveness of the biogeochemical cycles and leads to a decrease in stress on nonrenewable resources, then the binary structure of the matrix X is changed in the direction to intensify the resource-improverishment technologies.

Biocomplexity of the Okhotsk Sea

A trophical pyramid of the Okhotsk Sea ecosystem is described by the matrix $X = \|x_{i\,j}\|$, where $x_{i\,j}$ is a binary value equal to «1» or «0» under the existence or absence of the nutritive correlation between the ith and jth components, respectively. Biocomplexity is defined as

$$\xi(\varphi,\lambda, z, t) = \sum_{i=1}^{20} \sum_{j=1}^{19} x_{i\,j} C_{i\,j}\ ;$$

$$x_{ij} = \begin{cases} 1, \text{ if } B_m \ge B_{m,\min}; \\ 0, \text{ if } B_m < B_{m,\min}; \end{cases}$$

where φ and λ are geographical latitude and longitude, t is current time, z is the depth, $B_{m,\min}$ is the minimal biomass of the mth component consumed by other trophic levels, $C_{i\,j} = k_{j\,i}\, B_{i,*} / \Sigma_{j\,+}$ is the nutritive pressure of the jth component upon the ith component, $\Sigma_{i+} = \sum_{m\in S_i} k_{im} B_m$ is real food storage which is available to the ith component, $B_{m,*}$ = max{0, $B_m - B_{m,\min}$}, $k_{i\ m} = k_{i\ m}(t,\ T_W\ ,\ S_W)$ (i = 1, …, 17) is the index of the satisfaction of nutritive requirements of the ith component at the expense of the mth component of biomass; $k_{i\ m}$ (i = 18,19) is the transformation coefficient from the mth component to the ith component, k_{i20} is the characteristic of anthropogenic influence on the ith component; $S_i = \{i : x_{i\,j} = 1\ j = 1, \ldots , 19\}$ is the food spectrum of the ith component, T_W is water temperature, and S_W is water salinity.

A maximal value of $\xi = \xi_{\max}$ (≈ 20) is reached during spring–summer time when nutritive relations into the Okhotsk Sea ecosystem are extended, the intensity of energetic exchanges is increased, horizontal and vertical migration processes are stimulated. In the wintertime, the value of ξ is changed near $\xi_{\min}$ (≈ 8). The spatial distribution of ξ reflects a local variability of the food spectrum for the components. Calculations show that basic variability into the $\xi^* = \xi/\xi_{\max}$ is caused by migration processes. Under these processes the quick redistribution of the interior structure of matrices X and $\|C_{ij}\|$ occurred. Many fishes migrate to the shelf zone during springtime, and during winter they move to the central aquatories of the Okhotsk Sea. Therefore, $\xi^* \rightarrow 1$ during spring and $\xi^* \rightarrow 0.6$ during winter for the shelf zone. This means that the biocomplexity of the Okhotsk Sea ecosystem on the shelf decreases by 40% in winter in comparison with spring. For the central aquatories, ξ^* is changed to near 0.7 during the year. Such stability of a biocomplexity indicator is explained by the balance between nutritive correlations and productivity during spring, summer and winter.

It can be to establish that variability in ξ^* reflects the changes of fish congestions which are controlled by environmental conditions. Specifically, during springtime. Pacific herring *Clupea pallasi escapes* occupy the area with $T_W < 5°C$. Other fishes choose different depths for their feeding and spawning. All these processes have an influence on the variability of ξ^*. A more detailed investigation of correlations between ξ^* and the structural and behavioral dynamics of the Okhotsk Sea ecosystem demand additional studies.

Spatial distribution of the biocomplexity indicator in the Okhotsk Sea in the spring and summer period, designed by a technique described in the previous section is shown Figure 2. It reflects the level of complexity of the sea ecosystem. The basic variability in ξ is caused by the migration process.

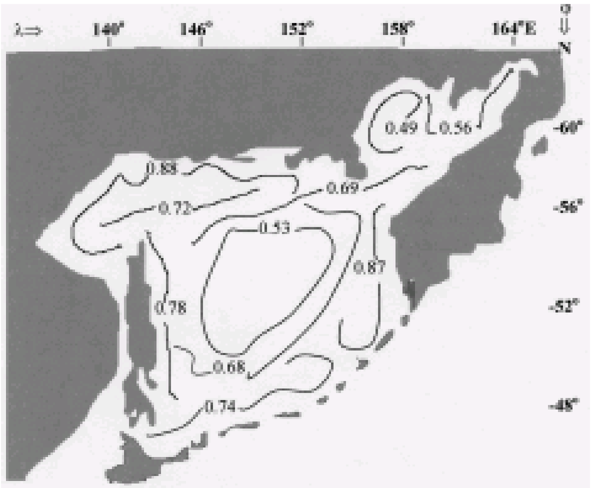

Fig. 2 Spatial distribution of the biocomplexity indicator in the Okhotsk See during spring and summer.

Conclusion

Biocomplexity is clearly an important characteristic of the NSS dynamics. It has importance for the complex study of interactions between living and non-living elements of environment and, more significantly, it can be used to make valuable contributions to the understanding and solution of key socio-economic and environmental problems. It is reasonable to expect that over the near future the biocompexity will be able to be used as an indicator analogous to such indicators as the normalized difference vegetation index (NDVI) and leaf area index (LAI) (Krapivin *et al.*, 2006). It appears that the only satisfactory way to develop an appropriate definition of a biocomplexity indicator is to summarize the many structural ideas of a series of global biospheric models. The synthesis of these models requires not only their compatibility with global databases, but also the interconnections between different sources of data.

The Okhotsk Sea ecosystem maintains a significant position in the global natural system. At the present time it has a low level of pollution, with fishing being the main anthropogenic 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 the environment. The OSE interacts with biosphere processes via the influence of the global climate, and on the Pacific Ocean. This influence is reciprocal.

This paper proposes a global model and biocomplexity indicator for only one category in which biospheric processes are considered to predominate. Further study will be oriented to the expansion of information, taking into account the global model, and it will be necessary to correlate the dependencies between socio-economic and biospheric components.

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