NUMERICAL SIMULATION OF BIOSPHERE DYNAMICS

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Contents

Summary

Numerical simulation of biosphere processes is the part of a wider scientific activity, which could be called global dynamics. Effective prevention of global crises is impossible without a sufficiently accurate forecast of the future state of the biosphere. Well-known forecast of global dynamics presented by the Club of Rome should be considered as a rather optimistic one. This forecast does not include the yet unvalued response of the biosphere to the global influence of humankind. The Earth's biosphere can be considered to be combined of two interacting subsystems: climatic and bio-geo-chemical ones related to one another. To determine the likely effect of a change, such as an increase in the greenhouse gas concentration, on the climate system, it is necessary to look how the system responds as a whole. There is a number of global models for numerical simulation of biosphere dynamics. A brief description of some of them is presented in the chapter. The predicting of the Earth's biosphere behavior in unprecedented dynamics range is the key problem of global dynamics investigation. However, the biosphere is unique and there are no possibilities for the comparative verification of models; and, obviously, it can not be the object of experimental investigations. A promising possibility to use man-made Closed Ecological Systems as physical models of the Earth's biosphere for verification of main principles of global ecological modeling is considered.

1. Introduction

Observations of the Earth from outer space in to a great extent promoted the creation of a “holistic” concept of the basic processes regulating changes in the global environment.

In accordance with this concept, the Earth is a "metabolic" system consisting of interacting components, so that a change in one component influences the other components. In the context of this global approach it seems to be useful to consider the Earth as an object including several different but interacting spheres: the lithosphere, the hydrosphere, the cryosphere, and the atmosphere.

The unique properties of the Earth as an entire system, as well as the greatest part of possible cardinal changes in the environment, are connected with the fifth basic sphere – biosphere being the totality of all living organisms. The biosphere is a very complex system and the forecast of its dynamics is possible only by means of some model reflecting essential properties of the biosphere. This model could be of mathematical or physical nature. In this chapter some mathematical models of the biosphere are primarily considered.

Numerical simulation of the biosphere processes is the part of a wider scientific activity, which could be called global dynamics. The main motivation of studies on global dynamics is the intention to overcome negative global tendencies, which were predicted in the past, and are detected now. Effective prevention of global crises is impossible without a sufficiently accurate forecast of the future state of the biosphere. Successful solution of other global problems is possible only with a satisfactory state of the biosphere and availability of natural resources.

2. Models of Global Dynamics by Club of Rome

The model of global dynamics suggested by J. Forrestrer is the first completed attempt to use a mathematical approach to the investigation of the world development. He took into account four groups of parameters, namely, the population sector, the pollution sector, the natural resources sector, and the capital stock sector. Each of these sectors contains one or two internal feedback loops. They are interrelated by numerous auxiliaries and are controlled by about 100 numerical constants.

Several assumptions are made in the model:

- Population increases and decreases according to the birth and death rates.
- The birth rate depends on the actual population size and on several auxiliaries ("birth rate multipliers") for food supply, material life standard, crowding, and pollution.
- The death rate also depends on the actual population size and, similar to the birth rate, on food supply, material life standard, crowding, and pollution.
- The level of pollution is determined by the rates of its generation and absorption.
- Pollution generation depends on the population size, on a switchable constant, and on the "pollution capital multiplier" determined by the capital sector.
- Pollution absorption depends only on the actual level of pollution, but in such an intricate manner that a table function is used.

This model showed that in 2060s the human population will catastrophically decrease to 1/6 of its maximum in 2020. The causes of this dynamics are the limitations of resources and the continuous growth of human pollution. This model allowed one to consider different scripts of world dynamics depending on different strategies of the joint control over the world development. Further the improved versions of this model called WORLD2 and WORLD3 showed similar predictions. For example, the world population size is predicted to have its maximum about 2035 when for the first time since the early 20th century the number of deaths will exceed the number of births.

The conclusions based on the results of the WORLD3 model include the following:

1. Human use of many essential resources and generation of many kinds of pollutants have already surpassed rates that are physically sustainable. Without significant reductions in material and energy flows, there will be in the coming decades an uncontrolled decline in per capita food output, energy use, and industrial production.
2. This decline is not inevitable. To avoid it two changes are necessary. The first is a comprehensive revision of policies and practices that perpetuate growth in material consumption and in population. The second is a rapid, drastic increase in the efficiency with which materials and energy are used.
3. A sustainable society is technically and economically possible. It could be much more desirable than a society that tries to solve its problems by constant expansion. The transition to a sustainable society requires a careful balance between long-term and short-term goals and an emphasis on sufficiency, equity, and quality of life rather than on quantity of output. It requires more than productivity and more than technology; it also requires maturity, compassion, and wisdom.

So, keeping the global status quo gives way to the crises whose reality was recognised officially in the Rio-de-Janeiro meeting. But the greatest part of society, including specialists, does not accept these forecasts yet. Thus the WORLD3 forecast could be considered as a rather optimistic one. This forecast does not include the yet unvalued response of the environment to the global influence of humankind.

3. The Problem of the Earth's Biosphere Stability

It is a wide spread opinion that the decrease of the human population and the essential decrease of industrial activity would return the biosphere to the pre-industrial state or at least would stop negative tendencies. Unfortunately, there is no reliable prediction of further dynamics of such a complex system including the global biota, the ocean as a temperature and CO_2 exchange machine, and the atmosphere as a climate machine. There is no data on limits of “elasticity” (or stability against “deformations”) of the Earth's biosphere as a whole. The slip of the Earth’s biosphere to the critical state became more and more noticeable. The degree of human interference in global bio-geo-chemical cycles at the present time possibly draws to the critical level: the values of some important variables and the rates of their change come near the levels having no historical analogues. First of all, it is displayed in increasing the CO_2 and CH_4 concentrations, global warming, global pollution, and in accelerating the process of elimination of animal and plant species.

In essence, all the aspects of the physical and chemical media of the Earth are absolutely different from those in an abiotic world. The determinative role of living beings in all geo-chemical cycles of the Earth is a relatively recent discovery. The most peculiar feature of the Earth's biosphere (at least through thousands years before the industrial era) in comparison with local ecosystems was the closure with respect to mass. The recognition of biotic factors as potential homeostatic regulators of bio-geo-chemical cycles allowed us to advance in the understanding of the natural metabolism that determines the composition of the atmosphere, the oceans, and sediment formations. So the human activity takes place in the background of important interactions and interconnections, which settled and changed the system of the Earth from the moment of its origin.

The possibility of serious changes in the Earth's environment sets a very difficult problem: to develop methods for analysis of the causes of these changes and to predict their dynamics. The empirical approach is not sufficient for getting necessary information due to the long-term response of local ecosystems and the great diversity of them. Models are necessary for describing the Earth's subsystems, their interactions and getting forecasts of their dynamics. The main question in studies of the global changes is: how are the processes of very different rates connected to one another? The understanding of these connections and describing them in models are the key problems of global modeling.

The Earth's biosphere can be considered to be combined of two interacting subsystems: climatic and bio-geo-chemical ones related to one another. To determine the likely effect of a change, such as an increase in the greenhouse gas concentration, on the climate system, it is necessary to look how the system responds as a whole. To do this, climate models are essential, because they integrate the main processes that occur within the climate system and calculate the adjustments and readjustments of its various elements as they respond to the original change.

4. Canadian Climate Change Model

Among climatic models the Canadian Global Coupled Model (CGCM1) is most known. In 1999, the U.S. National Academy of Science identified CGCM1 as one of the current leading performers in climate system simulation and recommended that its results be used in the U.S. National Climate Change Assessment.

The first version of the CGCM1 is a spectral model with triangular truncation at wave number 32 (yielding a surface grid resolution of roughly $3.7^o \times 3.7^o$) and 10 vertical levels. The model uses heat and water flux adjustments obtained from uncoupled ocean and atmosphere model runs (of 10 years and 4000 years duration respectively), followed by an “adaption” procedure in which the flux adjustment fields are modified by a 14 year integration of the coupled model. A multi-century control simulation with the coupled model has been performed using the present-day CO_2 concentration to evaluate the stability of the coupled model's climate, and to compare the modeled climate and its variability to that of the observed.

CGCM1 projections of climate change over the next century are based on the results of three greenhouse gases (GHG) plus aerosol runs (the most realistic of the scenarios used). All the three GHG+A runs show very similar trends in average global surface temperatures. They increase by about 1.7^oC above 1985 levels, rising to about 3^oC by

2075 and nearly 4.5°C by 2100. Neglecting the cooling effects of aerosols gives even higher increases, with average global surface temperatures rising by 2.4°C by 2050 and nearly 5.5°C by the end of the century.

An ensemble of four transient climate change simulations has been performed. Three of these simulations use an effective greenhouse gas forcing change corresponding to that observed from 1850 to the present, and a forcing change corresponding to an increase of CO_2 at a rate of 1 percent per year (compounded) thereafter until 2100. The direct forcing effect of sulphate aerosols is also included by increasing the surface albedo based on loadings from the sulphur cycle model. The fourth simulation considers the effect of greenhouse gas forcing only. The change in climate predicted by the model depends directly on this specification of greenhouse gas (and aerosol) forcing, and of course this is not well known. The prescription described above is similar to the IPCC "business as usual" scenario, and using a standard scenario allows the results of this model to be compared to those of other modeling groups around the world.

The ability of a climate model to reproduce the present-day mean climate and its historical variation adds confidence to projections of a future climate change. A comparison of modeled and observed global annual average surface air temperature anomalies from 1900 to 1990 showed that the overall agreement in temperature trend and in the magnitude of stochastic interannual variability is the same. In both the model and observations, the increase in global mean temperature over this century is roughly 0.6°C.

Due to the high complexity of the model, numerical simulation should be verified by a control simulation with fixed greenhouse gas forcing. An expanded time series of modeled global annual mean air temperature spanning the period from 1900 to 2100 was considered. The small drift in this control run illustrates that the flux adjustment scheme is relatively successful.

Between 1980 and 2050 the prescribed CO_2 concentration doubles, and over this time the greenhouse gas only run exhibits an increase in temperature of 2.7°C. The increase over the same period in the greenhouse gas plus aerosol run is 1.9°C; the difference of 0.8°C is the cooling effect of the aerosols. These results differ from the results of the equilibrium calculation, which showed a global average warming of 3.5°C upon doubling the CO_2 concentration. The difference between the transient warming at the time of CO_2 doubling, 2.7°C, and the equilibrium value of 3.5°C illustrates the ocean's role in sequestering heat. However, the overall pattern closely resembles that of the earlier equilibrium calculations in which the warming is largest in the polar regions, and larger over land than over ocean. A notable difference is the hemispheric asymmetry in warming, whereby the warming is larger in the northern hemisphere than in the southern one, in contrast to the equilibrium calculations where the warming is roughly equal in the northern and southern polar regions. This asymmetry in the fully-coupled model results from the more vigorous vertical mixing between the surface and deep waters of the Southern Ocean and is a general feature of fully-coupled simulation. Indeed, enhancement of this vertical exchange at certain locations in both the Southern Ocean and the Labrador Sea actually leads to a slight local cooling of the surface temperatures, despite the global average warming.

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Biographical Sketches

S.I. Bartsev was born January 27, 1955, Slavgorod, Altay Region, Russia. He completed his Diploma in Biophysics at the Krasnoyarsk State University, Krasnoyarsk, Russia in 1977. In 1986 he obtained the Russian degree of candidate in Physics and Mathematics at the Institute of Biophysics of the Russian Academy of Sciences, Krasnoyarsk for the thesis "The heterogeneity of population of luminescent bacteria with respect to light intensity". From 1977 to 1978 he was a special student in the Institute of Physics of the Russian Academy of Sciences in Krasnoyarsk, Russia. From 1981 to 1983 he was a post-graduate in the Institute of Biophysics of the Siberian Branch of Russian Academy of Science. From 1983 to 1987 he was a researcher in the same Institute. From 1987 to 1990 he was a lecturer at the Krasnoyarsk State University (department of Higher Mathematics). From 1990 to 1991 he was a Scientific Secretary of the Institute of Biophysics of SB RAS. From 1991 to 1997 he was a Senior Scientist at the theoretical department of the Institute of Biophysics (SB RAS). Since 1991 S.I. Bartsev is a Senior Researcher at the theoretical department of the Institute of Biophysics (SB RAS). Dr S.I. Bartsev's special fields of research activity include creation and control of artificial biospheres, principles of space life support system design, biosphere crises, different applications of neural network algorithms. He wrote about 50 scientific papers. He has contributed to Life Support System modeling and assessment. His current work centers on biosphere crises and global modeling including optimization of bio-techno-sphere configuration, considering the Earth's biosphere as Life Support System of huge space ship.

R.G. Khlebopros was born March 21, 1930, South Ukrain. He completed his Diploma in physics at the Kiev University, in 1953. Scientific Degrees: Doctor of Sciences (Physics and Mathematics), Professor of Ecology. From 1953 to 1963 he was a physics teacher, technical school, Nizhny Tagyl (the Urals). From 1963 to 1975 he was an engineer, junior researcher, senior researcher at the theoretical department, Institute of Physics (USSR Academy of Sciences, Siberian Branch), Krasnoyarsk. From 1975 to 1988 he was the head of the laboratory of mathematical methods of research, Institute of Forest and Wood (USSR Academy of Sciences, Siberian Branch), Krasnoyarsk. Since 1988 R.G. Khlebopros is the head of theoretical department, Institute of Biophysics (Russian Academy of Sciences, Siberian Branch), Krasnoyarsk. Prof. R.G. Khlebopros's special fields of research activity include mathematical modeling in biological processes and ecosystems; economic estimation of ecological objects. He wrote more than 100 scientific papers. He has contributed to the optimization of forest management. His current work centers on the problem of interaction of ecology and economy. He develops the methods of the treatment of the long-term ecological utility overcoming the problem of the competition between economic and ecological types of environmental management.