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GLOBAL MODELS, THE BIOSPHERIC APPROACH (THEORY OF THE NOOSPHERE)

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PREFACE

The coevolution of mankind and the biosphere is one of today's principal research problems. Clearly, human activity has begun to rival nature's ability to modify the variability of the earth's climate or even to generate climatic changes. Human intervention into the climatic system could have profound consequences for the biosphere, and thus careful analysis and consideration of both the environmental and societal implications of such intervention are critically needed.

For the past several years, researchers at IIASA have been examining problems such as these. In 1978, for example, a meeting was held on "Carbon Dioxide, Climate and Society". This meeting brought together experts from around the world to assess the state of knowledge on the prospects of climate change resulting from increasing atmospheric injections of carbon dioxide and in particular to review work on this subject in the IIASA Energy Systems Program. In the same year, IIASA hosted the International Workshop on Climate Issues organized by the Climate Research Board of the US National Academy of Sciences and a preparatory meeting for the World Climate Conference organized primarily by the World Meteorological Organization (WMO) of the United Nations. In 1980, a Task Force meeting on the Nature of Climate and Society Research was convened to advance our knowledge of the relationship of climate to specific aspects of physical and social systems. More recently, in 1982, an international workshop on "Resource and Environmental Applications of Scenario Analysis" was organized. This workshop focused on innovative approaches for dealing with issues like climatic change which involve considerable uncertainty and multidisciplinary analysis. Finally, a major 2-year project is currently being initiated with the support of the UN Environmental Programme. This project will investigate the impacts of short-term climatic variations and the likely long-term effects of CO_2-induced climatic changes on agricultural output at the sensitive margins of food grains and livestock production.

Within the framework of its climatic studies, IIASA has continually attempted to disseminate information about similar studies performed at research centres in the IIASA National Member Organization countries. This paper presents the approach and the system of analytic tools developed for investigations of global biospheric problems at the Computing Center of the USSR Academy of Sciences, Moscow, USSR. The paper was presented at the 9th Global Modelling Conference, held at IIASA in 1981.

Janusz Kindler
Project Leader
Impacts of Human Activities on Environmental Systems

ABSTRACT

The problem of the coevolution of mankind and the biosphere, i.e., the relationship between the process of the evolution of the biosphere and the evolution of human activity which provides a homeostasis for human civilization, has become one of the principal problems of human ecology.

The first step in an extensive program of interdisciplinary research is the creation of a system of mathematical models which would serve as a framework for planning international research programs.

The research described herein has two stages. The first stage, a still primitive system of models was constructed and analyzed, using systems dynamics techniques. This system of models, outlined in the second section of the paper, has already helped the authors in their contacts with experts in biology, soil science, etc., and the creation of an information base has in essence, turned into a discussion of plans for future work. Studies connected with simulating the evolution of the biosphere were developed in three directions: simulation of processes of a biotic nature, simulation of climate, and simulation of human activity.

Experimental results obtained using this system in the "if ... then" mode, may be helpful for understanding, at least on a qualitative basis, possible impacts of human activity on the evolution of the biosphere assuming that the present day trends remain unchanged. This system of models is at present programmed at IIASA and is ready to be used for simulation experiments.

The second step in the research is based on an understanding of the fact that the systems dynamic approach is not sufficient for the elaboration and study of the system of models which describes human activity. Furthermore, it is necessary to analyze and coordinate models developed by experts in varied branches of science - biologists, climatologists, economists, etc. Thus, it is necessary to elaborate new mathematical techniques that can be used in the investigation of global coevolution problems. Some principles for the development of these techniques were formulated at the Computing Center of the USSR Academy of Sciences and are presented herein. The three main principles are:

(1) Linear parametrization of comprehensive submodels;

(2) Models of human activity are split into two levels - the decision-making level and the technological level - and a description of the system of models at the technological level only;

(3) Analysis and coordination of the system of models by constructing a set of all reachable values of performance indices (The Generalized Reachable Sets Approach).

The linear parametrization procedure for a climate model which is essentially the Mintz-Arakawa global atmospheric circulation model as described by Gates et al (1971) and modified to account for the climatic trends due to the influence of anthropogenic factors, is described in the third section of the paper.

The problems of modeling human activity and the main features of the Generalized Reachable Sets approach, as well as the general scheme of analysis of global biospheric models, are presented in the fourth section of the paper.

This work, which is now in the early stages, calls for a great deal of scientific effort over a long period of time. The authors anticipate that the importance of the research in this direction will be internationally recognized and supported.

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The term global models has been widely disseminated as a result of the work of the Club of Rome. This term is usually associated with systems of mathematical models describing world economic processes, including a certain number of ecological characteristics (demographic factors, pollution, etc.). However, there is a range of problems connected with the study of the global character of the dynamic processes that take place in the biosphere, that are just as meaningful and just as significant for the future of mankind. The study of such problems began in the USSR at the beginning of the 70s, independent of the work of the Club of Rome. This paper summarizes some of the results of our work.

1. THE PURPOSE OF THE RESEARCH AND THE POSSIBILITIES OF THE MODEL

1.1 What is Coevolution?

In the opinion of V.I. Vernadski (1926), the biosphere represents an integrated system whose evolution is determined by the interaction of its biotic and abiotic components. Mankind is a natural element of the biosphere, and its existence outside of the biosphere is unthinkable. The existence of civilization in the modern sense of the word is only possible within a relatively narrow range of parameters. The growing power of mankind poses the problem of a selection of strategies of social development which are capable of guaranteeing not only an existence, but also the joint evolution of mankind and the environment.

The activity of people inevitably exerts an influence on the biosphere and changes living conditions. But the rates at which these conditions change, do not necessarily influence the degree to which people can adapt to these changes. The relationship between the evolution process of the biosphere and the evolution of human activity, provides a homeostasis for human civilization that we have termed coevolution.

The problem of coevolution has become, in our view, one of the principal problems of human ecology. Its solution will require unprecedented efforts on the part of mankind, and in order that such efforts be undertaken, mankind should have an extensive knowledge of the general laws governing the evolution of the biosphere.

1.2 The Language of Interdisciplinary Research

The study of the properties of the biosphere as a single integral unit is still very limited. There is no doubt that existing information is inadequate to express any definitive opinion concerning the choice of strategies for the development of society. For this reason, coevolution will require quite an extensive scientific program of interdisciplinary research. It will have to include the experts from widely differing professions - biologists, climatologists, physicists, economists, mathematicians, agriculturists, etc. It will also require the participation of experts in the humanities. The manifold activities of these disciplines should be united, the information has to be collated, international programs should be worked to help solve particular problems, etc. On what basis can such a unification of the efforts of researchers be achieved? In the first place a common language should be created, enabling experts from various fields of knowledge to understand concrete objectives (and in a number of cases the contents) as well as the research of their colleagues working in other areas of the same program.

Such a language can only be a language based on a formalized description, i.e., the language of mathematical models.

Thus, we consider our first objective to be the creation of a system of models which would serve as the framework of a general scheme for concrete research, the basis for planning, and the management of international research programs directed towards the elaboration of strategies providing for the coevolution of mankind and the environment. Those strategies would guarantee man's life on earth. We consider one of the results of our activities to date, to be the fact that although the system of models that has been built up until now is rather primitive, it has already helped us in our contacts with experts in the field of biology, soil science, etc. The creation of an information base has, in essence, turned into a discussion of plans for joint work.

1.3 Research into the General Laws Governing the Biosphere

The study of the biosphere as a unified whole was begun by V.I. Vernadski (1926). As a result of his research, the interrelation of many factors, and in particular the role of living matter in the formation of the upper sheath of the Earth have become evident. The next great step forward in the understanding of the general laws governing the development of the biota were the findings of V.N. Sukachev (1964) and N.V. Timofeev-Resovski (1961) on biogeocenosi. The notion of the biosphere as an aggregate of elements whose inner relationships are significantly stronger than its outer relationships already contains definite recipes for the analysis of general planetary biogeocenosi. Nevertheless, these general qualitative judgements are not sufficient for the problems that stand before mankind today. Systematic research is needed that would provide quantitative evaluations of the general biogeocenotic process and also make it possible to evaluate the effect of anthropogenic influences. It should be noted, that during the last decade a number of studies have appeared that have played an important role in the formation of views on the objectives and methods of analysis of global processes. Examples of such studies are those of V. Ja. Sergin and S. Ja. Sergin (1976) concerning the theory of paleo-climate and the dynamics of glaciers, as well as the numerous works on the circulation of biogenic elements. This research was begun in the 30s by Kostizin (1935) and has provided an important direction in science. This research should be continued utilizing modern methods for processing information.

Thus one of the most important objectives of our work is the creation of a system of models, within whose framework it is possible to describe the basic properties of the dynamics of the biosphere with the necessary degree of accuracy, and which would serve as a point of departure for the study of the evolutionary trends of the biogeocenotic processes in the world. This system of models should be created for use in a conversational mode. Thus, our task is to create a man-machine system in which a system of models would simulate reality.

1.4 The Problem of Linear Trends

One of the problems is the choice of research strategies. During the study of complex systems, as various questions accumulate before the researcher, the choice of their queuing order plays a decisive role in the entire outcome of the research program. The study of the linear trends of the basic parameters of the biosphere is a problem of primary importance.

The dynamic model of the biosphere may be represented by the following equation:

$$\frac{dx}{dt} = F(x,u,t) \tag{1}$$

where x - is a vector of phase variables that describe the dynamics of the biosphere, and u - anthropogenic factors. This means that during the first stage of research, we attempt to separate the problem of the evolution of the biosphere and the evolution of the characteristics of human activity.

Assuming $x = \hat{x} + y$ where $\hat{x}$ characterizes the contemporary quasi-stationary state and assuming that the values y and u are small, we obtain

$$\frac{dy}{dt} = F_x y + F_u u$$

We call the matrix F_x the matrix of natural evolution, the matrix F_u the matrix of anthropogenic evolution, and the value $F_u u$ the value of linear trends.

Such treatment of the problem is convenient, as it immediately defines the problem. Having determined the matrix F_u, we may make use of the method of the construction of sets of possible solutions. Designating the set of possible anthropogenic loads on the biosphere as V, we attempt to obtain its reflection in the space of those parameters of interest to the researcher. Such an approach also makes it possible to construct iteration procedures needed for the various recounts.

It stands to reason that the construction of the sensitivity matrix F_u makes it possible to obtain evaluations that characterize changes of the parameters of the biosphere for only relatively small intervals of time, tens, and in extreme cases, hundreds of years. But it is precisely this period that is of greatest interest to mankind. If it finds the strength within itself to overcome the crisis of the next decades, then one can assume that it will acquire the experience necessary for its subsequent development.

1.5 The Problem of Critical Parameters

In the evolution of any complex non-linear system it is possible to distinguish the relatively "calm" course of the process, when its parameters are not in the vicinity of their bifurcation values. In this situation, a chance perturbance may disturb the equilibrium of the system (to be more exact the quasi-equilibrium) only temporarily. The inner forces of damping that are inherent to nature return the system to its initial state (or close to the initial one). It is quite another matter with situations that are close to the values of the "load on the biosphere" during which new states of equilibrium emerge. According to the terminology of A. Poincare, they are called bifurcational. They respond to those values of parameter u, that revert the derivative of the right hand side of equation (1) to zero

$$\frac{dF(x,u)}{dt} = \phi(x,u) = 0 \qquad (2)$$

There may be many states of equilibrium. For example, in Euler's classical example concerning the equilibrium of a pivot, after the load has exceeded a critical value, the new state of equilibrium turns out to be a continuum--any sinusoid that forms the surface of the revolution is the equilibrium position. However, it is impossible to predict what state of equilibrium the system will come to--it may depend on unforeseen chance factors. In the case of the biosphere, we do not know of any other states of equilibrium except for those that are observed. For this reason, the study of the critical loads will, at some point in the future, be an important scientific problem--we do not have any guarantee that the present day load on the biosphere is sufficiently removed from the critical one. But, there is an indirect basis to suppose that a number of characteristics of the biosphere are close to their critical values. For example, an increase in the average temperature by 2.5^{o} to 4^{o} would probably lead to the beginning of an irreversible melting of glaciers. What will the properties of the new state of equilibrium of the biosphere be like, will they permit the existence of man? We do not know anything about this.

1.6 Methods of Systems Analysis

Among the objectives that we are setting in our program purely methodological problems occupy an important place. In what way should the research of a system whose elements represent objects that are so varied in their physical content be organized? How should one cope with the fantastic dimensions of the problems that emerge? How should one create a simplified version of the models? Presently, we do not have sufficient experience, and its acquisition will be an important stage in the realization of such research programs.

Thus, the present stage in the history of man requires in our view, the intervention of the human intellect in the formulation of the principles for its further development. But this intervention may be justified only if a new scientific discipline emerges--the dynamics of the noosphere and the study of the conditions of coevolution, i.e., providing the basis for life. The principal objective of our efforts has been to investigate and shape the development of the appropriate tools.

2. SIMULATION OF BIOTA

Studies connected with the construction of a system of mathematical models simulating the functioning of the biosphere, were developed in three directions: simulation of processes of a biotic nature, simulation of climate, and simulation of human activity. To some extent, these studies were carried out independently. The organization of the studies was conditioned by the complexity of investigation, by the necessity to refine some principles, and to understand special features and methods of description. It simultaneously generated certain duplication. For example, a description of geochemical cycles is impossible without taking into account their impact on climate, and criteria for modelling human activity are connected with peculiarities of environmental evolution, etc. Therefore, one had to deliberately introduce some simplifications, i.e., parametrization of large blocks by hypothetical relationships which should be specified later when developing other studies. Thus, each of the three main directions has the possibility of using closed models. We shall call them training versions as they are used today mainly for training the investigators themselves. This section deals with the training version of a model for the circulation of biogenic elements.

2.1 General Description of the Model

The biogeocenotic model of the biosphere, developed at the Computing Center of the USSR Academy of Sciences, provides an approach to a combined description of complex processes of a biotic and abiotic nature.

The main difficulty in developing the model is due to insufficient knowledge of ecological and climatological processes. This lack of information is not only with regard to the quantitative characteristics of these processes but also with regard to their basic qualitative relationships. Therefore, when constructing a model, one will often have to take into account not only the variance of certain parameters but also the possibility of different alternatives for the dynamic processes themselves.

The biosphere model consists of interacting blocks which are elaborated comparatively independently. Such construction allows one to define each block without changing other blocks. When describing the biosphere, we pick out three blocks: the atmosphere, ocean and land. The division of land into regions is in accordance with natural, economic or political boundaries, and in this description, the atmosphere and ocean are considered to be indivisable. This assumption proves to be especially correct if we take into account that the mixing processes in the atmosphere and in the ocean proceed much more quickly than on land (e.g., typical times for mixing in the atmosphere are of the order of several months only).

The state of each block in the model is defined by a set of variables (Figure 1) which jointly form the vector of the basic phase variables of the model. All the accepted variables have been studied in a sufficiently aggregated form; we know their qualitative and sometimes also their quantitative relations. But a synthesis of the available information is made for the first time. In addition, the structure of inner and outer biogeochemical, ecological, social and economic relations is taken into account.

We tried to use all the available information about processes in the biosphere, i.e., their quantitative characteristics, etc. Also, there is the possibility of using computer experiments with the model, allowing analysis of alternative hypotheses, both of natural and of socio-economic factors.

The model is described by a Cauchy problem for a system of nonlinear ordinary differential equations representing all the relationships between the components of the biospheric regions under consideration. The model is realized in the form of a programme in FORTRAN-IV and is used for training at the Computing Center of the USSR Academy of Sciences and at Moscow University.

The model includes more than 400 coefficients requiring a quantitative definition, and about 200 relationships requiring a mathematical description. Table 1 gives the most important coefficients whose values have been taken from various literature sources and they were used as a starting point for computer experiments with the model.

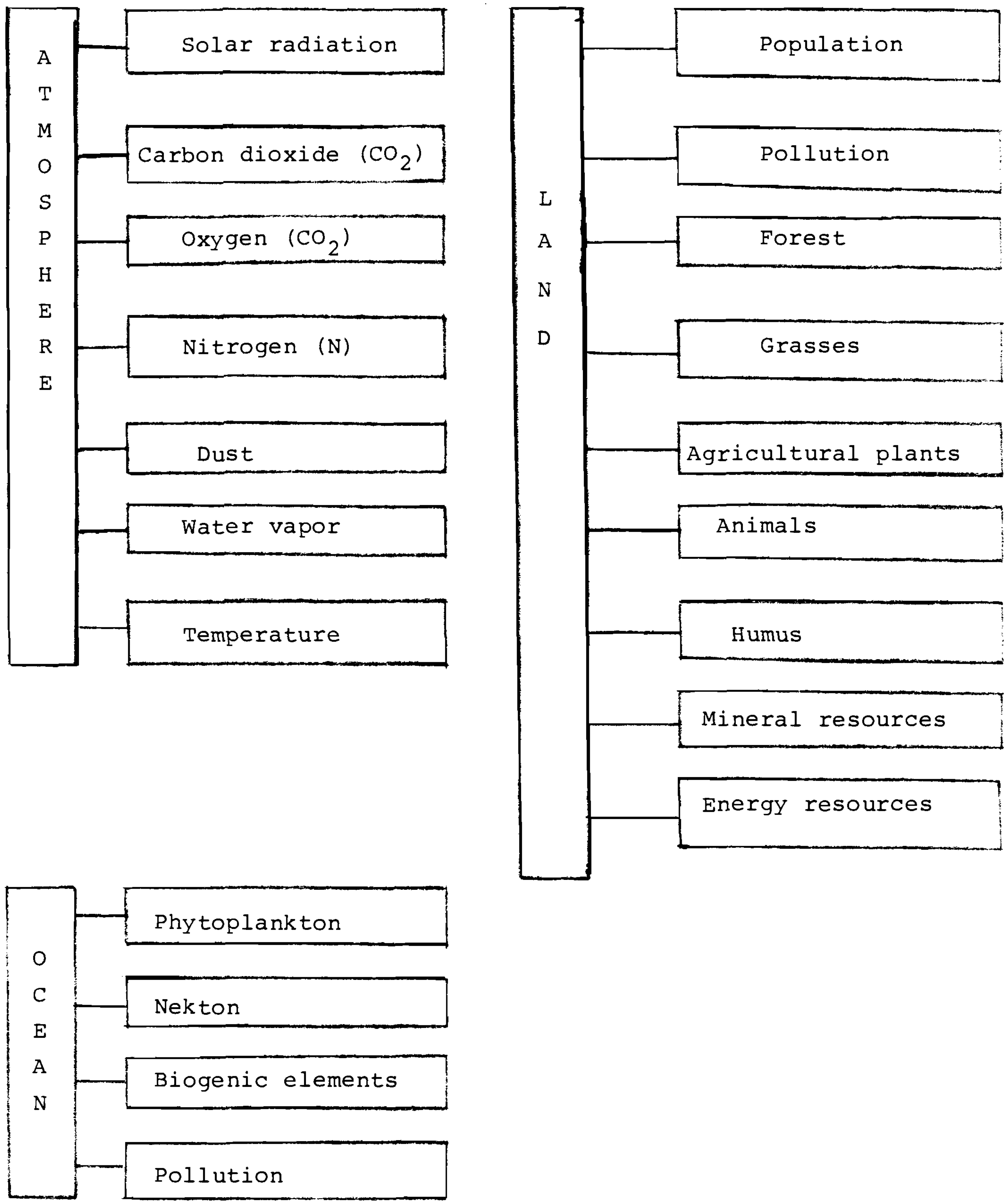

Figure 1. Variables which constitute the Three Interacting Blocks of the Biosphere Model

Table 1. Characteristic parameters of the biosphere used in the model

Parameter	Value
Total area of the biosphere ($10^3 km^2$)	509000
including:	
land	147610
ocean	361390
forests	4072
land suitable for agriculture	3140
land currently used for agriculture	1370
Level of solar radiation energy over the Earth's surface, at freezing point (cal/min)	$2,548 \cdot 10^{18}$
Efficiency of solar energy use (%)	
by the total biosphere	0,13
by the land	0,3 - 0,46
by the ocean	0,04 - 0,07
Albedo of the Earth - atmosphere system	0,3
Mean gas temperature of the atmosphere near the Earth's surface (°C)	14,5
Total mass of the atmosphere (10^9tn)	$5,13 \cdot 10^6$
Total industrial coal resources (10^9tn)	7640
Energy consumption per person in Europe (kcal per day)	70
Average rate of annual increase in energy production per person (%)	4
Rate of increase in consumption of non-renewable resources by humanity (% per year)	5
Amount of industrial pollutant emissions into the atmosphere (10^9tn per year)	15
Amount of pollution entering the ocean (10^9tn per year)	1,5
Amount of dust in the atmosphere (tn)	$10,5 \cdot 10^6$
Annual dust entering the atmosphere (tn)	
due to dust storms	$5,4 \cdot 10^7$
due to anthropogenic activity	$1,8 \cdot 10^7$
Biomass of the biosphere (10^9tn of dry substance)	1840
land (%)	99,8
forests (%)	90
nekton (10^9tn)	5,3
Brutal food reserves (10^6tn)	725

contd.. 11

Table 1. contd ....

Parameter	Value
Amount of food obtained by man (10^9tn)	
over land	1,3
in the ocean	0,017
Pure primary production (PP) of biosphere (kcal per year)	$65{,}2 \cdot 10^{16}$ - 68,6910
including:	
over land	$37{,}8 \cdot 10^{16}$ - $42{,}6 \cdot 10^{16}$
in the ocean	$26{,}1 \cdot 10^{16}$ - $27{,}4 \cdot 10^{16}$
PP consumption (%)	
by nekton	50
by animals	30
by people	1
dies off	19
Soil humus reserves (10^9tn)	2400
Characteristics of the population in 1970 (%)	
mean birth-rate	33,8
mean death-rate	10

2.2 The Atmosphere Block

The basis for the atmosphere block is given by the description of solar radiation flux. The atmosphere regulates the flux, secures the radiation balance stability and creates the necessary conditions for life on our planet. The upper layers of the atmosphere receive radiation flux from the sun, and are evaluated on average by $E_0(t) = 1.94$ cal/cm^{2}min. The atmosphere reduces this flux, partially absorbing and reflecting it. Analysis of the experimental data allows the use of the following approximation for describing this process: $E(t) = E_0(t)\exp(-\alpha B(t) - \beta)$ where α is the coefficient of solar energy absorption by the atmosphere due to dustiness and cloudiness, β is the transparence index of clean atmosphere, B is dust in the atmosphere. According to available climatological data we take values of $\alpha = 0.114$, $\beta = 0.477$.

Propagation of solar radiation energy through the ocean depends on the water transparence and can be described by the following relationship: $E(z,t) = E(t)\exp(-\alpha_1 z)$ where z is the depth (in meters) and α_1 is the vertical radiation reduction, α_1 being an integral characteristic of water quality.

A great influence on the general radiation balance of the earth is exerted by its surface albedo, depending on the state of the land and ocean surface (area covered by greenery, urbanized surface, ocean waves, etc.). Strictly speaking, albedo should be a function of the state variables of the model, but we consider it as a constant, assuming that its changes during the time periods under consideration are practically negligible.

Changes in the biota structure alter the carbon exchange, and generate climatic changes which influence, in their turn, the changes in processes of a biotic nature. But the up-to-date state of climatological studies does not allow the prediction of safely zonal climatic changes due to anthropogenic influence. Therefore, we consider the simulation of climate part of the model, as a point model, i.e. the state of the atmosphere is described by values of solar radiation energy, by general amounts of CO_2 (Carbon dioxide), O_2 (Oxygen) and aerosols in the atmosphere and by the mean global atmospheric temperature near the earth's surface. Such a choice of variables allows more or less, the influence of human activity on the climate of the planet, and of climatic factors on the biological processes of the land and ocean to be taken into account.

The main dependences in the system of climatic variables of the model are represented in the form of cause and effect relationships shown in Figure 2.

The dependence of atmospheric temperature on CO_2 content has been calculated by several scientists, with very little difference in the results obtained. In the model, this dependence is taken in accordance with the calculations of Rakipova and Vishnyakova (1973), and the influence of temperature on the moisture and precipitations regime is neglected.

Among the anthropogenic factors, there are two which essentially have an impact on the climate. These are fuel burning, and nuclear power stations which generate great quantities of heat (10^{20} joules/year). Industrial activity results in an increase in aerosol emissions into the atmosphere and that also disturbs the thermal regime of the planet.

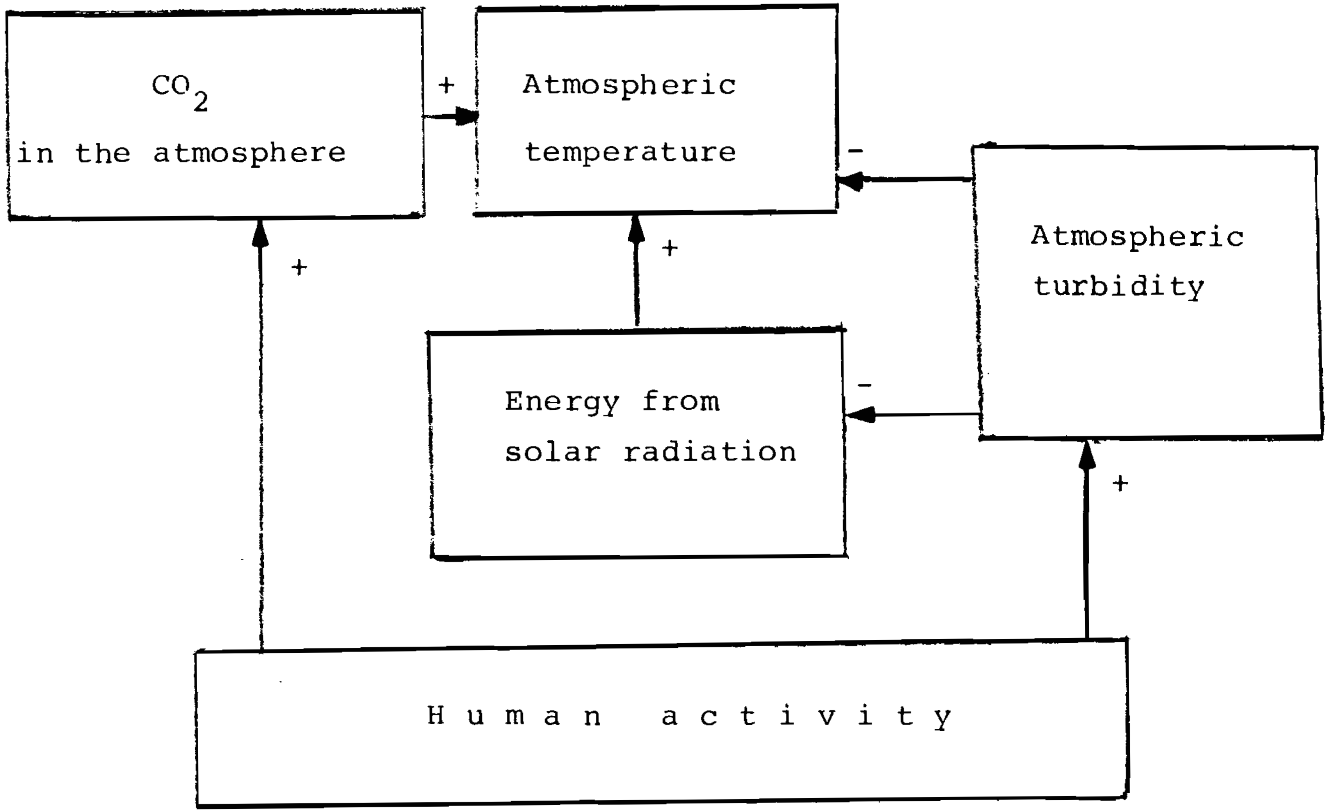

Figure 2. Cause & Effect Relationship of Main Dependences in the System of Climatic Variables

The presence of O_2 is essential for numerous metabolic processes in the atmosphere. Although the amount of oxygen in the biosphere is stabilized, according to modern evaluations, the model takes into account the real regimes of oxygen exchange between different biospheric components and regions, as well as a possibility of equilibrium disturbances. Some quantitative characteristics of the oxygen cycle processes are given in Table 2.

One of the most intensive and important biospheric processes is carbon circulation. The presence of carbon in the atmosphere, mainly in the form of CO_2, influences to a large extent, the climate of the planet. The climatic conditions and amount of CO_2 (which results from the decomposition of dead organic matter in the soil) in the atmosphere at each moment are the factors on which the intensity of both the atmospheric CO_2 assimilation by plants, and its eduction into the atmosphere depend. The CO_2 content in the atmosphere is influenced mainly by the balance between its consumption and eduction in these two processes. It is also necessary to take into account the CO_2 eduction due to volcanic activity. The influence of anthropogenic factors on the carbon rotation is also essential.

With the burning of fuel, a lot of CO_2 is educted into the atmosphere (about 0.7% of the total amount of atmospheric CO_2 per year, which is about 10% of the CO_2 necessary for the growth of the plant biomass). Destruction of forests and the reduction of other areas covered by vegetation, increases the scale of anthropogenic influence on the CO_2 cycle.

The gas exchange between the atmosphere and ocean is described by Machta's (1971) model, and the land-atmospheric exchange by Tarko's (1977) model. Some quantitative characteristics of the global CO_2 rotation processes are shown in Table 3.

The data available on nitrogen cycles in the biosphere suggests a rather simplified scheme of its circulation (Figure 3). This scheme can be further complicated after obtaining more complete information on the quantitative characteristics and structure of the nitrogen fluxes in the biosphere.

The atmosphere contains water in a gaseous state, and the character of water circulation is determined by all the biospheric

Table 2. Characteristics of the O_2 circulation in the biosphere used in the model

Process	Quantitative characteristics
Amount of O_2 in the atmosphere	
by volume (%)	20,946
by weight (%)	23,15
weight (tn)	$1,184 \cdot 10^{18}$
Amount of O_2 educed by photosynthesis (tn per year)	$4,67 \cdot 10^{11}$
by land plants including forests (%)	11,3
by water plants (%)	88,7
Annual consumption of O_2 by fuel burning	$9 \cdot 10^{12}$
Annual reduction of O_2 in the atmosphere (10^9 tn)	9 - 10
Amount of O_2 required for 1 mg of oil to be oxidated (mg)	0,4
Index of the reduction in the O_2 exchange coefficient between the atmosphere and water, when the oil film thickness is 40 mkm	3

Table 3. Quantitative characteristics of global CO_2 fluxes in the biosphere

Process	Quantitative characteristics
CO_2 concentration in the atmosphere in 1970 (%)	0,0319
Mass of CO_2 in the atmosphere (tn)	$2,1 \cdot 10^{10}$
Annual CO_2 assimilation (tn)	
by land plants	$6 \cdot 10^{10}$
by phytoplankton	$0,46 \cdot 10^{12}$
Average annual CO_2 increase (by millionth parts of volume)	
1962-1965	0,46
1970-1971	1,48
Rate of CO_2 production by people (tn per year)	$16 \cdot 10^9$
Rate of CO_2 emitted from the earth (tn per year)	$1 \cdot 10^8$
Rate of CO_2 eduction due to respiration and humus decomposition (tn per year)	$3 \cdot 10^{11}$
Amount of dissolved CO_2 in hydrosphere (tn)	$13 \cdot 10^{13}$
Amount of CO_2 breathed out by a man or an animal (m^3 per year)	124
Optimal CO_2 concentration for respiration and photosynthesis (%)	0,03

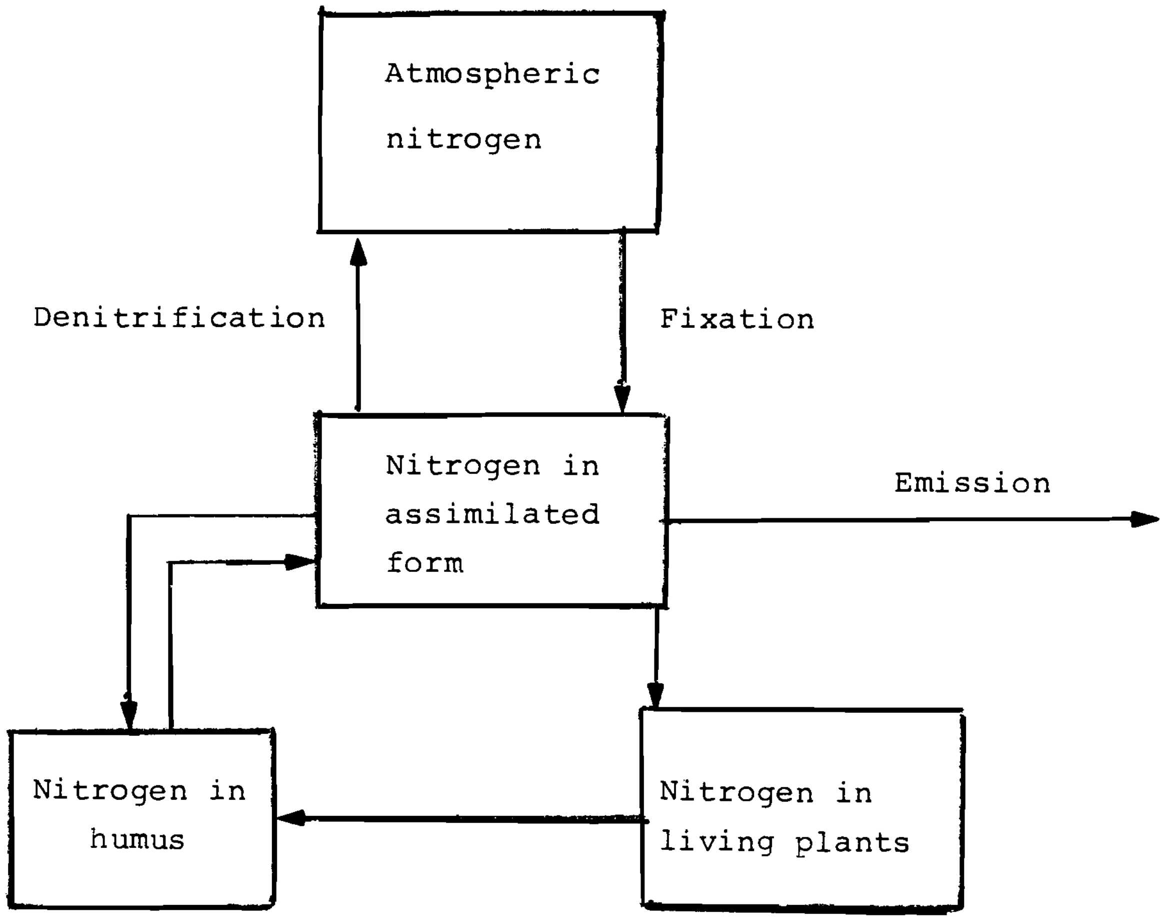

Figure 3. Nitrogen Cycle in the Biosphere

processes. The relative content of water in the atmosphere is not large but is of great importance as one of the basic factors of atmospheric turbidity (cloudiness) which in many respects, defines climate. In addition, the bioproductivity of plants depends substantially on the rate of precipitation and on humidity.

In the model under consideration, one has accepted a simplified scheme of water circulation, which takes into account the water vapor fluxes between land regions, between land and ocean, atmospheric precipitation, evaporation from the ocean, land surface, and the transpiration of plants.

2.3 The Ocean Block

For purposes of the present study, the ocean block is represented by a point model (that is the same as a model with ideal mixing), which contains the following variables: content of phytoplankton, zooplankton, nekton and of biogenic nourishing elements, the extent of ocean pollution, the CO_2 content in the upper mixed layer and in deep layers of the ocean.

The ocean has recently become an important source of food. However, it contributes only about 1% (of energy equivalents) to the total gross production of food (Vinogradov et al. 1976). Appropriate methods have to be developed for the rational management of these food reserves.

The importance of the ocean for the gas balance of the atmosphere is also taken into account in the model, mainly in the exchange of CO_2. The exchange of CO_2 between the atmosphere and the ocean depends to a large degree on the temperature of the atmosphere and on the CO_2 content in the air, which has increased over the last few years. In other words, CO_2 exchange depends directly on human activities.

The biospheric processes of the ocean are described by the equations obtained by Vinogradov et al.(1976). Fishing is defined by the technology used by a region of land. The model assumes that some investment will be made for replenishing marine life resources although not much has been done in this direction as yet. Photosynthesis is the main source of organic matter in the ocean. It is known that the photosynthesis rate, as a function of light intensity has one maximum at the optimum value of E(t) = E^*_{ph} and decreases with the deviation of the light intensity from the optimum value. Besides, R_{ph} depends on temperature, biogenic elements concentration, phytoplankton biomass and on other parameters. The equation for the phytoplankton rate can be derived by using the corresponding phenomenological dependences.

We assume that the Libikh principle of limiting factors is correct. According to this principle, the photosynthesis rate depends only on one factor, although the factors themselves can cause each other to change in the process of the system's development.

The model includes a scheme of the vertical rotation of biogenic elements. It is assumed that the biogenic elements reserves are not limited in deep ocean layers (deeper than 200 m), so that they can limit the photosynthesis only in upper layers. The biogenic elements are transported to the photic zone by the upwelling currents and by vertical mixing. The mixing rate is one of the parameters of the model. The biogenic elements are taken out of the upper layer mainly in the form of a "dead bodies rain". The assimilation rate of biogenic elements by phytoplankton is proportional to the intensity of photosynthesis.

The rate of change in the nekton biomass is regulated by the temperature of the environment, by the character and intensity of trophic relations (ration), by natural mortality, by mortality due to pollution and by mortality due to population overcrowding.

It is natural that the introduction of such a generalized element as nekton into the model is only a rough approximation for the real structure of the system. However, the approximation seems to be quite satisfactory for the initial version of our model, since nekton is in the highest level of the trophic pyramid in the ocean ecosystem, and its energy content is rather small in comparison with other levels. The accuracy of the nekton description influences, to a small extent, the global substance and energy cycles. On the other hand, nekton is a human food resource, and further details of its description will be necessary for a more refined representation of food relations structure in the dynamics of human population.

2.4 Land Regions

Vegetation on land is characterized by a large variety of species and by a large range of gas exchange productivity factors. Therefore, the gross primary annual bioproduction of land, varies from 28140 kcal/m^2 in tropical forests to 480 kcal/m^2 in a desert. The concept of a land region is introduced to take into account the variety of vegetation and to keep the point character of the model blocks. It allows the zone character of the earth's vegetation to be taken into account at least approximately without introducing space coordinates. The model involves three types of vegetation: forests, cultivated crops and grassland.

A change in biomass for each type of vegetation is described by a first order equation

$$\frac{dx_i}{dt} = R_x^{(i)} - M_x^{(i)} - x_i \sum_j c_{ij} R_j$$

where $R_x^{(i)}$ is the photosynthesis rate which is a complex function of light intensity, humidity, humus state, the amount of fertilizers put into the soil, the gas regime of the atmosphere, etc; $M_x^{(i)}$ is the death rate of plants, and the sum on the right hand part of the equation simulates the real consumption of the plant biomass by animals and people.

The products of photosynthesis are consumed by animals. They are treated in the model as a single state variable of the biosphere. The variable is characterized by some average growth and death rates. The animal bioproduction in its turn is consumed by man.

The soil forming processes are of great importance in the matter and energy cycles. The numerous stages of soil humus formation, which is the last link in a chain of biogeochemical organic matter transformations, are described by one component--humus. There are different estimates of the amount of humus in the biosphere (Kovda, 1975), and they do not differ much. Therefore an average estimate equal to $2,3 \cdot 10^{12}$tn has been taken in the model. Besides, the model is insensitive to variations in the parameter.

It must be noted that humus is of great importance in the gas balance in the atmosphere. The model assumes that the rate of change in humus depends on the accumulation intensity of the organic wastes of plants. It is assumed that the decomposition rate is directly proportional to the mass of decomposing substances, and it increases exponentially with temperature. That a considerable rise or fall in temperature depresses the activity of soil microorganisms and, hence, decreases the decomposition rate is taken into account. It has also been taken into account that the humus decomposition rate decreases with deviations of humidity from some optimum value.

The description of the demographical block is the most difficult part of simulation. While the cause--consequences dependences including a mortality coefficient (more exactly, an index of mean life duration) seem to be more or less clear, there is no unique and clear understanding of the processes describing the birth-rate dynamics in the human population. Extrapolations based upon demographical statistics are not suitable here since the world system evolution is computed for many decades hence, and the whole previous demographical experience shows how rapidly and inexplicably the basic demographical parameters can change. Therefore the demographical dependences accepted in the model are, to some extent, hypothetical. However, the model under consideration is more complicated than well-known models of exponential growth (with parameters verified by demographic statistical data) and it involves the inverse cause effect relationship in contrast to the other models.

2.5 Human Activities

In the following sections, the problem of describing human activities and some special features concerning the description of an economic system as a block of a certain system of ecological models are discussed. It should be noted that one of the fundamental principles of systems analysis must be satisfied: each main component of a simulation system is to be closed, i.e., it should be able to operate as an independent simulation system. Over the last few years human activities have become a determining factor in the evolution of the biosphere. For this reason, a special parametrization of the major aspects of those human activities affecting the biosphere has been built, apart from developing a special system for describing human activities.

The stress on the environment caused by man-made pollutants varies greatly. When describing the "Atmosphere" block we already mentioned the discharges of CO_2 and aerosols into the atmosphere which cause thermal changes. But this stress goes beyond the influence on the atmosphere. The variations in the global carbon cycle directly affect the humus generation process, and those mineral resources that are easily extracted are reduced as well. The reverse impact of environmental changes on the pattern of human activities is also multiform. In the model, all these effects are parametrized in the form of the following hypothetical time dependences:

(1) Pollution generation rate per capita (characteristics of the living standards and the technology of social production).
(2) Pollution dissipation rate.
(3) Rate of mineral resource consumption.
(4) Rates of increase in the area of arable land and the average yield of the agroecosystem.
(5) Fractions of capital investment in agriculture, in resources regeneration, in the exploitation of new resources, and in combating pollution.

The "Human Activities" block makes it possible to change, in due course, the values of the coefficients of the mutual resources and food exchange between the land regions, and to change the time dependences for other model parameters.

Until the beginning of the last century, man could only make use of solar energy released by different biological processes. But in the last 150 years the situation has changed radically. In the last 20 years, with the use of nuclear energy new prospects have appeared before mankind. For example, the USA produces 240 kilowatt-hours per capita per day, and the figure is annually growing by approximately 2.5%. In Europe the total energy consumption per capita averages 31.2 kwh per day and it is growing annually by almost 4%. The total energy production has doubled in 10-15 years. And, at the same time a man should consume only 0.004 kwh per day to maintain his normal metabolism.

The population growth and the corresponding increase in energy production result in atmospheric soil and water contamination, and a rise in the environmental temperature. It is estimated that annually mankind burns 2.7 billion tons of coal and 1.6 billion tons of oil and contributes more than 1.25 billion tons of pesticides to the soil. In addition, $1.5 \cdot 10^{10}$ tons of CO_2 are discharged annually into the atmosphere and 9×10^9 tons of O_2 are consumed. The general worsening of the absorption capacity of the biosphere brings about the steady increase in CO_2 concentrations and a decrease in the amount of O_2 in the atmosphere.

The model includes a generalized component, namely, pollution. The component represents only the average characteristics of different pollutions. For one thing, it has been done so as not to make the model too bulky, and, for another, we suffer from a scarcity of comprehensive data on the effect of different pollutants on the biogeocenosical processes.

To determine the rate of change in the pollutant concentration values we make use of the Forrester equation which describes the increase R_z in proportion to the population growth with a time dependent coefficient. In this case, we postulate the increase in R_z when the living standards rise.

Pollution is wiped out by natural decay and by artificial neutralization. The latter depends linearly on the amount of resources allocated for the purpose and varies inversely with the cost of the volume unit or weight unit neutralization of a pollutant.

The ocean is contaminated by pollutants from the land. The model makes it possible to take into account decreasing water transparence, the biomass growth rate and the increasing death rate coefficient due to ocean pollution.

2.6 Mineral Resources

For the present generation the mineral resources may be considered practically nonrenewable, because the rates of geological processes resulting in mineral formation are negligible. In the last few decades the nonrenewable mineral resources consumption rate has been growing steadily, approximately in proportion to the population.

In the model, use is made of the generalized Forrester equation to describe the processes leading to changes in the nonrenewable mineral resources in the biosphere. It made it possible to consider either a jump-like or a stationary variation in the initial condition for the relevant differential equation. Transition to new mineral resources is modeled by substituting a set of initial conditions by another one in a certain time interval.

2.7 Model Experiments

To perform experiments with the model we need a set of different policies or scenarios. They must involve the variants of future social development, various control policies, estimates of scientific and technological advances, etc. Here we would like to present the results of several model experiments. The first one was to provide an answer to the following question: in what way would the values of the different parameters change provided the existing trends remained the same? The experiment assumes that the structure of capital investment in industry and agriculture remains at the 1970 level, and that there are no changes in demographic processes, in the rates of energy production development, and in the index of air pollution as a function of the power resources extraction and some other trends and parameters.

However, all the predictions, if they can be so called, are, of course, very conventional. But they may be helpful to obtain some qualitative but not quantitative, understanding of the feasible consequences if the present day development trends for the system under consideration remains the same.

The atmospheric gas composition oscillations are slower, the atmospheric components are more inertial. The atmospheric dust loading is rising sharply and by the year 2125 it will reach a fourfold value as compared to the present situation.

Atmospheric pollution dynamics is almost the same as that of the population density, but land pollution dynamics is more complicated. Land pollution is more persistent than that of the atmosphere and land pollution generation is more closely allied to economic activities.

A sharp population rise results in decreasing per-capita food production by almost 30%. The albuminous food production is affected the most. Although the overall calorific value of diets would correspond, more or less, to the minimum requirement, vegetable food would begin to occupy the major position. The generalized effect of environmental pollution and the declining of the albuminous component in diets would result in a sharp fall in the population density, which by the end of the 22nd century would be fourfold in value in comparison with the existing level. The period of decline, lasting for over a hundred years, is followed by the period of relative stability at the approximate present-day level. By the year 2400, the meanings of all other variables will have returned to the present-day values (except non-renewable resources). As the unique character of the biosphere makes it impossible to experiment directly on it or on some of its subsystems, the model may be of help in studying different hypothetical situations (especially of stress). The "if ... then" modeling type is of particular interest.

For example, it would be useful for a better understanding, to trace the effects on the dynamics of the biosphere of such parameters as the rate of arable land cultivation and capital investment distribution. The run shows that if by the year 2000 the cultivated land area increased by 10%, and the animal husbandry production increased by 10%, and the rate of pollution generation falls by 10%, then by the year 2200, in comparison with the situation if these changes do not occur, the global population, environmental pollution and the atmosphere dust load will rise by 3.1%, 20.8% and 1.2% respectively; investments in agriculture will fall by 4.7%; the food supply will rise only by 6.8%; and the level of material security will rise by 5.8%. Yet, if all arable land has been cultivated by the year 2050, the average per capita food supply will be 94.7% by the year 2200 as compared with the year 1970, instead of the above-mentioned 50%. The environmental parameters will remain within acceptable limits.

Finally, we will estimate the model's sensitivity to changes in capital investment distribution. We will consider the experimental results when the capital investment distribution is described by two step functions with a jump in the year 2000. It so happens, that even in this simplest class of control actions, there exists a situation when the biosphere model parameters assume the values acceptable to Homo sapiens. In order that it may take place it is necessary that the capital investment in natural resource regeneration and in environmental protection should be increased twice and ten times after the year 2000, respectively.

The concept of a land region is introduced in the model; it is concretized by setting the initial values for all components. As all the processes in the climate and water sectors are assumed to vary only along the meredional direction, a region is linked with the area by means of defining the average latitude of the region. We can define a region as an economic, social and geographical unit and, depending upon the definition chosen, make different experiments aimed at estimating the role which the region plays in the biosphere model. Suppose, for example, there are two regions with similar initial conditions for energy, natural and manpower resources. Region 1 takes steps to decrease twice the pollution generation rate by the year 2000, to decrease the rate of mineral resource consumption by 15%, to increase the animal husbandry production by 10% and to decrease fishing by 25%. Then, given the conservation of the present-day human influence on the biosphere in Region 2, the global average environmental conditions will improve very slightly and the general trend with a negative derivative will remain. Calculations show that if two regions have approximately like resources, no environmental protection steps taken in one of the two regions may change the existing trend, though, the climax of the biosphere can be postponed by 150 years. There is a possibility for region 1 to chose its own control strategy preventing the climax of the biosphere if only the ratio of region 1 resources to region 2 resources is 50:1.

The model was built for the sake of experiment and the modeling results obtained cannot be regarded as real predictions. Besides it is hardly likely that if mankind watches the change for decades, similar to those described above, the new ideas leading to the radical reconstruction of production relations will not occur.

3. THE CLIMATE MODEL

In our model of the biosphere the climate, and its change, is now described by a very simple model of the Budyko-Sellers type which operates with the global temperature of the atmosphere.

This level of accuracy is too low for our goal. The ecological model needs a geographical distribution of the meteorological parameters which are the main influence on the growth of the biomass. This information may be obtained from a big modern numerical model built on the hydrothermodynamic equations of the atmosphere and ocean.

The climate model has to describe the real physical-chemical regime of the biosphere. It has to have a high quality because the quality of the climate model leads to the success in the global modeling of the biosphere.

After Monin's and Shishkov's (1979) definition "the climate is the statistical ensemble of states which the ocean-land-atmosphere system passes over time for some decades". This definition reflects the role of three components which are the main input to the state of the environment, i.e., inert ocean, light unstable atmosphere and land which suffers mostly from human impact.

When we began our work there was no precedent in the creation of the biological model and the model of human activity. But many scientists have worked on climate modeling, thus, we decided to use one of the existing models as the basic model of climate. The problem of the model choice was not simple.

We need a climate model which has reasonable computational complexity. On the basis of this model we would like to arrive at conclusions on the influence of climate on human activity and to choose a strategy of behavior which should be adequate for coping with the vagaries of the future climate. The climate model has to produce at least geographical distributions of the seasonal fields of air temperature near the surface, photoactive solar radiation and precipitation. The deviations of these values from the mean fields due to anomalies, dispersions, etc., are also very important. These demands dictate the level of model resolution. We should analyze the regional situations and forecast the estimations of productivity of the natural and artificial biocenosi. It dictates the maximum mesh size for the space finite-difference grid. It has to be about 5^{o}-15^{o} in the latitudinal (longitudinal) direction. In this case we are able to distinguish between the basic agricultural and industrial regions. The model has to have the real possibility of climate analysis for terms referring to various decades. The basis of the climate model is the atmosphere model. We found that the Mintz-Arakawa global atmospheric circulation model realized by Gates et al. (1971) is the best for our goal and we choose this model as the basic one.

It represents the hydrodynamic model of atmosphere, more correctly troposphere, between the surface and the tropopause which is defined as a 200 millibar level. The finite-difference equations of the model are written on the geographical grid with a latitude of 4° and a longitude of 5°. In the vertical direction, the troposphere is approximated by two layers of the same mass. The surface represents the map of the earth with a real distribution of land and ocean with sea ice, a real height of land with continental ice sheets and snow cover. The position of the sun and the sea surface temperature are regarded as the boundary conditions.

This model describes the large-scale motions of air masses, created by non-uniform energy release in the rotating troposphere The sources and sinks of energy are created by solar radiation and the phase transitions of water in the atmosphere and on the surface. The transport of short-wave solar radiation and long-wave thermal radiation emitted by the air and the surface depends on the thermodynamic state of the atmosphere and on the amount of clouds. The water transport in the atmosphere, followed by evaporation and condensation, and the creation and dissipation of clouds plays an exclusive role in the mechanics and energy of the atmosphere. It is enough to say that the evaporation of the water on the surface needs about one-third of all the solar heat absorbed by the atmosphere. The amount of CO_2 and aerosols in the atmosphere, the albedo of the surface and thermal pollution, are supposed to be prescribed quantities in the model of global circulation. They are "input" values to the climate model which have to be produced in other blocks of the global model.

The climate model has to have a description of the ocean. The ocean global circulation models are probably too complex for climate modeling but the simple ocean models give too general information which is not sufficient even for the determination of the boundary condition for the atmosphere model and for the performance of the complete ecological model. The accepted ocean model has to produce the geographical distribution of the parameters of the surface layer of the water and the CO_2 flux through the air-water interface.

The Borisenkov (1976) model of the ocean-atmosphere exchange was chosen. It should be completed by some simple model of the upper layer of the ocean. The Borisenkov model describes the global energy exchange between the atmosphere and the ocean well enough and the model of the upper layer makes it possible to obtain the information which is necessary for the input into the model of the circulation of the atmosphere.

The ocean model has to have a dynamic description of sea ice. This problem has now some formal descriptions which are acceptable for global ecological modeling.

From the mathematical point of view any experiment with such a model of climate is a Cauchy problem. The solution of hydrothermodynamic equations is determined by the prescribed initial state of the atmosphere and ocean and the prescribed external conditions. The initial state has to be in agreement with the conservation of mass, momentum and energy.

Choosing as the initial state some typical situation on 1st January and integrating the model equations over a time period of 31 days, we obtain one of the possible realizations of the distributions of temperature, cloudiness, precipitation, etc., for January. Choosing another initial state and repeating the integration we obtain another possible distribution of meteorological parameters for January. In this manner we obtain a large set of realizations corresponding to the reasonable ensemble of initial states. After a statistical analysis of these realizations, we have an average pattern which might be called January climate.

We can do the same for other months. In order to do this, we have to change the external conditions: the position of the sun, the distribution of sea ice, the sea surface temperature. Now we need one representative of any season: January, April, July and October. The question how this model reflects the real atmospheric behavior is very difficult to answer. The direct method could be a statistical analysis of the observed data. This has to be done sooner or later. It is a laborious and difficult process. But we can estimate the quality of the model by the approximate tests. January, for example, is characterized by the westerly winds over the North Atlantic and Europe in the form of an irregular series of cyclones moving from west to east, by the Aleutian minimum, the vast domain of low sea-level pressure in the northern part of the Pacific, by the Siberian anticyclone which in January dominates Central Siberia, by cyclones revolving around Antarctica and by other phenomena. The model of the mean climate has to reproduce these patterns. Our model simulates these synoptical pictures. Thus, we can assume that the model of the global circulation of atmosphere has been checked by the calculation of the climate which has not yet been disturbed by human activity.

3.1 The Model of Linear Trends

To study the ecological situation we need much more than the above mentioned model. In the climatological block of the big model of the biosphere one might calculate the shifts of the mean climatic characteristics under the influence of anthropogenic factors. But we now have only some nominal versions reflecting the influence of contemporary anthropogenic impacts on the biosphere.

The next step is not trivial and it needs special discussion.

All the blocks of the biospheric model are connected by input and output parameters. It means that the biosphere model is one whole system with such large dimensions that it is impossible to make a straight calculation of the model either on modern computers or even perhaps on those of the future. Thus, it is necessary to propose a method for the analysis of the model blocks. At the same time, this method might serve for the organization of the man-computer dialogue. We propose an approach which permits a representation of the information in the form of a table (Table 4) which unites the input and output parameters.

For the climatic model this matrix may be called the matrix of linear climatic trends. The upper string has the names of the basic input parameters of the climatic model (albedo A, thermal pollution Q, carbon dioxide concentration CO_2, etc.) and the first column has the names of the basic output characteristics which are input variables for other blocks of the global ecological model (biota, agriculture, etc.). The last values are temperature T, photoactive radiation S, and precipitation P. The boxes have the partial derivative $\partial T/\partial A$, $\partial T/\partial Q$, ..., $\partial S/\partial A$, ..., calculated for the basic state of the model.

Table 4. Matrix of linear climatic trends

	A	Q	$[CO_2]$
T	$\partial T/\partial A$	$\partial T/\partial Q$	$\partial T/\partial [CO_2]$
S	$\partial S/\partial A$	$\partial S/\partial Q$	$\partial S/\partial [CO_2]$
P	$\partial P/\partial A$	$\partial P/\partial A$	$\partial P/\partial [CO_2]$

This form of matrix for linear climatic trends is oversimplified. The first column not only has the mean temperature but the set of values which determine its geographical and seasonal patterns. The definition of the anthropogenic climatic trend means the change of the basic meteorological parameter under the influence variations in the basic set of parameters which determine climate. In their turn, these variations are determined by the industrial and agricultural activity of people today and in the near future. This table of linear trends represents the parametrization of climatic changes and is in accordance with the above mentioned demands.

Let us suppose for example, that a scientist proposed some definite scenario for industrial activity. We calculate the amount of energy which will be produced after this scenario, CO_2 pollution, albedo change caused by change in vegetation type, etc. We will do these calculations up to a year for a specific period of time which is not very remote. This is because only such conditions may guarantee the convenience of the estimations.

We can easily calculate the interesting climatic characteristics for any geographical point if we have the matrix of linear trends. For example, the temperature T* in year t* is

$$T^* = T_o + (Q-Q_o)\frac{\partial T}{\partial Q} + (A-A_o)\frac{\partial T}{\partial A} + \ldots$$

where T_o, Q_o, A_o, ... are the nominal values.

From our supposition about linearity of trends, we easily calculate the change of climatic parameters as a function of time

$$T(t) = T_o + \frac{T^*-T_o}{t^*-t_o}(t-t_o) \quad .$$

Using these estimations we can correct the precalculated scenarios of development. The scheme of linear trends reveals the possibilities of the decomposition of the model and the organization of rational procedures for its analysis.

3.2 Perspectives and Difficulties

The method of "the tables of linear trends" determines the program of our activity for the near future. Two basic difficulties arise in the realization of this program. The first is connected with the gigantic amount of calculations necessary for the realization of any real scenario, the second created by the first, is the huge amount of information created during the process of modeling.

The principal feature of the above mentioned hydrodynamic models of climate is the large amount of computer time necessary for the solution of one problem. This large amount of computer time necessary for one integration of the model is the principal obstacle in the creation and the work of the climate model. We need an algorithm which permits us to calculate the equations of the model a hundred times faster than any of the modern algorithms.

The work with the global circulation model creates large sets of data. Work with the global model of the biosphere will create more information. The analysis of this information represents the final part of the problem for climate modeling. We would like to emphasize that the final state is as important as every preceding stage in solving the problem.

The amount of information which arises in the modeling is so vast that it is impossible to use it in non-organized form. The modeling is not complete if the results obtained are not presented in the form of zonal and geographical distributions of basic meteorological characteristics, fluxes of different forms of energy, and if the spectral analysis of results which are necessary for the work of an ecological and economical model does not exist. For this aim it is necessary to have a vast set of special diagnostic programs.

Thus, successful development of the subject which we called the dynamics of the biosphere needs a very high level of computer realization. Regardless of this, we have been working with these models for some years and the creation of a complete global model is now at the beginning stage. This work will need huge efforts by many scientists for many years. We anticipate that it will be transformed by international research and with information banks which will be constantly modified. This service will help in the study of the different development scenarios which are elaborated by scientists in different countries.

4. ON THE MODELING OF HUMAN ACTIVITY

4.1 Some Features of the Problem

The formalized description of human activity is the most difficult part of global modeling. An adequate model for the activity of mankind is hardly likely to be elaborated in the near future. This is why we discuss two levels of description as was done for the climate model. One of the levels is the simple parametrization of the world economy as in Forrester's model. It permits a closed global biospherical model and a computational experiment, described in the second section of the paper, can be conducted. It is clear that this mode of description is not sufficient. In this section a new concept is discussed as well as some preliminary results.

The interaction between mankind and the biosphere is determined first of all by the production activity (including exchange and consumption). Therefore the economic models form the basis of a formalized description of human activity.

The main difficulty in modeling economic processes is in the leading role of human behavior in a process of this kind. Certainly the natural regularities described in physics cannot be violated in economic processes but in the economy these regularities are of minor importance. Though the natural regularities cannot be ignored (for example, it is impossible to produce anything without corresponding production resources), the conservation law, as well as other principles of natural sciences, can not exhaust all mathematical models for economic processes. Therefore, models of economic processes are not closed - there exist free variables (controls). The choice of the values of control variables cannot be described by regularities anologous to natural ones. To obtain an adequate description of economic processes it is necessary to describe the goals of groups of people and to understand the regularities of decision making in human society. It should be noted that the regularities of decision making have not been sufficiently studied yet (Kornai, 1971; Galbraith, 1973).

Therefore, at present, an adequate model of economic processes must contain a great number of controls which are not determined in the model. This fact plays an important role in our approach: we do not exclude this uncertainty from the study. This feature distinguishes our approach from investigations by Forrester and Meadows. Forrester and Meadows include a parametrization of economic mechanisms in their models and in their studies, obtain the possibilities of economic mechanisms described in the model instead of the limits of growth of the economic system. The control variables in global models cannot be excluded from the investigation so easily - this is the principal difficulty of human activity analysis.

The second difficulty is that human activity is not static. Production activity of mankind is characterized by variations. Two decades ago, the energy consumption was two times less than now and oil and gas consumption were 40% instead of 60%. After the investigation of the Club of Rome was fulfilled the concept of zero growth became well known. We think that this concept is not suitable and not practicable - it is impossible to stop mankind in its aspiration to implement new ideas. Certainly this implementation of ideas should not result in a growth in the consumption resources and pollution - it is necessary to change the structure of production activity to restrict the influence on the biosphere. The evaluation of suitable limits on this influence is the main goal of our investigation.

In the investigation, we used dynamic models of production activity based on well-known balance equations and control variables. Global models are now constructed at various institutions and we do not want to choose one particular model - our investigation has a methodological character and is not connected with any particular model. As an example of a model illustrating our approach, we use a simplified version of the model of the world economy elaborated at the UN by a group of experts led by Leontief (1977). This choice was based first of all on the existence of information. Before we deal with the illustrative model, a description of the method used for investigation on human activity will be presented.

4.2 Investigation of Controlled Systems on the Basis of the Construction of Generalized Reachable Sets

We shall try to evaluate reasonable limits for the human impact on the biosphere. Since we cannot give an adequate description of decision making mechanisms for the production activity of mankind, it is necessary to use a method which gives the possibility of analyzing global models with control variables not being fixed in advance. One of the most widespread methods of analysis for controlled models consists of choosing a unique indicator of the performance of the system, and revealing the best control variables which provide the best variant for the system's performance. We think it is impossible to apply this method of analysis to global modeling since it is impossible to formulate a unique indicator of performance for human activity: there are many problems to be solved. This fact determines a great deal of approaches in choosing the variants of world economic development.

For this reason, we apply an alternative method of analysis to controlled models developed at the Computing Center of the USSR Academy of Sciences during the last decade. This is the Generalized Reachable Sets (GRS) approach (Lotov, 1980). This method is intended for studying mathematical models with exogenous variables. One of the main directions of GRS applications is the analysis of multiobjective systems. In this case the GRS approach consists of an explicit description of the set of all values of performance indicators which are reachable with the aid of feasible controls. This set we call a Generalized Reachable Set (GRS).

The mathematical definition of the GRS for linear static models is as follows:

Let the model be presented in the form of a finite system of linear inequalities

$$Ax \leqq B$$

where A is a given matrix, B is a given vector, $x \varepsilon E^m$ is a control vector. The indicators vector $f \varepsilon E^m$ is connected with the control vector x.

$$f = Fx,$$

where F is a given matrix. For this system the GRS denoted by G_f is defined as

$$G_f = \{f \varepsilon E^m: f = Fx, Ax \leqq b\} \quad .$$

This definition gives the set G_f in an implicit form. The GRS approach consists of the construction of the set G_f in an explicit form

$$G_f = \{f \varepsilon E^m: Df \leqq d\}$$

and in further investigation of this set.

The set G_f can be constructed precisely if the model under study and performance indicators are linear and algebraic.

In different cases, the set G_f can be presented in the explicit form mentioned above only approximately.

To construct the set G_f in an explicit form for a linear static model (that is to calculate the matrix D and the vector d) we apply methods for excluding the variables in a linear inequality system (convolution of linear inequality systems). The first convolution method was introduced by J.B. Fourier (1826). In the 20th Century the Fourier method was modified. During the last decade at the Computing Center of the USSR Academy of Sciences algorithms for removing nonessential inequalities were elaborated. These algorithms make it possible to overcome the main disadvantage of the convolution method consisting of rapid growth in the quantity of nonessential inequalities in the system. These algorithms were implemented in the program system POTENTIAL (Bushenkov and Lotov, 1980) which constructs the set G_f in explicit form and is a mean of investigating this set in the expert-computer dialogue. This program system constructs GRS for dynamic models as well. The expert obtains two dimensional projections and cross-sections of the GRS. The application of the GRS approach is illustrated by a simple version of the UN model for the world economy.

4.3 Analysis of a Simple Version of the UN Model for the World Economy*

In this model the world is presented as four regions (the first and the second regions represent industrialized nations, the third and the fourth represent developing nations). The economic system of each region is described by the balanced model of the Leontief type. The following production branches were presented:

(1) agriculture;
(2) mining;
(3) investment goods;
(4) consumption goods;
(5) services;
(6) pollution demolishing abatement.

Pollution was described as a linear function of the gross output of the productive branches and of consumption, the structure of which was fixed in advance. The restrictions on capital, capital investment and the labour force were imposed. It was possible to use the production of four primary industries in foreign trade, while prices were fixed in advance.

Some results are presented in Figures 4-8. It is necessary to stress that initial data as well as the structure of the model were quite arbitrary therefore the results can be used for illustration of our approach but not for some practical inference on world economy.

Reachable values of the consumption indicator λ_1 and pollution level F for the first region are presented in Figure 4 while foreign trade is absent. Both indicators are measured in conventional units. The set QPMR describes all reachable combinations of values $\{\lambda_1, F\}$. Certainly, an increase in the consumption indicator λ_1 and a decrease in the pollution indicator F are preferable. Hence the curve QPM (the effective set) is most interesting. Beginning at the point Q the curve shows that first the value of pollution F is increasing quite slowly with the increase in the consumption level λ_1. Afterwards at the point P there is a break. When λ_1 is near to its maximum level λ_1^A (the index A shows that this maximal level is calculated when

*The initial information for this investigation was prepared by I.S. Menshikov and A.S. Zlobin from the Computing Center of the USSR Academy of Sciences. The calculations were fulfilled by V.A. Bushenkov.

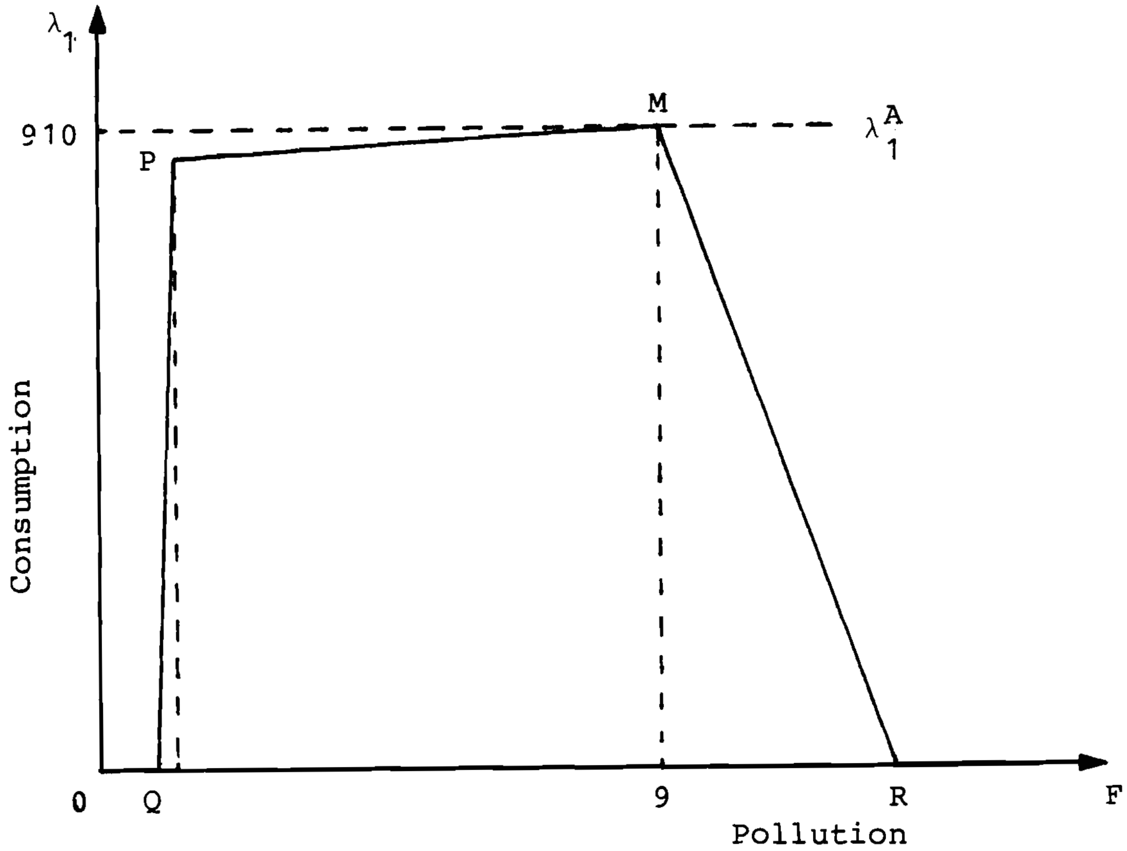

Figure 4. Reachable Values of the Consumption Indicator and the Pollution Level for Region One

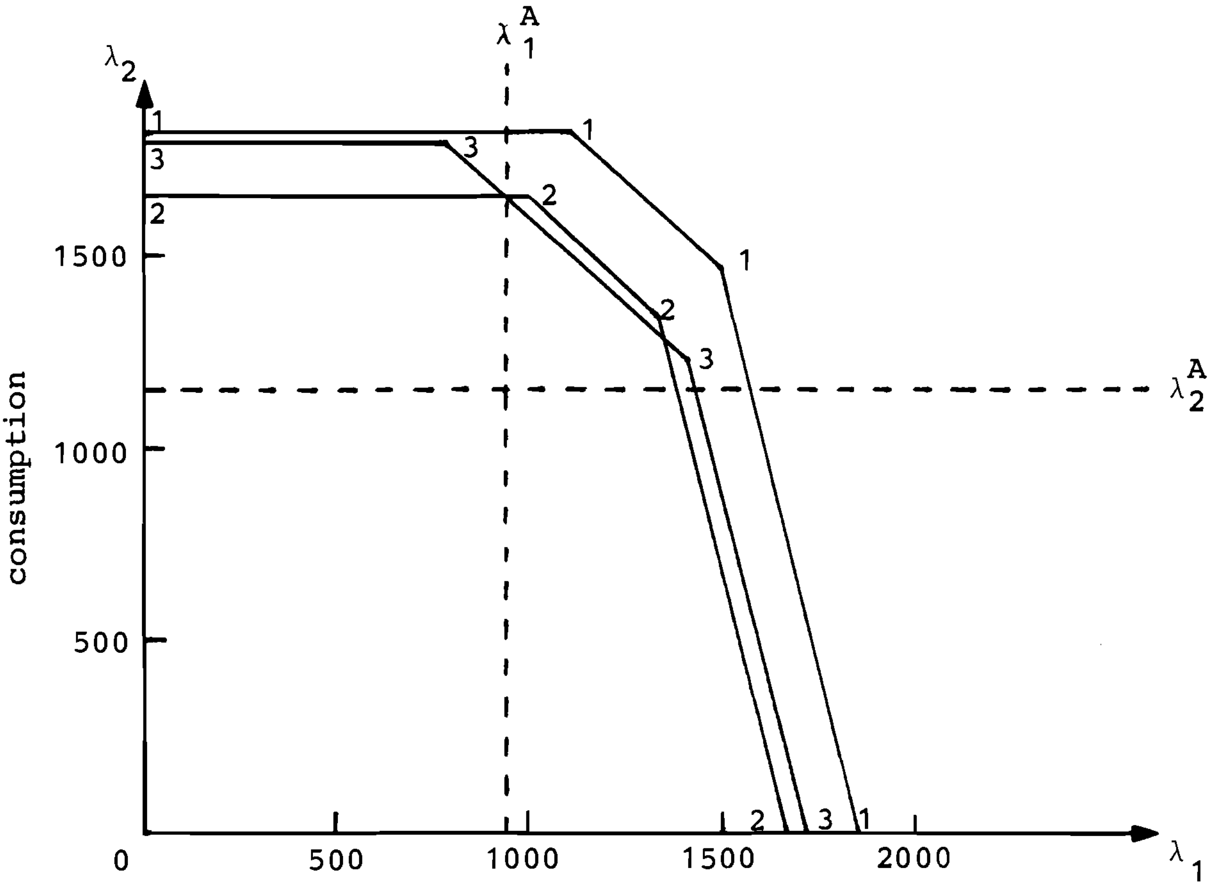

Figure 5. Reachable Consumption Values of Regions One and Two

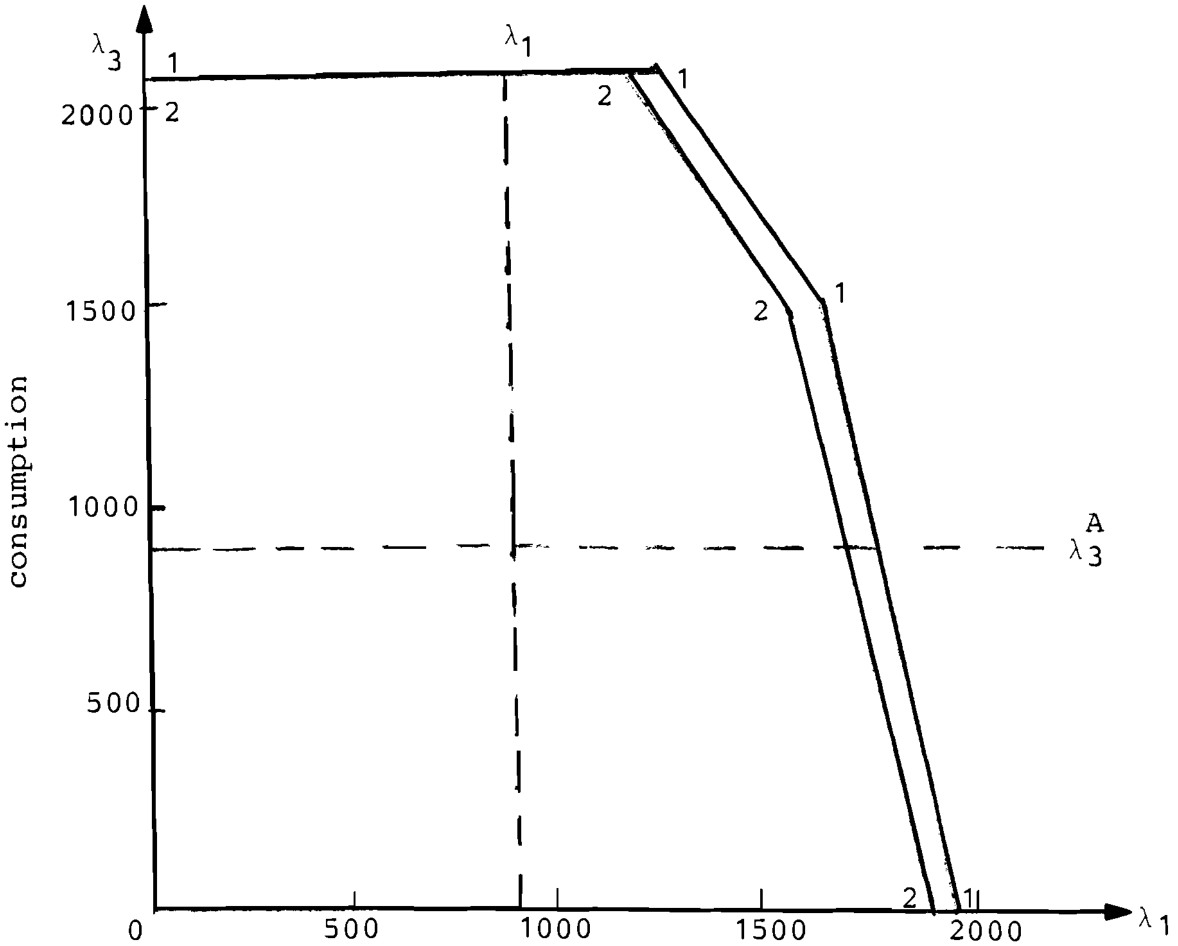

Figure 6. Reachable Consumption Values of Regions One and Three

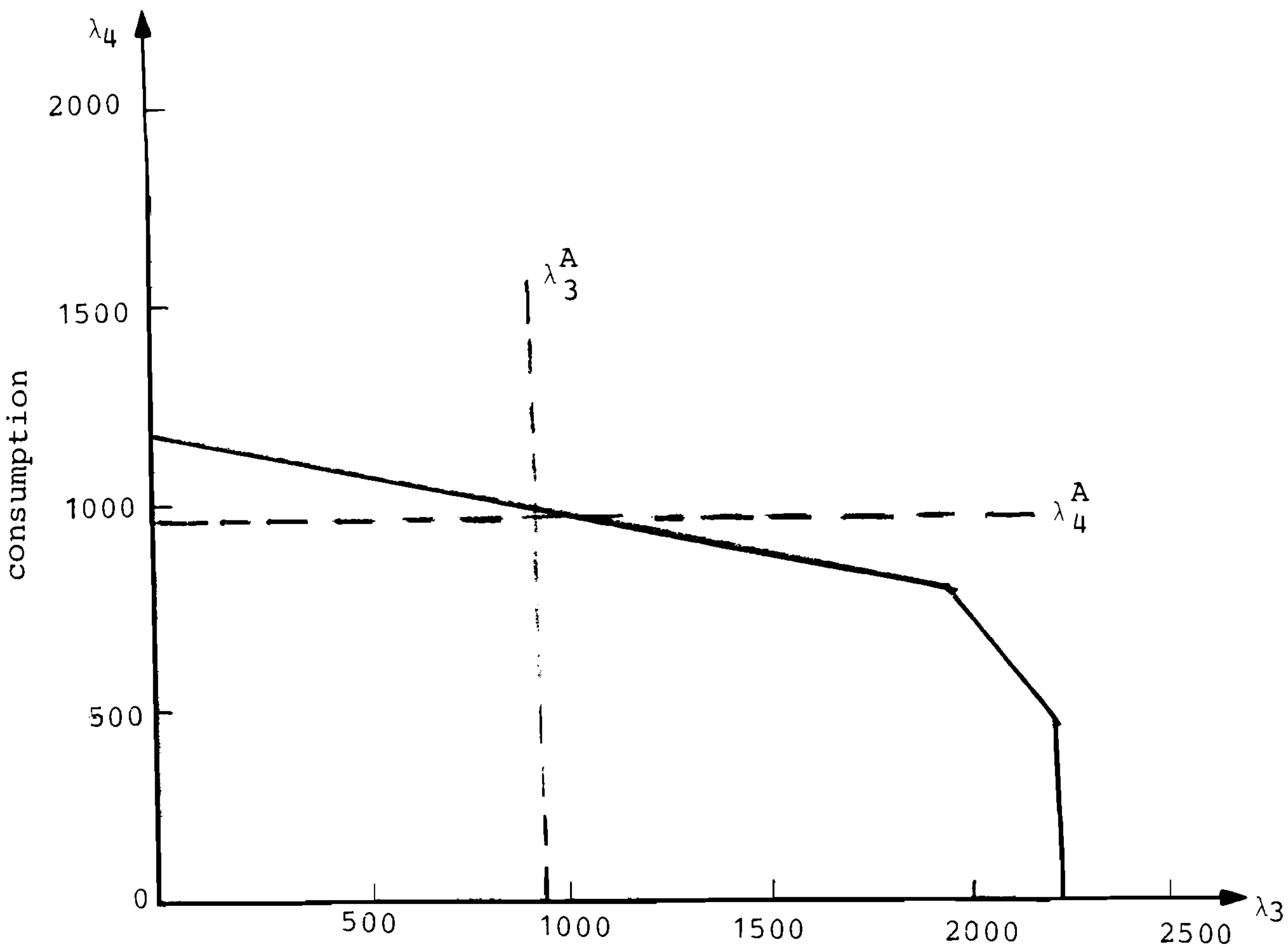

Figure 7. Reachable Consumption Values of Regions Three and Four

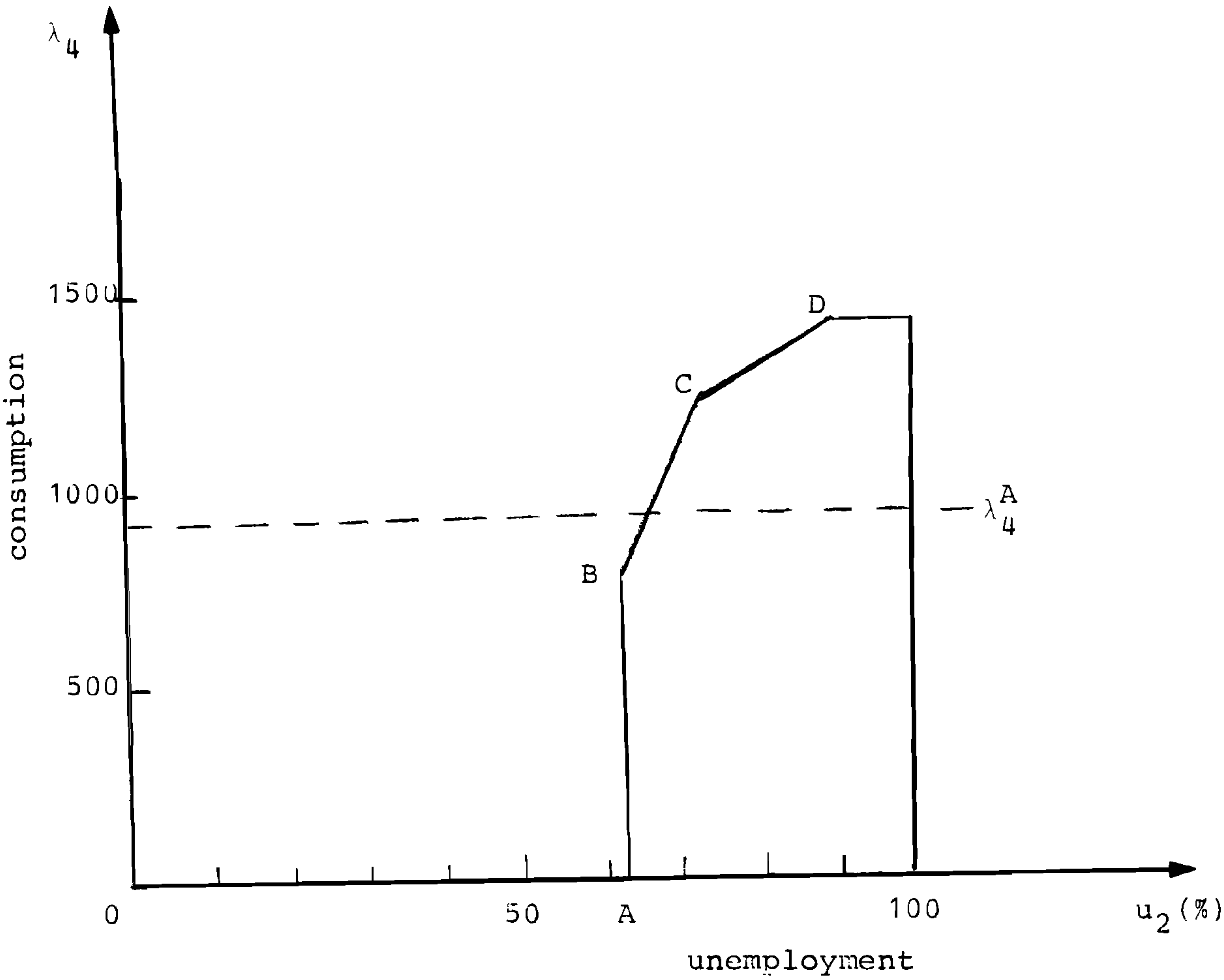

Figure 8. Effect of Increased Consumption in Region Four on the Level of Employment in Region Two

foreign trade is absent, that is in autarchy condition), the level of pollution increases rapidly. At the point M the value of F is about twenty times greater than at the point P but the consumption level λ_1 is only 1% greater. The same picture exists for foreign trade but the curve QPM is shifted. This picture shows that in the model only 1% consumption is necessary to solve the pollution problem. This is why in Figures 5-8 pollution is absent. In Figures 5-8 the interdependence between the values of consumption indicators $\{\lambda_1,\lambda_2,\lambda_3,\lambda_4\}$ and unemployment indicators $\{u_1,u_2,u_3,u_4\}$ are shown. Trade between regions is not fixed. Some restrictions on unemployment in some regions are imposed.

The reachable values of consumptions in the first and the second regions (values λ_1 and λ_2) are presented in Figure 5. The values λ_1^A and λ_2^A represent consumption in autarchy. Curve 1 represents the boundary of the set of all reachable values of $\{\lambda_1,\lambda_2\}$ when unemployment in the first and the second regions is absent, unemployment in the third and the fourth regions is equal to 10% of the whole labour force, the consumptions in the third and the fourth regions is equal to the autarchy level (about 1000 units). Curve 2 represents the same boundary but unemployment in all regions is 10%, the consumptions in the third and the fourth regions is the same as for curve 1. Curve 3 represents the same boundary but unemployment is the same as for curve 1, consumption in the third and the fourth regions is greater and equals 1200 units. This picture shows the advantages of world trade since reachable values of $\{\lambda_1,\lambda_2,\lambda_3,\lambda_4\}$ exist, which exceed autarchy levels for all regions simultaneously.

The reachable values of consumption in the first and in the third regions (values λ_1 and λ_3) are shown in Figure 6. Curve 1 represents the boundary of the set of all reachable values $\{\lambda_1,\lambda_3\}$ while unemployment in the first region is absent, unemployment in all other region is equal to 10%, consumption in the second region equals 1200 units, in the fourth 1000 units. Curve 2 shows the same boundary while unemployment in the first and in the second regions is equal to 5%, in the third and the fourth equal to 10%, consumption in the second region is equal to 1500 units, in the fourth region to 1000 units.

The reachable values of consumption in the third and the fourth regions in the case of no trade with other regions and full employment, are presented in Figure 7. This picture shows that trade between the third and the fourth regions only cannot increase the value of consumption in both regions simultaneously.

The effect of an increase in the consumption level in the fourth region on the employment in the second region u_2 is presented in Figure 8. Since the effectiveness of production makes employment minimal, the curve ABC shows the dependence of employment in the second region on consumption in the fourth region. Here consumption in all regions except the fourth are fixed ($\lambda_1 = 1300$, $\lambda_2 = 1200$, $\lambda_3 = 1000$ units), unemployment in the first region equals 2%, unemployment in the third and the fourth regions is equal to 10%. The curve ABC shows that the increase in consumption in the fourth region can increase the employment in the second region.

These and other cross-sections and projections of the GRS of indicators $\{\lambda_1,\lambda_2,\lambda_3,\lambda_4,u_1,u_2,u_3,u_4\}$ give the expert an understanding of the possibilities of the model under study. Experts can choose suitable combinations of indicators. Certainly the Figures 4-8 are an illustration only: in a dialogue with the computer, the experts can obtain hundreds of pictures of this kind.

4.4 Some Further Developments in the Modeling of Human Activity

Here we enumerate the main directions of our investigation of human activity:

(1) modification of methods for the GRS construction. Simultaneously alternative methods are elaborated using (Ereshko, 1979) optimization techniques and constructing effective points only;

(2) modification of the model of world economy. Application of the models with an explicit description of energy production as well as other inputs of the climate model;

(3) investigation of properties of models by means of the GRS approach;

(4) investigation of mechanisms of decision making. This is the most difficult problem in modeling human activity.

At present, at the Computing Center of the USSR Academy of Sciences, mathematical models of economic mechanisms of various types are investigated. A model of a market economy was constructed which demonstrated that in a model of this type, an increase in price for natural resources may result in an economic crisis, even if the quantity of these resources is infinite (Petrov and Pospelov, 1979). Methods based on the theory of games and devoted for analysis of models of economic mechanisms in centrally planned economies were developed (Vatel and Moiseev, 1977) as well as models of decision making in enterprises were studied (Lotov and Chernykh, 1979).

5. GENERAL SCHEME OF GLOBAL BIOSPHERICAL MODEL

As was discussed above, the global biospherical model consists of three parts (climate, biological and human activity models). These models should be connected with information flows representing the interacting parts of the biosphere. The first variant of the biospherical model is used for elaborating the methodology of systems analysis of biospherical processes. The information flows in this variant are presented in Figure 9.

The inputs of the human activity model are the average values of temperature, precipitation and sun radiation (for regional and seasonal aspects). The outputs of the model are anthropogenic discharge of energy, CO_2 and other pollutants, as well as anthropogenic changes in albedo. The inputs of the climate model are the concentration of carbonic acid in the atmosphere, anthropogenic discharge of energy and changes in albedo. The outputs of the climate model are the inputs of the human activity model. The inputs of the biological model are the outputs of the climate model as well as discharges of CO_2 and other pollutants. The output of the biological model is the concentration of CO_2 in the atmosphere.

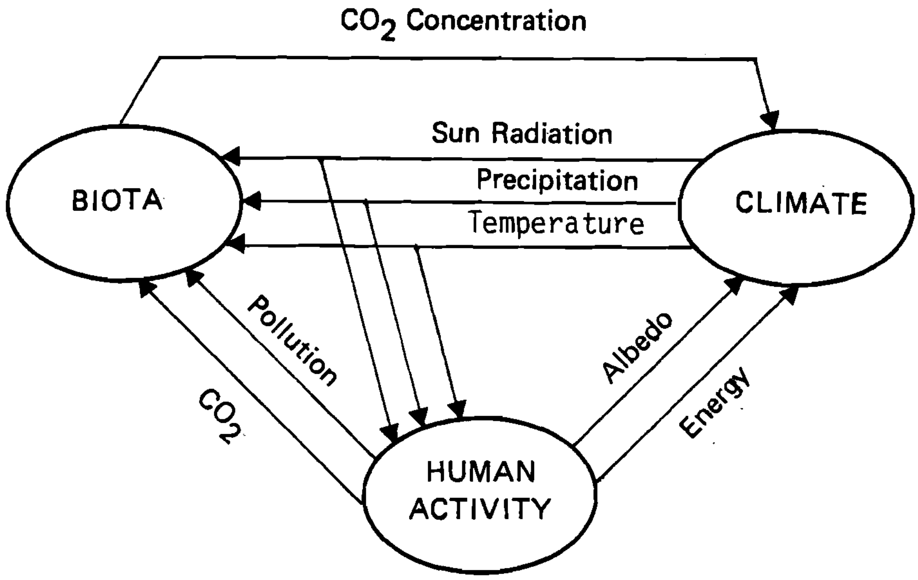

Figure 9. Information flow between the 3 parts of the Biospheric Model

At present the following mode of the models' interaction is elaborated. Experts, using perhaps information from some additional models describing the influence of climate on agriculture, formulate a system of restrictions on the inputs of the model of human activity. This restriction should describe admissible changes in regional climate conditions which preserves normal life in the regions. The set of admissible values of climate outputs by means of the climate and biological models are transformed into restrictions on the outputs of the human activity model. The set of restrictions on human activity describes all the variants of human influence on the biosphere preserving admissible climate in all regions of the world. The GRS is used to construct all the variants of the development of the world economy which do not violate biospherical restrictions on human activity as well as satisfying economic equations. These variants describe the real limits of growth of the world economy. The graphical analysis of the GRS for some indicators of the world economy (consumption and employment in regions and so on) provides the possibility of choosing the most suitable variant while not destroying the equilibrium in the human biosphere system.

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