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Interim Report IR-03-041

Analysis of Global and Regional Changes in Biogeochemical Carbon Cycle: A Spatially Distributed Model

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Contents

Abstract

This report presents a view on the current state and perspective of mathematical modeling of global and regional biosphere and climate changes under anthropogenic inputs. A spatial model of carbon cycle in the “Atmosphere - Plants – Soil” system is described, and the impact of industrial CO_2 emissions, deforestation and soil erosion on the dynamics of the “Atmosphere – Terrestrial Ecosystems – Ocean” system is analyzed. The countries’ carbon dioxide budget of 1995 is estimated. Consequences of several scenarios of the implementation of the Kyoto Protocol to the UN Framework Convention on Climate Change are discussed. The stability of the biosphere and climate are treated from the point of view of the biosphere’s ability to compensate anthropogenic inputs. In this context, the issue of the validity of the Le Chatellier principle in the biosphere is considered.

Keywords: *mathematical modeling, ordinary nonlinear differential equations, control theory, global biosphere processes, Le Chatellier principle, anthropogenic actions, global warming, carbon dioxide cycle, carbon budget, Kyoto protocol.*

Mathematics Subject Classification (2000): 93C10; 93C15; 93C83; 93D05; 93D15; 92B05; 92D25; 92D40; 86A05; 86A17; 86A30

About the Author

Professor Alexander M. Tarko is Senior Research Fellow and Head of the Biosphere Research Group at the Dorodnitsyn Computing Center of the Russian Academy of Sciences, Moscow, Russia. He is an expert in modeling, simulation and analysis of global and regional biosphere processes, with interests in modeling and analyzing the present state and possible futures of biosphere and climate interactions and changes under different human land use policy scenarios. He developed a mathematical approach to the analysis of biosphere stability, based on the Le Chatellier principle, and also the spatially distributed Global Carbon Dioxide Model and Nitrogen Cycle Model, containing models of the “Atmosphere – Terrestrial Plants – Soil” and “Atmosphere – Ocean” systems. Professor Tarko gives lectures on Mathematical Ecology, System Analysis, Simulating Modeling, and Problems of Environment at Moscow Institute of Physics and Technology. Alexander M. Tarko is a member of the Russian Academy of Natural Sciences. He is a Principal Investigator in several projects supported by the Russian Foundation for Basic Researches. He is the author of more than 150 scientific publications. In August 2002 Professor Tarko visited the IIASA’s DYN Project. During his stay with IIASA he gave the GHG seminar on “Modeling of the Global and Regional Biogeochemical Cycles of Carbon and Nitrogen”, and also the YSSP seminar on “Investigation of Large Scale Biosphere Processes with the Aid of Global Carbon Dioxide and Nitrogen Cycles Modeling”.

Analysis of Global and Regional Changes in Biochemical Carbon Cycle: A Spatially Distributed Model

Alexander M. Tarko (tarko@ccas.ru)

Introduction

Human activity has led to sharp and global changes in processes in the biosphere. The changes have an irreversible character. The quantity of greenhouse gases in the atmosphere (carbon dioxide, methane, chlorofluorocarbons etc.) is growing. Global warming is accelerating, ecosystems are being disturbed, landscapes are changing, forests are being reduced, and soil erosion is developing. If mankind does not revise modern intensities and technological methods of the utilization of resources of the biosphere, a catastrophic change in the biosphere is very probable. An important problem is to find ecological, technological and economic conditions which will prevent the crisis, being acceptable to both mankind and the biosphere.

Mathematical modeling is a powerful tool to investigate changes in the biosphere subject to human impacts and to generate acceptable scenarios of future development. Moreover, mathematical modeling is practically the single method to analyze large-scale changes in the biosphere, since any physical experiments with the entire biosphere are impossible. A fruitful mathematical approach is modeling global and regional biogeochemical cycles of carbon and nitrogen. The global carbon cycle is especially important. On the one hand, carbon being a component of live and dead organic matter in the biosphere, acts as an indicator of ecological processes. On the other hand, carbon contained in the atmosphere as a component of the carbon dioxide greenhouse gas, influences climate on the planet. The nitrogen cycle is of a next grade of importance.

In this paper, a spatial model of global carbon cycle in the “Atmosphere – Plants – Soil” system (APS) is presented. The model is complemented by a simpler model of carbon cycle in the “Atmosphere – Ocean” system, and on this basis, behavior of the entire “Atmosphere – Plants – Soil – Ocean” system, influenced by the anthropogenic activity, is analyzed.

1. Global warming and problem of stabilization of the CO_2 content in the atmosphere

Growth of the quantity of carbon dioxide in the atmosphere is a result of carbon dioxide releases to the atmosphere due to burning of fossil fuels (industrial releases), reduction of the forest biomass and erosion of soils. Regular measurements of CO_2 started at the Mauna Loa monitoring station in 1958. Now CO_2 is measured worldwide at more than 10 stations. The comparison of the CO_2 concentration of the middle of the XIX century, which were received from the analysis of ice cores in Antarctica, and the CO_2 concentration registered in the last three decades showed that this value had increased for 25% in the last 150 years.

Figure 1 shows the growth of the CO_2 concentration registered at two monitoring stations in 1958 – 1993 and the growth of industrial releases in 1958 – 1998. We see that within 35 years the quantity of CO_2 in the atmosphere has increased for 13%, whereas the industrial releases have increased 2.6 times. Figure 2 shows the seasonal dynamics of the CO_2 concentration, registered at several monitoring stations. We see that for each monitoring station, in every year the CO_2 concentration curve lies higher than that in the previous year.

It is remarkable that after 1970 the rate of annual growth of CO_2 releases has decreased, which is seen in Figure 3 showing the dynamics of industrial releases (averaged over 10 years) in 1960 – 1999. The growth rate of industrial releases reduced from 5.1 percent/year in 1971 – 1973 to 0.92 percent/year in 1983, and again reduced from 1.88 percent/year in 1993 to 0.67 percent/year in 1999. Altogether, after the acceptance of the UN Convention on Climate Change in 1992, the average growth rate of industrial releases decreased 2.8 times. In 1997, 1998 and 1999 the absolute values of CO_2 releases decreased too.

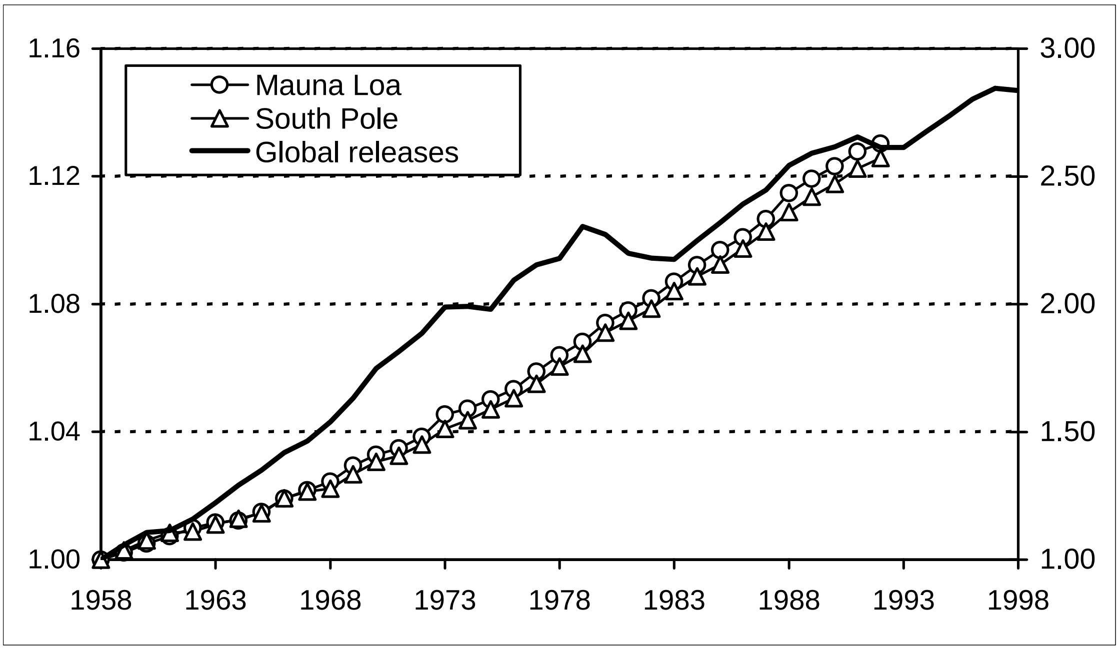
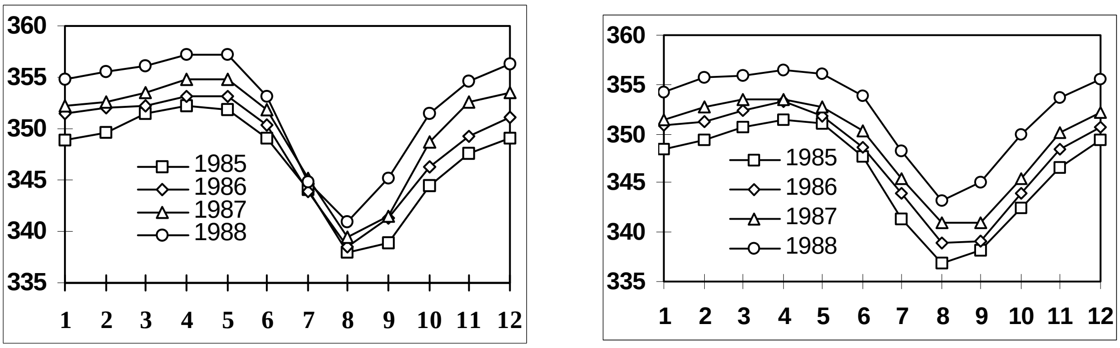


Figure 1. The dynamics of the atmospheric CO_2 concentration, registered at the Mauna Loa and South Pole monitoring stations (left axes, relative units) in 1958-1993 and global releases of CO_2 to the atmosphere due to burning of fossil fuels (right axes, relative units) in 1993-1999.

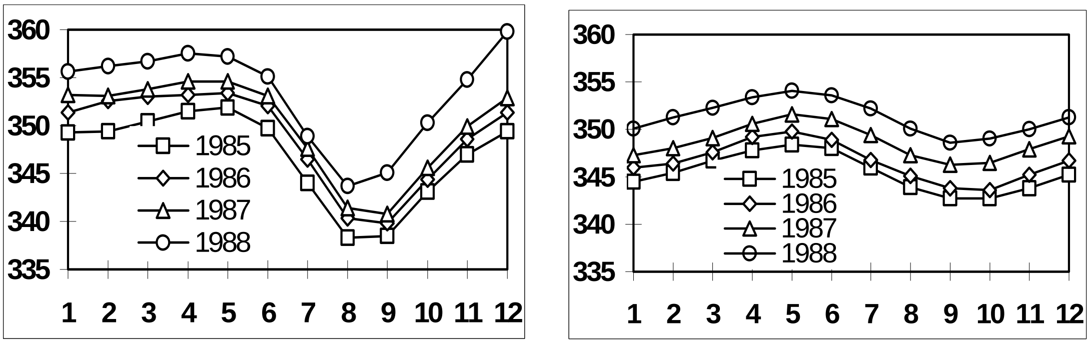
Station Cold Bay, 55N, 162W

Ocean Station “M”, 66N, 2E



Station Mould Bay, 76N, 119W

Station Mauna Loa. 19N, 155W



Cape Kamukasi, 19N, 154W

Equator 0N, 150W, Pacific Ocean

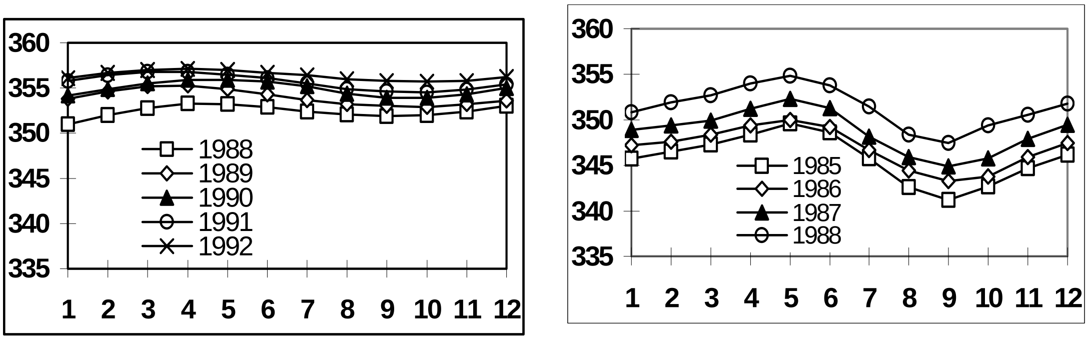


Figure 2. The seasonal dynamics of the atmospheric CO_2 concentration (ppm), registered at several monitoring stations.

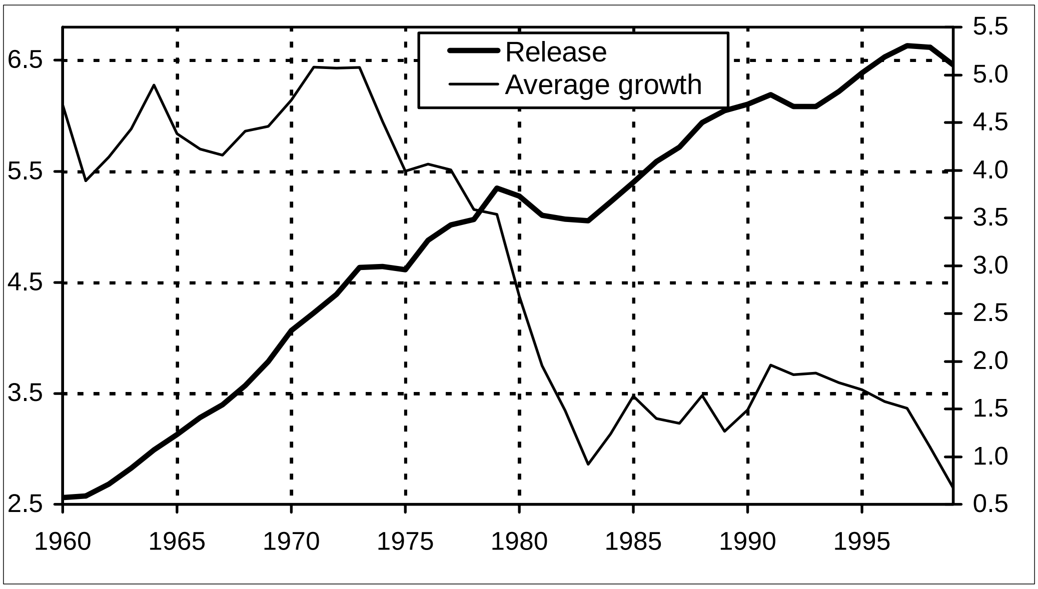


Figure 3. The average growth of industrial releases (right axes, per year percentage averaged over 10 years preceding the given year) and industrial CO_2 releases (left axes, Gt C/year) in 1960-1999.

Another fact is that during the last 150 years the annual global temperature of the atmosphere was growing. Figure 4 shows the curve of the atmospheric temperature in 1856 –1999 (Jones, et al., 2000). The years 1878 – 1911 and 1944 – 1976 were periods of cooling, and the most recent period of global warming was 1976 – 1999.

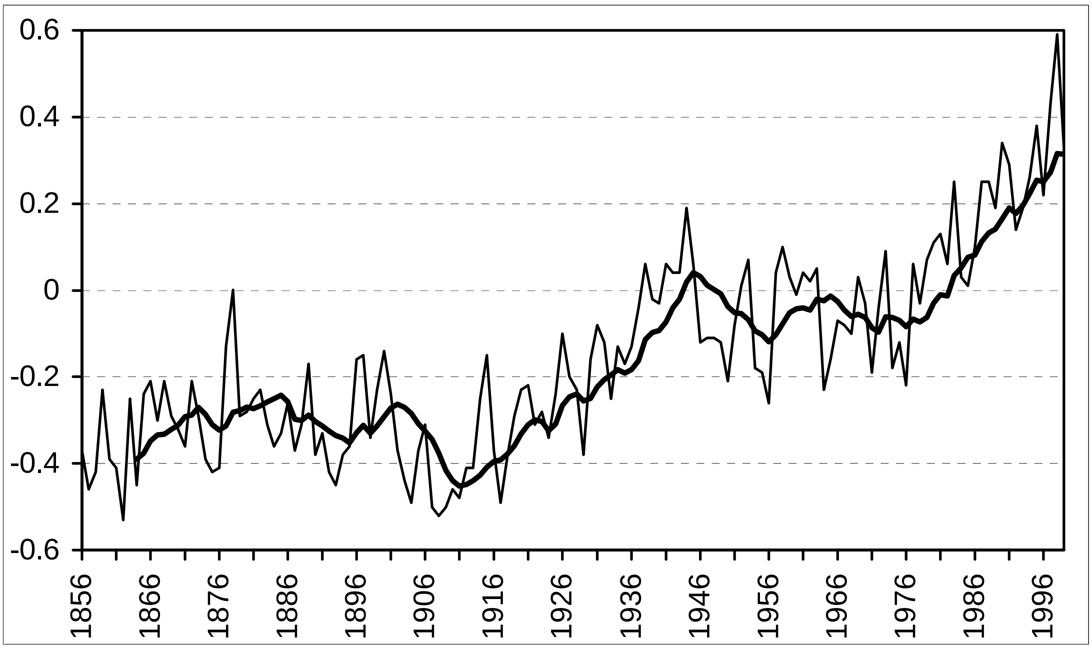


Figure 4. Anomalies of the global atmospheric temperature in 1856 – 1999, degrees C.

It is necessary to note that a causal relation of warming to the growth of the CO_2 concentration in the atmosphere has yet not been established. It is not known for sure whether the current warming is due to the growth of CO_2 in the atmosphere. In this context, it is critically important to prove the physical significance of the models that predict global warming, especially if these models influence decision making.

In 1992 in Rio de Janeiro the Framework Convention on the Climate Change was accepted. According to it, releases of CO_2 and other greenhouse to the atmosphere should be considerably reduced in the coming decades. No doubt, the leaders of the countries, who signed the Framework Convention, knew about the uncertainty in the identification the key driving factors of climate change, as well as about the possibility of serious economic, social and ecological consequences of global warming. However, they agreed that emissions of greenhouse gases to the atmosphere should be significantly reduced. This decision was based on the precaution principle that was authorized at the Conference in Rio de Janeiro. According to this principle, "the Parties should take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects. Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures, taking into of account that policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost". The decision on such expensive preventive measures was based on the care of the nature and population and was targeted to a long time horizon. In 1997 the Kyoto Protocol providing more detailed recommendations on the reduction of greenhouse gases emissions was signed.

What is the degree of the uncertainty in relating the growth of the concentration of CO_2 to the increase of the atmospheric temperature, as estimated now? This estimation is, first of all, connected with the uncertainty of the results of the calculations of the increase of the temperature due to the growth of the concentration of CO_2 , that are provided by modern models of general circulation in the atmosphere and in the ocean. For the estimation of such uncertainties, climatologists use the difference between the value of the temperature increase that accompanies doubling of the atmospheric CO_2 and its modern value, $\Delta T2x$. According to Andronova and Schlesinger, 2002, if $\Delta T2x$ is less than 1.5° C, which is the lowest bound for the temperature increase, suggested by the Intergovernmental Panel on Climate Change (IPCC), then the anthropogenic impact on climate change (AICC) may not be a serious problem for humanity. Conversely, if $\Delta T2x$ is greater than 4.5° C, which is the highest bound for the temperature increase, suggested by the IPCC, then AICC may be one of the most severe problems of the XXI century. Andronova and Schlesinger, 2002, using a simple climate/ocean model and taking into account the natural variability and uncertainty in climatic radiative forcing, find that the temperatures between 1.0° C and 9.3° C give the 90% confidence interval for $\Delta T2x$. This estimate implies that the likelihood that $\Delta T2x$ lies beyond the IPCC range is 54%.

2. Models of global cycles in the biosphere

The first mathematical model of global biogeochemical cycles was elaborated in Kostizin, 1935; the model dealt with the oxygen and carbon cycles in the global "Atmosphere – Terrestrial Biota – Ocean – Crust" system. It was described by a system of 7 ordinary nonlinear differential equations and was studied analytically. The system of the model's equations contains two independent subsystems. One of them is the classical Volterra Predator-Prey system; it possesses periodic solutions with "fast" fluctuations of the weight of plants and animals; the fluctuation period varies from 15 years to 140 years. The other subsystem, under an appropriate choice of its parameters, has a "steady focus" solution and demonstrates "slow" fading fluctuations in the atmosphere and in the ocean with the period of millions years. The amplitude of the fluctuations increases with the amplification of the volcanic activity. The model shows also a very slow decrease of the carbon dioxide content and an increase of the oxygen content in the atmosphere.

Modern models of global cycles of biogeochemical elements appeared in the beginning of 50th . The pioneer effort was made by Suess, 1955, who estimated the ratio of the radioactive carbon C^{14} (which had constantly been formed in the atmosphere due to the action of space particles and the stable carbon C^{12} in the wood rings. It was stated that this ratio had been decreasing during the preceding decades; on this basis it was concluded that the concentration of CO_2 in the atmosphere had been increasing. The driving force of the effect discovered in Suess, 1955, is the "dilution" of the atmospheric CO_2 by the inflow of CO_2 due to the fossil fuels that practically do not contain C^{14} (the period of the half-decay of C^{14} is 5730 years). This proves the global character of the impact of burning of the fossil fuels on the atmosphere.

The first global carbon cycle models (Eriksson and Welander, 1956; Bolin and Eriksson, 1959; Eriksson and Welander, 1956; Revelle and Suess, 1957) described the dynamics of both C^{12} and C^{14}. They used a very simple representation of the processes in the "Atmosphere – Ocean" system and in the "Atmosphere – Terrestrial Vegetation" system; the number of the models' "boxes" – differential equations – was small. In further models, the number of variables was enlarged through the introduction of horizontal and vertical dimensions of the ocean and spatial dimensions of land ecosystems (Bjorkstrom, 1979; Hoffert, 1981; Keeling, 1973; Machta, 1971). Finally, models, which took into account other biogeochemical cycles (nitrogen cycles, and others) were constructed (Jorgensen and Mejer, 1976; Novichikhin and Tarko, 1984).

The majority of the initial models were aimed at predicting the concentration of CO_2 in the atmosphere. A qualitative analysis was carried out only in connection with estimation of the accuracy of the forecasts for the atmospheric CO_2 and the temperature. Nowadays, research is, in contrast, focusing on the understanding of the roles of terrestrial ecosystems, the ocean and its parts in the absorption of CO_2, and also on the assessment of feedbacks between climate change and changes in terrestrial ecosystems. Modern models provide a detailed description of important elements of biogeochemical cycles (which implies improvement of spatial and/or temporal resolution) and serve for the analysis of new empirical data such as data on the fluctuations of the concentration of CO_2 in the atmosphere.

3.A spatial model of the global carbon cycle in “Atmosphere – Plants – Soil” system

3.1 Description of the model

Here we present a version of the spatial model of the global carbon cycle in the “Atmosphere – Plants – Soil” system (APS). The model was elaborated in Tarko, 1982, 1985, 2001. In the model, the land territory is partitioned into cells of size $0.5^o \times 0.5^o$ on the geographical grid. In each cell there is vegetation of one of the types corresponding to a given classification (see Olson, Watts and Allison, 1985; Bazilevich and Rodin, 1967). The flow diagram of the model is shown in Fugure 5.

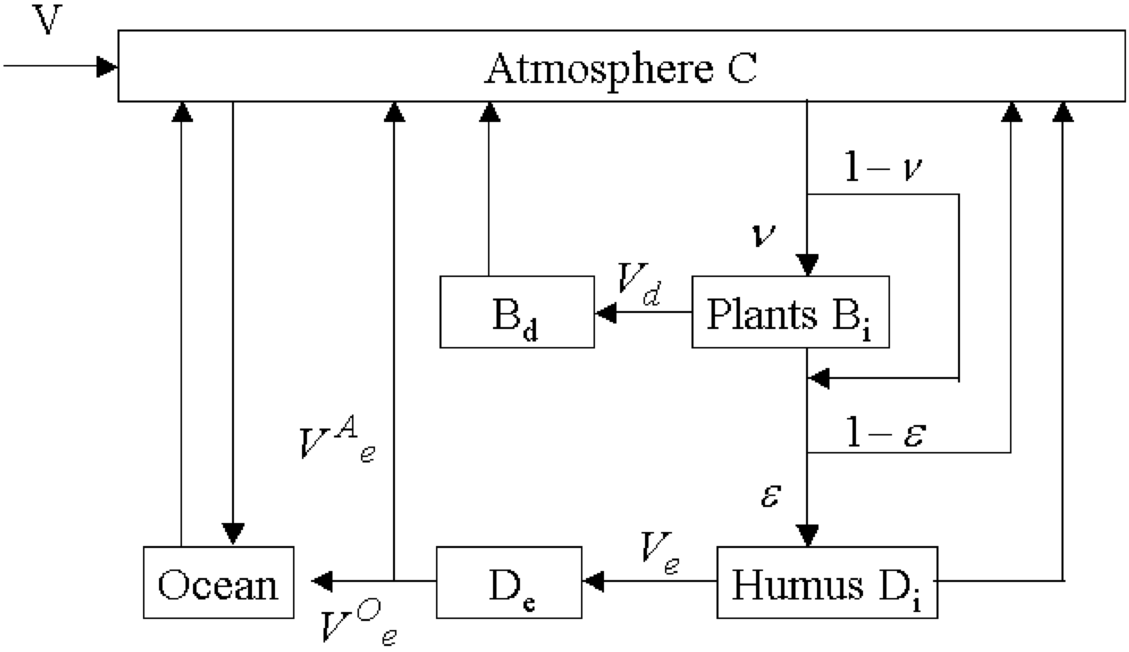


Figure 5. The flow diagram of the model. Here B_i and D_i are, respectively, the concentrations of carbon in the terrestrial plant biomasses and in humus in cell i, and B_d and D_e are, respectively, the concentrations of carbon in the cut down forests and in humus erased due to the inappropriate land use.

The model is described by a system of ordinary nonlinear differential equations. In each cell of land, numbered i ($i = 1,...,I$), the ecosystem is characterized by the quantity of carbon per unit area in the phytomass of living plants, B_i, and in soil humus, D_i. The area of cell i is denoted by σ_i. The time unit in the model is 1 year. The total quantity of carbon in the atmosphere is denoted by C. The climate in cell i is characterized by annual surface temperature, T_i, and annual precipitation, P_i. The values of T_i and P_i depend on C (a greenhouse effect) and are calculated using a general circulation model. Initial value of B_i, D_i, T_i, P_i are denoted by $B_i^o, D_i^o, T_i^o, P_i^o$, respectively.

It is assumed that annual production of vegetation in each cell i depends on C, as well as on the temperature, T_i, and precipitation, P_i, in this cell, and does not depend on the ecosystem type in this cell. The amount of humus, D_i, in a steady state in cell i is assumed not to depend on the ecosystem in this cell type either, and it is modeled as a known function of T_i and P_i: $D_i = D(T_i, P_i)$. The rate of humus decomposition, h, is represented as a given function of T_i and P_i: $h = h(T_i, P_i)$.

It is assumed that in the absence of anthropogenic CO_2 emissions to the atmosphere, the quantity of carbon in the biosphere is constant. Another assumption is that prior to the operation of anthropogenic inputs the system is in a steady state (usually 1860 is accepted as the year of the start of the industrial era).

The model takes into account three anthropogenic factors that impact the biosphere and result in the growth of CO_2 in the atmosphere. The first factor is burning of fossil fuels or industrial releases; we denote by V industrial CO_2 releases expressed in terms of the carbon outflow to the atmosphere. The second factor is utilization of the forest biomass. The phytomass of the utilized forest biomass is decomposed with a certain delay, and carbon concentrated in it goes to the atmosphere in the form of CO_2 ; we denote by B_d the amount of carbon in the utilized forest biomass. The third factor is soil erosion resulting from the inappropriate land use. The dead organic matter in the soil is decomposed with a certain delay, and carbon concentrated in it goes to the atmosphere in the form of CO_2. Part of the decomposed carbon goes into rivers and eventually into the ocean; we denote by D_e the amount of carbon carried out due to the soil erosion.

The dynamics of carbon in APS is described by the following system of equations:

$$\begin{aligned}
&dB_i / dt = \nu_i Q_i - m_i B_i - k_d^i B_i,\\
&dD_i / dt = \varepsilon(m_i B_i + (1-\nu_i)\, Q_i) - h(T_i, P_i)\, D_i - k_e^i D_i,\\
&dB_d / dt = \sum_{i=1}^{I} (k_d^i B_i \sigma_i) - q_d B_d, \qquad (1)\\
&dD_e / dt = \sum_{i=1}^{I} (k_e^i D_i \sigma_i) - q_e D_e - q_m D_e,\\
&dC / dt = -\sum_{i=1}^{I} ((1-\varepsilon_i)(m_i B_i + (1-\nu_i) Q_i) - h(T_i, P_i) D_i)\sigma_i + q_d B_d + q_e D_e + V,\\
&\sum_{i=1}^{I} \left(dB_i / dt + dD_i / dt\right)\sigma_i + C + dB_d / dt + dD_e / dt = V
\end{aligned}$$

$$i = 1, \ldots, I.$$

Here $Q_i = Q(C, T_i, P_i, B_i)$ is annual production of the plants per unit area in cell i, and $m_i, \varepsilon_i, k_e^i, k_d^i, q_d, q_e, q_m$ are coefficients. More specifically, $k_d^i B_i$ is the flow of carbon in cut-down plants in cell i; $k_e^i D_i$ is a measure of soil erosion in cell i; $q_d B_d$ is the flow of the decomposed organic matter from cut-down trees; $q_m D_e$ is the flow of the decomposed dead organic matter due to erosion; and $q_o D_e$ is the flow of decomposed soil to the ocean. According to Keeling, 1973, annual production depends on the concentration of CO_2 in the atmosphere and on the plant phytomass:

$$Q = F_o(1+\beta \ln(C/C^o))(B/B^o)^{2/3}. \qquad (2)$$

Here F_o is annual production for the initial state, B is the plant phytomass, expressed in carbon units, C^o, B^o are initial values of the corresponding variables, and β is a coefficient. Annual production depends on the value of phytomass, B. A functional relation developed in Tarko, 1982 states that annual production depends on the concentration of the atmospheric CO_2 as well as on the temperature and precipitation but does not depend on the plant phytomass:

$$Q = F(T,P)(1+\frac{\delta}{10}(C/C^o - 1)). \qquad (3)$$

A nonlinear form of this is

$$Q = F(T,P)(1+\frac{\delta}{10}[(C/C^o - 1)(1-(C-C^o)/KC^o); \qquad (4)$$

here K is a coefficient. According to (4), annual production grows (respectively, decreases) as the atmospheric CO_2 concentration grows within (respectively, beyond) a certain neighborhood of its initial value; the form of $F(T,P)$ expressing a nonlinear dependence of annual production on the temperature and precipitation is a result of statistical data processing (Moiseev, Aleksandrov and Tarko, 1985). The coefficient ν_i expresses part of annual production, which goes to trees. Accordingly, $\nu_i Q_i$ is the carbon flow to trees and $(1-\nu_i)Q_i$ is the foliage fall down. If $\nu_i = 0$, then the foliage fall down equals the annual production, hence, cell i is occupied by a grassland ecosystem, and B_i is a quasi variable. The outlined two approaches to modeling Q determine, generally speaking, different dynamic properties of the model; however simulations show that within a relatively narrow neighborhood of a steady state the differences in the system's operation are not so strong. The dependence of the quantity of humus on the temperature and precipitation, $D^0(T_i, P_i)$, in a steady state was received in a tabulated form on the basis of a statistical processing of measurement data (Moiseev, et. al., 1985).

Note that a relatively little information is needed to identify the model's parameters and functional dependences.

If the model departs from the preindustrial period, its initial conditions are chosen as a steady state of system (1), implying

$$m_i = \nu_i F(T_i, P_i)/B_i^o ,$$

$$h(T_i, P_i) = \varepsilon F(T_i, P_i)/D^o(T_i^o, P_i^o) .$$

These equations establish the values for the coefficients m_i provided the annual production $F(T,P)$ and initial phytomass B_i^o are known, and an extension of the second equation to all states specifies a representation for the rate of humus decomposition:

$$h(T,P) = \varepsilon F(T,P) / D^o(T,P).$$

The model is complemented by a simple model of carbon in the “Atmosphere – Ocean” system (Chan, et. al., 1979). As a result, a complete model of the global carbon cycle in the “Atmosphere – Terrestrial Ecosystems – Ocean” system is constructed.

3.2 Computer realization and validation of the model. Preindustrial state of the biosphere

A computer program controlled by Windows 95/98/NT/XP was developed to simulate the model. For the $0.5^o \times 0.5^o$ resolution the model involves around 60 000 terrestrial cells and around 120 000 differential equations. For simulations, the initial values for the phytomasses in the cells were taken from Olson, et. al., 1985 and from Bazilevich and Rodin, 1967.

The model was validated using a procedure traditional in global CO_2 cycle modeling. For simulations, the coefficient δ (see (4)) was identified using measurement data of 1860 (ice cores data) and of 1959 – 1998 (data of CO_2 monitoring stations); as said above, in this period the CO_2 concentration has grown for 25%. The identified value of δ agreed with the values obtained experimentally in plant laboratories. The $0.5^o \times 0.5^o$ geographical grid partitions the land surface into cells of approximately 50km × 50 km. A simulated map of annual production of world vegetation in the pre-industrial period is shown in Figure 6. The map was designed on the basis of the annual production model suggested in Tarko, 1982. A comparison of observed and simulated values of annual production in different points of the Earth surface shows that the deviations do not exceed the measurement accuracy. A similar simulated map of humus storage adequately reproduces its distribution over the Earth; it shows that maximum values of humus are reproduced in grassland ecosystems containing chernozems.

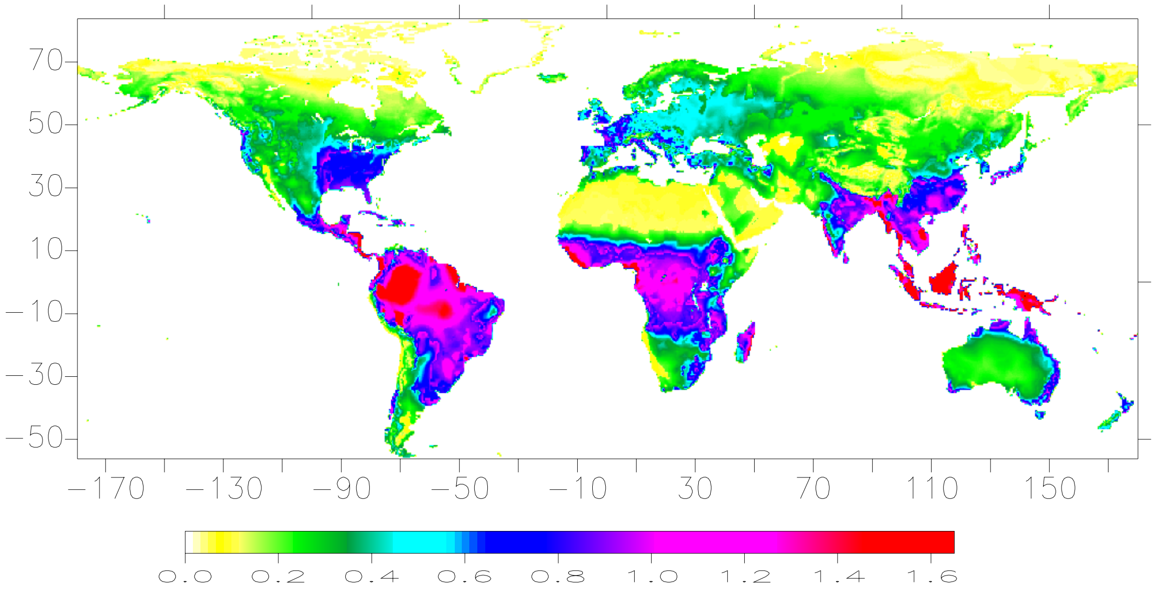


Figure 6 A. Computer map of the world vegetation annual production, kg C/(m^2 year)

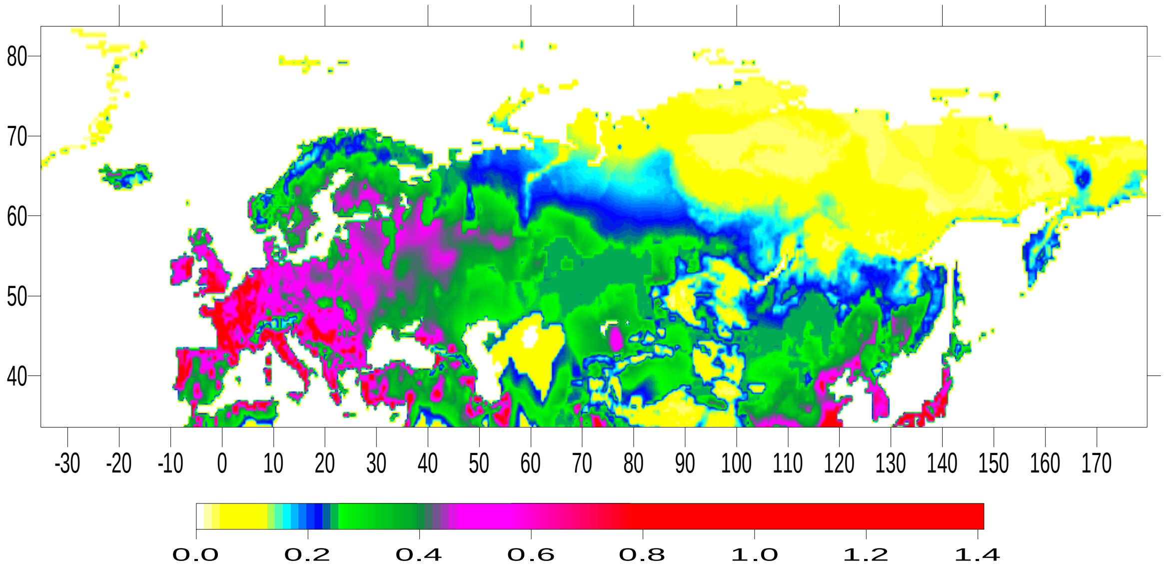


Figure 6 B. Computer map of the Europe vegetation annual production, kg C/(m^2 year)

3.3 Biosphere dynamics under the impact of industrial CO_2 emissions, deforestation, and soil erosion

The above model was used to simulate the dynamics of the “Atmosphere – Terrestrial Ecosystems – Ocean” system in 1860 – 2050 under the impact of three major anthropogenic factors leading to the increase of CO_2 in the atmosphere – industrial releases, deforestation and soil erosion resulting from an inadequate land use. The main feature of the scenario accepted for simulations are the following. Deforestation and subsequent destruction of tropical forests continue in 1950 – 2050. The rate of reduction of tropical forests equals 0.6% per year. Deforestation per a unit of area is identical in all cells. At deforested territories, grasslands appear. Soil erosion begins in 1860 and increases with the rate of 0.15% per year. Erosion per a unit of area is identical in all cells. Annual industrial releases in 1860 – 1996 are simulated using data of Carbon Dioxide Information Analysis Center (Marland, et. al., 2002). In the period following 1997 the industrial emissions are set to grow 3% per year, and according to Bolin, 1986, 20 Gt C/year is an upper bound for annual emissions.

The simulated dynamics of carbon parameters is shown in Figure 7. We see that the atmospheric CO_2 increases 1.8 times. The simulations show that the temperature and plant biomass are increasing, whereas the quantity of humus is decreasing during a long period, after which it begins to grow because of growth in annual production resulting from growth of the atmospheric CO_2 concentration and the increase of temperature (a compensation growth).

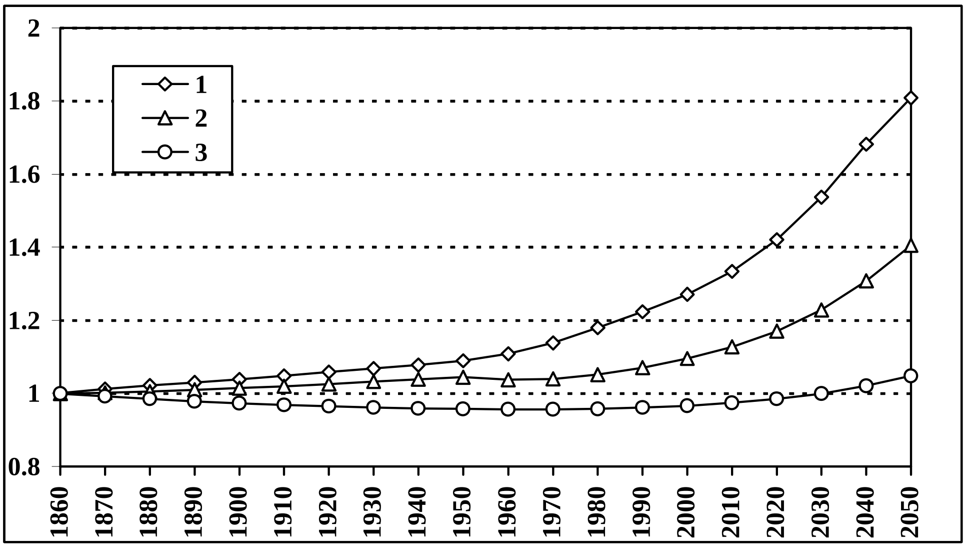


Figure 7. The simulated dynamics of relative values of carbon in the atmosphere (1), plants biomass (2), and soil humus (3) in 1860 – 2050.

The analysis of the zonal distribution of humus (Figure 8) shows that in 1860 – 2010, in high latitudes of the Northern hemisphere and partially in the Southern hemisphere, the quantity of humus grows, absorbing CO_2 from the atmosphere. Simultaneously, in middle and tropical latitudes of the Northern and Southern hemispheres, the quantity of humus decreases, which acts as a source of CO_2. After 2010, the humus absorption is kept in high latitudes of the Northern and Southern hemispheres and the quantity of humus starts increasing in middle and tropical latitudes of the Northern hemisphere. The areas of the humus increase grow, and finally CO_2 is absorbed in humus in tropical latitudes of the Southern hemisphere as well.

Change in the total carbon content (i.e., the amount of carbon in both phytomass and humus) at different latitudes in 1860 – 2050 is shown in Figure 9. In high and partially middle latitudes of the Northern and Southern hemispheres, the ecosystems absorb CO_2, and the CO_2 absorption area grows constantly. In the equatorial zone and partly in the middle zone, the ecosystems release CO_2, whereas the area of the release of CO_2 decreases and practically disappears in 2020. After 2020 practically all ecosystems absorb CO_2. A strongest absorption takes place in middle latitudes of the Northern hemisphere where plentiful forest ecosystems are concentrated. The degree of the CO_2 absorption decreases as the latitude approaches the equator.

The simulation shows that in 1860 – 2050 the territory of the world is constant global CO_2 sink although some ecosystems release CO_2. Forest ecosystems are the most powerful CO_2 absorbers. Grasslands are mostly CO_2 sinks too, however at some locations they act as CO_2 sources. The phytomass is constantly increasing in all ecosystems except of the tropical forests.

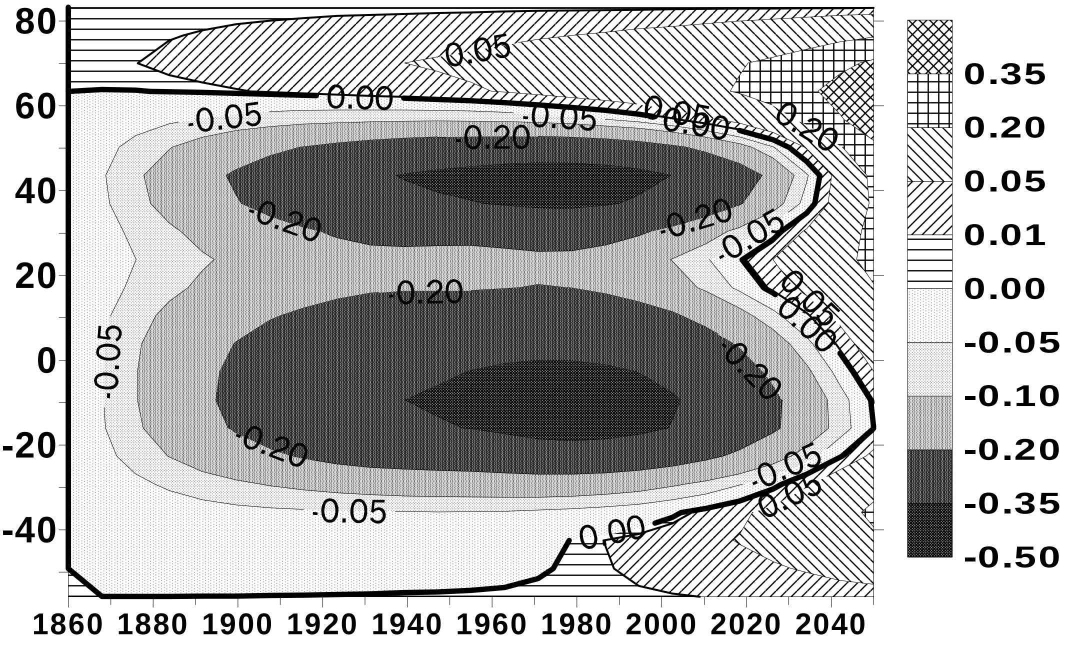


Figure 8. The simulated zonal dynamics of carbon in soil humus (kg C/m^2) in 1860 – 2050. The vertical axis shows latitudes. Positive (respectively, negative) values indicate the increase (respectively, decrease) of the humus content compared to 1860.

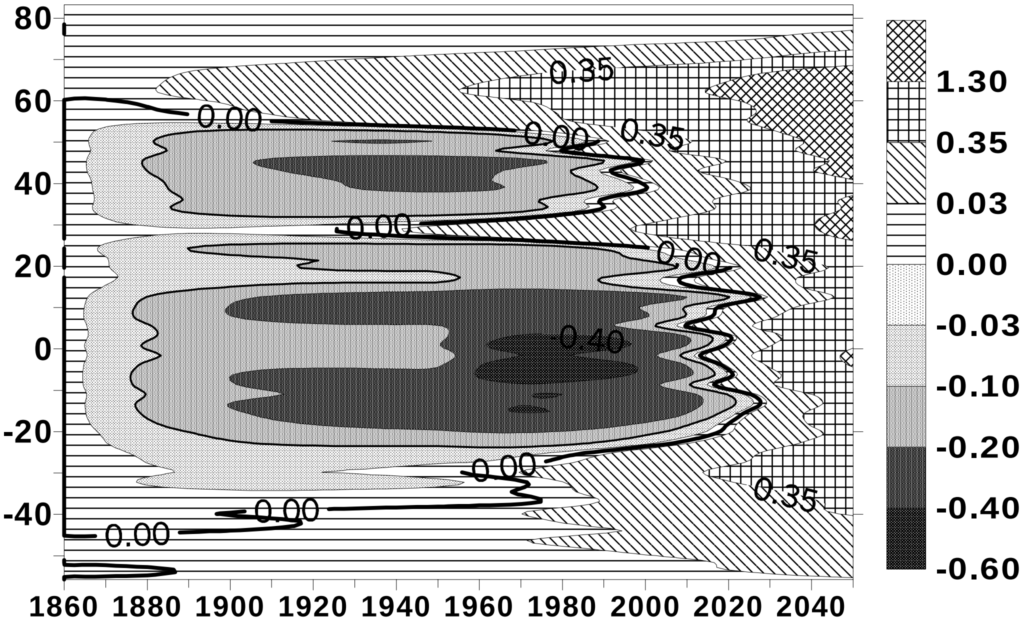


Figure 9. The simulated zonal dynamics of total carbon in terrestrial ecosystems (kg C/m^2) in 1860 – 2050.

The designations are the same as in Figure 8.

3.4 Carbon dioxide budget of countries in 1995

Let us recall that carbon budget is defined as annual production minus humus decomposition, minus deforestation, and minus soil erosion. Figure 10 shows results of simulation of carbon budget of ecosystems in 22 countries which are the greatest “producers” of industrial CO_2 releases, and the corresponding CO_2 releases in 1995. The greatest industrial emissions go from the USA, China and Russia, and the strongest CO_2 sinks are in Russia, Canada and the USA. In the majority of the countries industrial emissions exceed the ecosystems’ absorption abilities. The exceptions are Canada, Australia, and Brazil where the CO_2 absorption by ecosystems is stronger than the industrial releases, which is presumably due large territories and relatively small industrial releases in these countries.

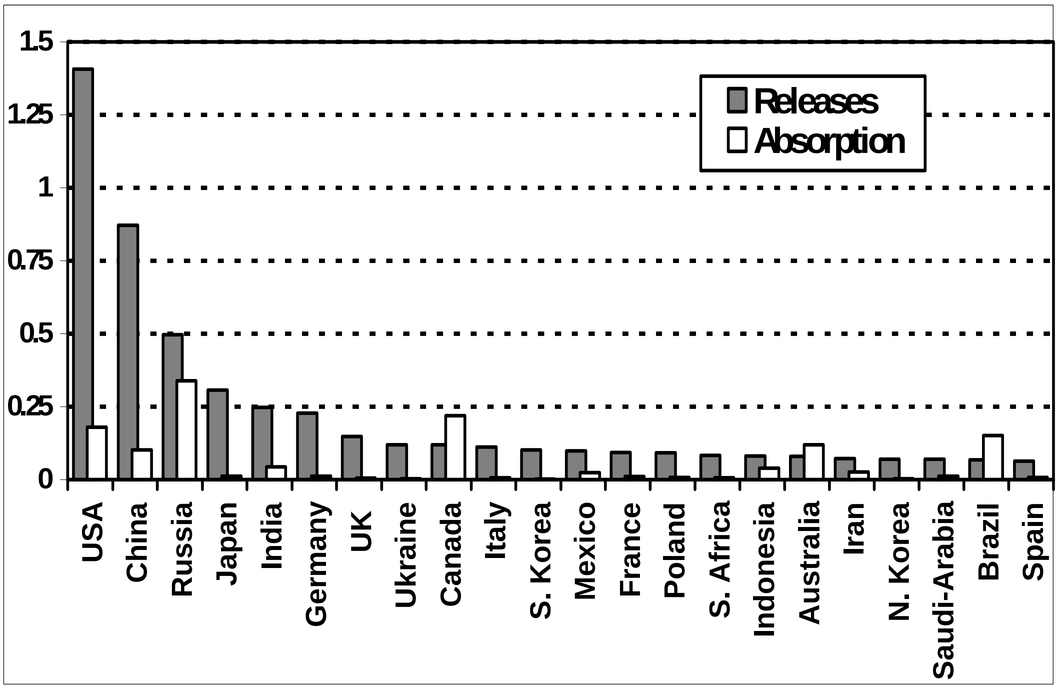


Figure 10. Countries' industrial releases and carbon absorption by ecosystems (Gt C/ year) in 1995.

3.5 Carbon dioxide budget of the biosphere

Simulations show the following balance of the world CO_2 flows in 1995:

Industrial releases	6.41 Gt C/year
Deforestation	1.08 Gt C/year
Soil erosion	0.91 Gt C/year
Absorption by terrestrial ecosystems	4.05 Gt C/year
Absorption by ocean	1.05 Gt C/year
Remains in atmosphere	3.30 Gt C/year

The last row indicates that 51% of industrial CO_2 emissions remain in the atmosphere, which corresponds to measurement data.

3.6 Estimation of the effect of the implementation of the Kyoto Protocol to the UN Framework Convention on Climate Change

In accordance with the Kyoto Protocol to the UN Framework Convention on Climate Change (1997), by 2010 all countries should reduce greenhouse gases emissions of to the level of industrial CO_2 emissions in 1990. Here we present results of the use the model for the analysis of the effects of various restrictions on the reduction of CO_2 emissions. The following scenarios were considered (see Figure 11):

Scenario 1. This is our basic scenario of anthropogenic impacts, presented in subsection 3.3.

Scenario 2 corresponds to the Kyoto Protocol. In scenario 1 industrial CO_2 emissions are fixed at the level of 1990 in the period following 2010.

Scenario 3 corresponds to a 10 years delay in the fulfillment of the Kyoto Protocole. In scenario 1 industrial CO_2 emissions are fixed at the level of 1990 in the period following 2020.

Scenario 4. This is scenario 1, in which deforestation and soil erosion stop in 1990.

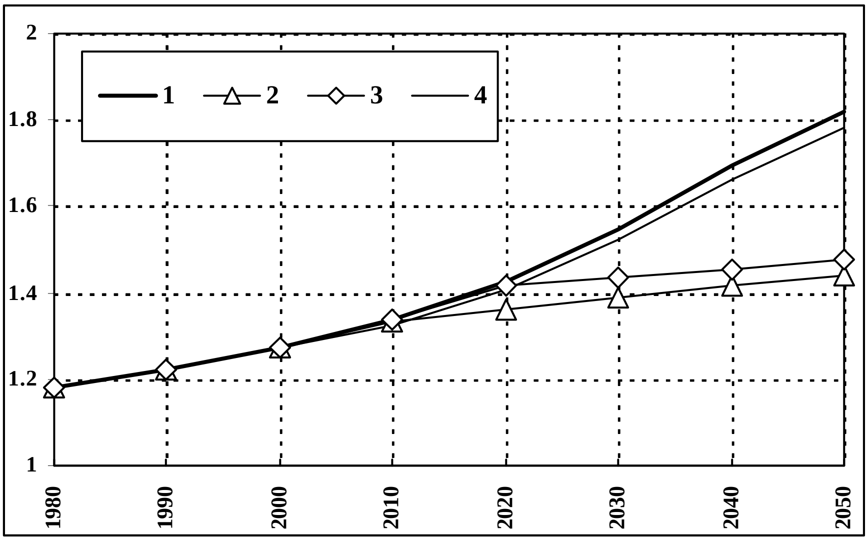


Figure 11. Results of simulation of the Kyoto Protocol scenario (scenario 2) and other CO_2 emission reduction scenarios. The dynamics of the values of carbon in the atmosphere are shown relative to 1860.
In the legend, the figures designate scenarios.

It is obvious that restrictions on the emissions are effective. In scenario 1 the growth of CO_2 concentration in the atmosphere is significant: in 2050 it is 1.82 times more than in 1860. In scenario 2 (the Kyoto Protocol scenario) and in scenario 3 (the 10-years-delayed Kyoto Protocol scenario) the increase of the CO_2 concentration is much less: 1.47 and 1.56 times, respectively. We see that the 10 years delay in the implementation of the Kyoto Protocol does not result in a significant change in 2050. The termination of deforestation and soil erosion does not lead to a significant reduction of CO_2: in scenario 4, in 2050 CO_2 is 1.78 times more than in 1860. This effect in reduction of CO_2

(compared to scenario 1) is much weaker than the effect of the reduction of industrial emissions (scenarios 2 and 3).

Now we present results of our estimation of the consequences of the refusal of the USA to participate in the fulfillment of the Kyoto Protocol. We assume that all countries, except for the USA, fulfill the Kyoto Protocol. For 1860 − 1999, we use statistical data on industrial emissions of CO_2 (Marland, et al., 2002). As the fulfillment of the Kyoto Protocol begins in 2010, the model input data should include the rates of growth of CO_2 emissions in all countries in 2000 − 2010 and the rates of growth of CO_2 in the USA after 2010. We estimate these uncertain data as follows. We introduce two scenarios, A and B. In scenario A, we average the annual rates of growth of CO_2 releases over the 15 years period preceding 1999, and assume that the annual rate of growth of CO_2 releases in all countries in 2000 − 2010 equals this average growth rate (1.41% per year); we also assume that after 2010 the rate of growth of CO_2 releases in the USA equals its average rate in the 15 years period preceding 1999 (1.5% per year). In scenario B, we use the same method with the averaging period of 5 years prior to 1999; this estimates the growth rate as 0.77% per year for all the countries and 1.15% per year for the USA. For simulations, the above mentioned scenario of deforestation and soil erosion in 1860 − 2050 is also used.

We consider 4 sub-scenarios:

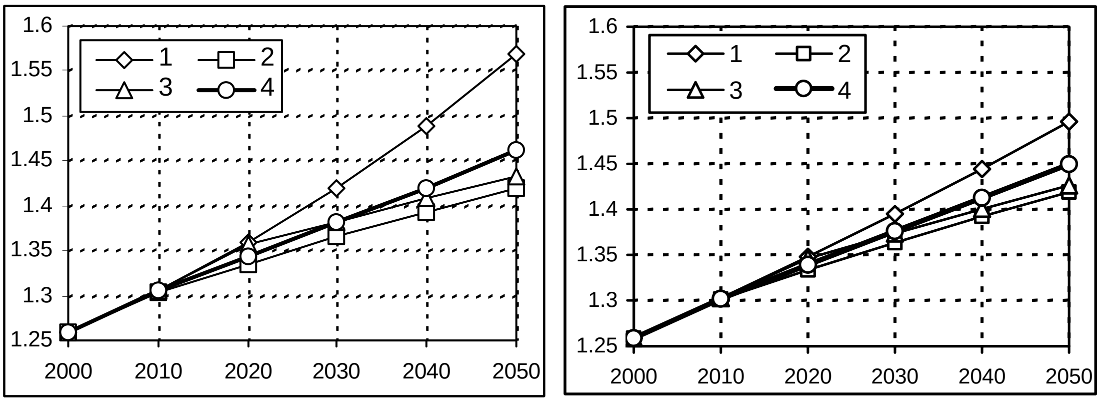
Sub-scenario 1. The countries do not fulfill the Kyoto Protocol, and the rate of growth of CO_2 emissions after 1999 is found through averaging its annual growth over the 15 years (scenario A) or 5 years (scenario B) preceding 1999.

Sub-scenario 2 corresponds to the Kyoto Protocol. In 2000 − 2009 the rate of growth of CO_2 emissions is modeled as in sub-scenario 1, and after 2010 the total industrial emissions fix at the level of 1990.

Sub-scenario 3 corresponds to a 10 years delay in the fulfillment of the Kyoto Protocole. In 2000 − 2019 the rate of growth of CO_2 emissions is modeled as in sub-scenario 1, and after 2020 the total industrial emissions fix at the level of 1990.

Sub-scenario 4 corresponds to the Kyoto Protocol fulfilled by all countries except for the USA. In 2000 − 2009 the rate of growth of CO_2 emissions is modeled as in sub-scenario 1; and after 2010 the total industrial emissions of all countries except for the USA fix at the level of 1990, whereas rate of growth of CO_2 emissions in the USA is found through averaging its annual growth over the 15 years (scenario A) or 5 years (scenario B) preceding 1999.

The simulation results are shown in Figure 12 and in Table 1.



Scenario A Scenario B

Figure 12. Results of simulation of 4 sub-scenarios of CO_2 emissions reduction, including sub-scenario 4, in which the USA do not fulfill the Kyoto Protocol. The dynamics of the values of carbon in the atmosphere are shown relative to 1860. In the legend, the figures designate sub-scenarios.

	Growth of atmospheric CO_2 by 2050			
Sub-scenario	Scenario A (15 years averaging)		Scenario B (5 years averaging)	
	times	ppm	times	ppm
1	1.568	455	1.496	434
2	1.420	412	1.419	412
3	1.433	416	1.426	414
4	1.461	424	1.450	421

Table 1. Increase of atmospheric CO_2 in 1860 – 2050.

We see that in scenarios A (15-years averaging) and B (5-years averaging), the situation where all countries disagree to fulfill the Kyoto Protocol (sub-scenario 1) implies that in 2050 the amount of CO_2 grows 1.57 (respectively, 1.5) times compared 1860. If the Kyoto Protocol is fulfilled by all countries (sub-scenario 2), the amount of CO_2 grows 1.42 and 1.419 times in scenarios A and B, respectively. The 10 years delay in the fulfillment of the Kyoto Protocol (sub-scenario 3) results in the increase of CO_2 1.433 and 1.426 times in scenarios A and B, respectively. Finally, in the case where the USA do not fulfill the Kyoto protocol the amount of CO_2 grows 1.46 and 1.45 times in scenarios A and B, respectively.

Thus, the decision of the USA not to participate in the Kyoto Protocol has a serious impact on the increase of CO_2 by 2050, whereas the fulfillment of the Kyoto Protocol by all other countries has a remarkable effect. In case the USA do not participate in the

Kyoto Protocol (sub-scenario 4), the relative gains in the increase of CO_2 in 2050 (compared to sub-scenario 1) are 28% and 40% under scenarios A and B, respectively. Note that 5-years world averaging (scenario B) reflects the effect of the reductions of the rates of CO_2 releases, which were made by major countries in 1995 – 1999 in view of the Kyoto Protocol. These reductions resulted in a relatively small growth of CO_2 during the 5 years preceding 1999. Accordingly, scenario B implies a relatively small growth of CO_2 until 2050, provided all countries fulfill the Kyoto Protocol (sub-scenario 2).

In addition, it is necessary to note that the given calculations are fair in case of the default of the Kyoto Protocol by one country only. In spite of the 15 years and 5 years statistics we can suppose that in the future the number of such countries will be increased. The Kyoto Protocol provides concrete constraints on the CO_2 releases for a few countries only and does not suggest them for many others. The recession of growth of CO_2 emissions, achieved in several recent years was determined by the economic development in several advanced countries and also in countries with transition economy (Russia, Ukraine, et. al.). In several countries, which are not well developed economically and which have large population and large natality of population (Table 2), the rates of growth of industrial CO_2 emissions vary from 3.3% to 6.9% per year, which is high enough. In these countries the efficiency of the transformation of energy from burning of fossil fuels to electricity and other kinds of energy use are significantly lower than in the developed countries.

	Duration of the averaging period preceding 1999	Average growth of CO_2 releases (percent/ year)	Real gross domestic product per capita growth, percents/year in 1997	Population, million persons in 1997	Natality, percent/ year in 1997	Time of population doubling, years
India	5	5.0	3.2	967.1	1.78	41
Indonesia	5	4.5	2.4	209.8	1.53	47
Brazil	5	5.1	1.6	167.7	1.35	53
Pakistan	5	3.3	0.8	132.2	2.25	33
Bangladesh	5	6.9	3.6	125.3	1.84	40
Nigeria	4	6.5	0.2	107.3	3.07	24
Mexico	3	3.9	5.4	96.8	1.83	40

Table 2. The average annual growth of CO_2 releases, growth of gross domestic product per capita and natality in several countries

Therefore, one can not deny a scenario, according to which in 10 – 30 years in these and similar countries the rate of economic development and the population size will become so high that the countries will have no alternative to forcing CO_2 emissions; accordingly, they will have to reject the constraints of the Kyoto Protocol. As a result, the world's rate of CO_2 releases may exceed the 3% annual growth rate that was assumed in the simulated scenario described above. Presently, the developed countries can make an important contribution to the development of other countries and, accordingly, the world development for decades if they provide other countries with advanced technologies. In this case the widely discussed trade off on the quotas of CO_2 emissions within the framework of the Kyoto Protocol could be helpful.

Summarizing, we can note that the above 15-years and 5-years averaging scenarios provide a useful information on the possibilities of future development; however, one should always remember that the real global development is extremely complex and the distortion of the forecasts is very probable (in the previous paragraph, we outlined one of possible distortion mechanisms).

3.7 Application of control theory

In the analysis of anthropogenic impacts on the biosphere, it is important not only to identify consequences of different economic strategies but also to estimate a "price" for reaching desired values of biosphere parameters. Let us, for example, consider a problem of reaching a constant level of atmospheric CO_2 within a given time horizon; the problem includes finding a corresponding integral value of industrial CO_2 releases. For this purpose methods of control theory can be used. An application of a control-theoretic technique, with scenario 1 in the basis, leads to a conclusion that stabilization of the level of CO_2 in the atmosphere after 2000 requires a significant reduction of emissions; the corresponding numerical results are shown in Figure 13.

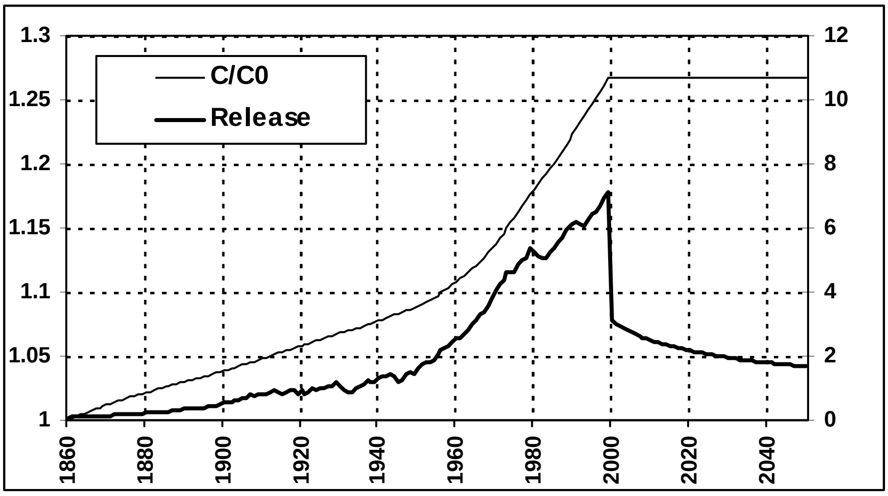


Figure 13. Industrial releases (right axis, Gt C/year), at which the concentration of CO_2 in the atmosphere (the left vertical axis, relative units) remains constant after 2000. The basic scenario of industrial releases, deforestation and soil erosion is used for period 1860-1999.

3.8 Le Chatellier principle and stability of the biosphere. Sustainable development of the biosphere

The stability of steady states of a multi-dimensional model can be verified via a numerical analysis of the sensitivity of model's trajectories to the choice of initial values of its state variables. For the APS model discussed here, this kind of analysis shows that the model's steady states are stable and there are no fluctuations in the system. However, Lyapunov's stability of the steady states is not the unique characteristic property of the biosphere. The analysis of the stability of the biosphere includes also the identification of a degree, to which the biosphere is able to compensate the impact of antropogenic inputs.

The Le Chatellier principle well-known in physics and in chemistry claims that an external action that removes a system from its steady state gives rise to processes within the system, that tend to weaken the results of this action. It is natural to apply this principle to global ecology. A.M. Tarko suggests the following approach to the analysis of the validity of the Le Chatellier principle for matter conserving systems such as the global carbon cycle in the biosphere. It is supposed that a matter conserving system is described by a system of ordinary (generally, nonlinear) differential equations. The Le Chatellier principle is treated as the fulfillment of the following condition for the state variables X_l:

$$0 < dX_l^* / dM < 1. \qquad (5)$$

Here l is number of a state variable, M is the total amount of matter in the system, and * designates the steady state. The fact that the system is matter conserving implies that the total amount of matter in it is constant provided there are no internal sources of matter in the system: $\sum_1^n X_i = M = const.$ A less restrictive condition (necessary for (5)) is

$$0 < dX_i^* / dM, \quad i = 1,...,n. \qquad (6)$$

Here n is the number of the state variables. This understanding of the Le Chatellier principle allows one to verify its validity for a multi-dimensional system using a relatively simple numerical test: for every state variable, one increases instantly its steady state value and checks whether the steady state values of all other variables increase. Another form of the Le Chatellier principle, which is equivalent to (6), is that for all state variables one has

$$dX_i^* / dX_j^* > 0, \quad i, j = 1,..., n, \quad i < j. \qquad (7)$$

A geometrical interpretation of (7) is that the curve of system's steady states "grows" on the $\{X_i, X_j\}$ plane; if this is not so, the Le Chatellier principle is violated. It should be noted that the above defined Le Chatellier principle is a stronger requirement than Lyapunov's stability: a system stable in its steady state may not satisfy the Le Chatellier principle.

An analysis of model (3), involving simulations and employing a linear form of the dependence of annual production on the quantity of CO_2 in the atmosphere shows that the Le Chatellier principle is valid for the system. However, the higher is the concentration of CO_2 in the atmosphere, the less is known about the dependence of annual production on the quantity of CO_2 in the atmosphere. The increase of the quantity of CO_2 in the atmosphere leads to a nonlinear dependence of annual production on it. Moreover, laboratory experiments show that at high concentrations of atmospheric CO_2 the depression of photosynthesis is possible.

Now we present results of the implementation of two complementary modeling techniques for period 1860 – 2100. The first technique uses a linear dependence of the growth of annual production on the quantity of CO_2 in the atmosphere (see (3)), and the second one uses a nonlinear dependence (see (4)). The application of the first technique (Figure 14 A) allows us to state the validity of the Le Chatellier principle. The application of the second technique shows that after 2050 the Le Chatellier principle can be violated, terrestrial ecosystems can become a source of CO_2 and the quantity of CO_2 in the atmosphere can grow significantly (Figure 14 B).

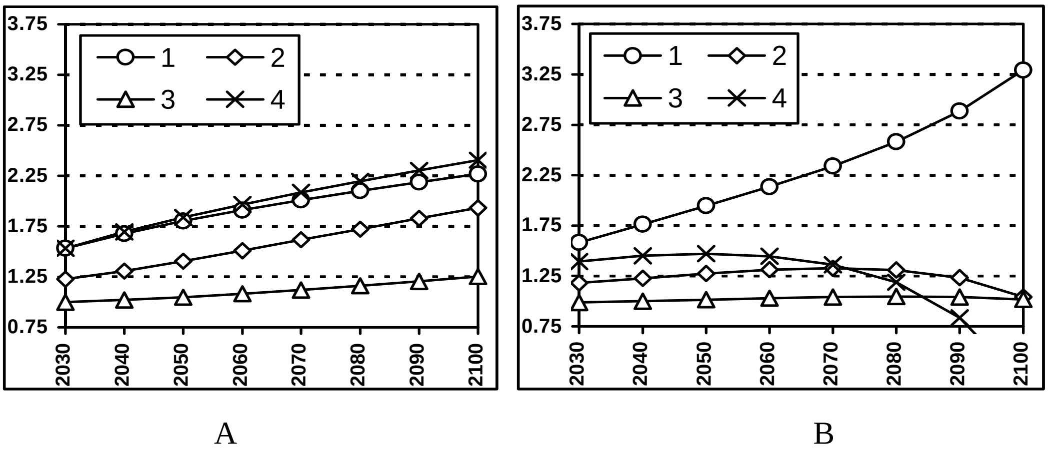


Figure 14. The simulated carbon dynamics (relative units) in the atmosphere (1), phytomass of plants (2), humus (3) and annual production (4) in 1860 – 2100. In cases A and B the dependence of annual production on the quantity of CO_2 is linear and nonlinear, respectively

Thus, with the present uncertainty in knowledge on the terrestrial plants production process, we can conclude that within a small neighborhood of the present state the Le Chatellier principle is valid, whereas at states relatively far-distant from the present one the Le Chatellier principle can be either valid or violated. It should be mentioned that the Le Chatellier principle can be viewed as a criterion of sustainable development of the biosphere: if the Le Chatellier principle is fulfilled, the sustainable development of the biosphere is ensured and otherwise it is violated.

4.Conclusion

Presently, a number of scientific programs are aimed to solving fundamental and applied problems of ecology and mathematical ecology. In these programs a number of novel experimental methods of research are implemented. The complexity of experimental studies and modeling techniques is growing rapidly.

Mathematical modeling biogeochemical cycles is an efficient tool to explore consequences of various large-scale anthropogenic influences on the biosphere. It opens a possibility to estimate the contribution of terrestrial ecosystems and the ocean in the absorption of carbon dioxide from the atmosphere. The modeling approach presented in this paper shows that forest ecosystems and the ocean act as strongest CO_2 absorbers at moderate latitudes of the Northern hemisphere. A strong advantage of global models of the carbon dioxide cycle is that they enable to estimate feedbacks between global climate change including change in the concentration of CO_2 in the atmospheric and processes in terrestrial ecosystems and the ocean. Despite some uncertainty in the understanding of a causal relation between global warming and CO_2 growth, the idea of stabilization of the quantity of CO_2 in the atmosphere is on the way to the practical realization, which reflects one of the fundamental cares of mankind: sustainable development.

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