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DISCUSSIONS

Role of the Biosphere in the Formation of the Earth's Climate: The Greenhouse Catastrophe

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Abstract - An analysis is undertaken to reveal the role that various processes in living and nonliving nature play in the establishment of the chemical composition of the atmosphere and the temperature balance of the Earth. An inference is made that the biospheric mechanisms of CO_2 removal from the atmosphere are insufficient in the situation of the current anthropogenic impact and the existence of potentially dangerous CO_2 sources in nonliving nature, which may be activated with the increase in the Earth's average temperature. It is shown that the sustainability of natural systems responsible for the maintenance of the chemical composition of the atmosphere is itself impaired as the human activity destroys climate-forming biocenoses. This can lead to an irreversible change in the Earth's climate, with the result that the Earth's average temperature would rise to 100–150°C and above. This will render life on the Earth (at least in its present form) impossible. A radiative–adiabatic model of the greenhouse effect is constructed and used to make asymptotic estimates of the increase in the Earth's average temperature with varying concentration of greenhouse gases over a wide range. On the basis of this model, an integral model of the change in the Earth's climate is constructed, which takes into account the thermal inertia of the ocean and the aerosol pollution of the upper atmosphere. It is demonstrated that an irreversible (catastrophic) change in the Earth's climate (the greenhouse catastrophe) can take place in relatively near future - in 200–300 years.

Key words: biodiversity, climate-forming biocenoses, climate, modeling, greenhouse effect, greenhouse catastrophe, sustainable development

INTRODUCTION

The Earth's climatic system involves an enormous number of simultaneous processes. These processes occurring simultaneously in both living and nonliving nature have quite a diverse nature and differ greatly both in energy and spatiotemporal characteristics and in extent to which they are studied. The problem of modeling (and furthermore, control) of the climate seems to be virtually unsolvable. This work abandons a conventional modeling method, in which maximally detailed mathematical (numerical) models are attempted to be constructed from the very beginning.

A preliminary analysis of the cause-and-effect structure of the phenomenon under investigation proved to be surprisingly fruitful as applied to the climate modeling problem. This analysis revealed an hierarchy of processes and feedbacks in the system and thereby substantially simplified the problem at the step of mathematical modeling proper.

Proceeding to the description of the main results of the work, note that such a preliminary analysis of the cause-and-effect structure of the phenomenon can be useful not only at the step of modeling but also at the step of searching for ways of optimal control of complex phenomena involving a great number of simultaneous processes.

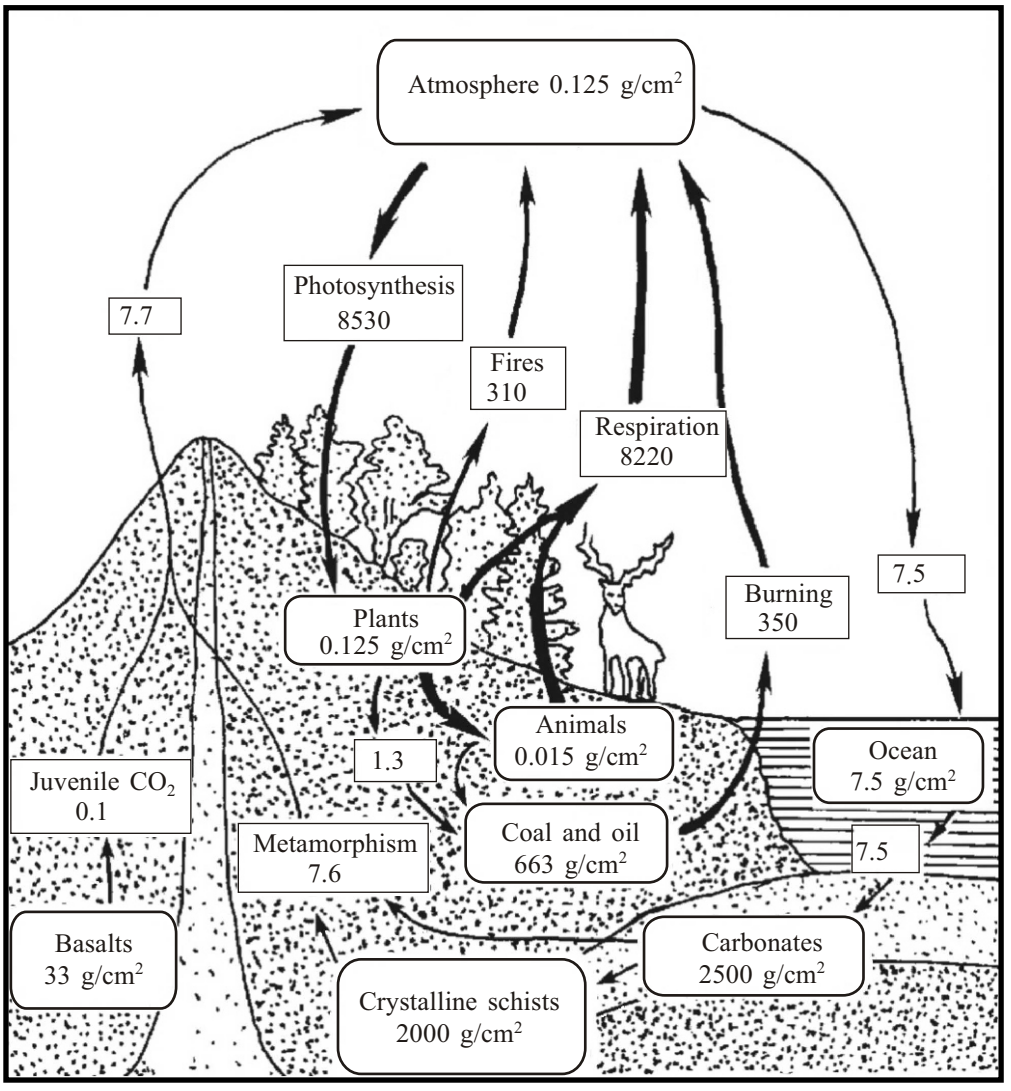

Fig. 1. Carbon cycle ($= 10^{-6}$ g per cm^2 per year).

ROLE OF VARIOUS PROCESSES IN THE FORMATION OF THE CHEMICAL COMPOSITION OF THE ATMOSPHERE AND THE TEMPERATURE BALANCE OF THE EARTH

Carbon cycle. Insufficiency of the biological mechanisms of CO_2 removal. Figure 1 shows the amount of carbon (per cm^2 of the Earth's surface) in various spheres of the Earth and the rate of its transfer between the main regions of its occurrence in terms of $= 10^{-6}$ g per cm^2 per year [1].

Note a dramatic (several orders of magnitude) insufficiency of the biological mechanisms of CO_2 removal from the atmosphere as compared to its anthropogenic emissions. Although the total photosynthetic production of organic substances is 8530 (in terms of carbon) and is much larger than the anthropogenic CO_2 emissions of 350 , most of organic carbon returns to the atmosphere in the form of CO_2 through respiration, decay, fires, etc. The difference between the rate of biogenic CO_2 fixation (through photosynthesis and the formation of carbonates) and the rate of release of CO_2 fixed by photosynthesis (through respiration, fires, etc.) is small and is only 8.8 , which is about 50 times lower than the rate of anthropogenic CO_2 emissions to the atmosphere. Unfortunately, many works (especially popular science publications) compare the total photosynthetic production of organic substances and the anthropogenic CO_2 emissions, which creates the illusion of a trivial reversibility of the current changes in the Earth's atmosphere.

The role of various biocenoses in the long-term CO_2 removal from the atmosphere was analyzed.

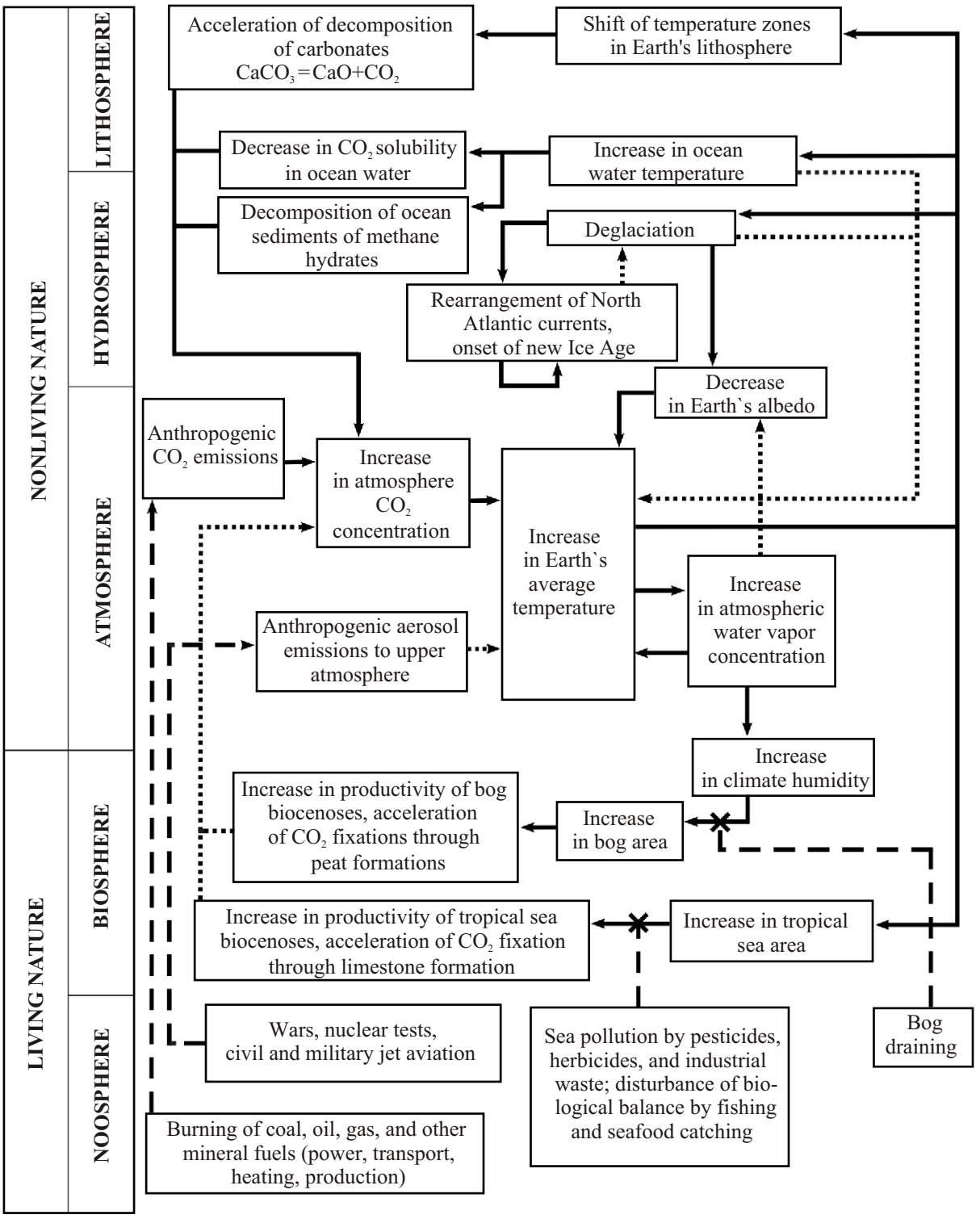

Fig. 2. Cause-and-effect diagram of the basic climate-forming processes.

Contrary to the popular opinion that "the forest is the lungs of the planet", the role of forest biocenoses in the long-term CO_2 fixation proved to be extremely small, because virtually all of the carbon fixed by photosynthesis returns to the atmosphere in the form of CO_2 through respiration, decay of dying leaves and wood, and also forest fires.

The long-term CO_2 removal from the atmosphere requires that much of the carbon fixed by photosynthesis be inaccessible for oxidation. Such

conditions take place only in bog biocenoses and tropical sea biocenoses (Fig. 2).

In bog biocenoses, dying plants fall into standing water with an extremely low dissolved oxygen content and are accumulated there with virtually no decay (the partial anaerobic decay to form methane does not change the overall pattern). Partially decayed plant debris accumulated in bogs produce peat seams, from which lignite and coal deposits form.

Over the last 100 years, the total bog area on the Earth has been almost halved and continues to decrease because of bog draining. Correspondingly, the rate of CO_2 removal from the atmosphere lowers. Note that bog draining is often accompanied by extinction of endemic species adapted to live only under definite conditions of certain bogs located in a specific climatic zone. Therefore, the restoration of the bog area is now associated not only with the difficulty of removing lands from agricultural use but also, in some cases, with the impossibility of restoring wholesome biocenoses.

In tropical sea biocenoses, the CO_2 removal from ocean water, to which CO_2 passes from the atmosphere, occurs somewhat differently. Carbon dioxide is used as a structural material by heterotrophic organisms in the formation of calcareous shells and coverings. Virtually all carbonates in the Earth's crust (limestones, dolomites, marble, chalk, etc.) are of biogenic origin. Among the most important climate-forming species are coral polyps and foraminiferal plankton (a total of about 80 species).

Unfortunately, the state of climate-forming tropical sea biocenoses has been studied poorly. There is fragmentary information on the death of coral reefs [2]. No systematic monitoring of the state of foraminiferal microplankton is performed, although one can assume that it is foraminiferal plankton that must be one of the components of the tropical sea biocenosis that are most sensitive to ocean dumping of pesticides and herbicides.

Since it seems unlikely that the rate of CO_2 removal from the atmosphere by the biological mechanisms can increase more than 50-fold (to compensate for the anthropogenic CO_2 emissions), processes in nonliving nature that affect the carbon dioxide concentration were analyzed to find mechanisms that maintain the stability of the chemical composition of the atmosphere and, consequently, the sustainability of the Earth's climatic system as a whole.

Greenhouse catastrophe. Role of natural (nonanthropogenic) CO_2 sources. Figure 2 presents a cause-and-effect diagram of the basic climate-forming processes. The arrows indicate the cause-and-effect relationships between processes: the solid arrows show the direct (stimulatory) effect and the dotted arrows represent the reverse (inhibitory) effect. The crisscrossed arrows indicate the cause-and-effect relationships that existed in the past but were broken (or weakened) by the anthropogenic impact (dashed arrows).

The analysis of processes in nonliving nature revealed no mechanisms of maintaining the stability of the chemical composition of the atmosphere (first of all, with respect to the CO_2 concentration). The found negative feedbacks between the CO_2 concentration and the Earth's average temperature were either simple damping (as, e.g., the thermal inertia of the ocean or the dissolution of an additional amount of CO_2 in ocean water with increasing CO_2 concentration in the atmosphere) or relatively weak feedbacks (the temperature–humidity–albedo feedback). An unusual negative feedback related to the rearrangement of North Atlantic currents can even lead to a temporary decrease in the average temperature in Northern Europe and America (a peculiar kind of another Little Ice Age) [3–5], but none of the revealed feedbacks is suitable to be the global stabilizing factor.

But then it proved that there are a lot of processes in nature that implement a positive feedback between the CO_2 concentration and the Earth's average temperature. In essence, these processes are related to natural (nonanthropogenic) sources of CO_2 emissions to the atmosphere, which are activated with the increase in the Earth's average temperature (Fig. 2). Of prime importance among such sources are the following:

(1) An increase in the ocean water temperature upon the change in the Earth's average temperature will cause a decrease in the CO_2 solubility in ocean water. The excess of carbon dioxide will enter the atmosphere. Since the amount of CO_2 in ocean water is at least 60 times higher than that in the current atmosphere, this CO_2 source is a great potential danger.

(2) Still larger amount of fixed CO_2 is contained in the Earth's crust (approximately 50 000 times

larger than in the Earth's atmosphere and about the same as in the Venus' atmosphere) in the form of carbonate-containing rocks (limestones, dolomites, marble, chalk, etc.). The decomposition of carbonates both due to a shift of temperature zones in the Earth's lithosphere upon the increase in the Earth's average temperature and due to the human impact on the Earth's crust (underground nuclear tests, drilling, etc.) can cause the release of enormous amounts of CO_2 to the atmosphere.

(3) Other potentially dangerous natural CO_2 sources are ocean sediments of methane hydrates. Methane hydrates are stable only at high pressures and low temperatures. An increase in the ocean bottom water temperature can lead to the decomposition of methane hydrates and the release of large amounts of methane and CO_2 to the atmosphere (through the methane oxidation by methane-oxidizing bacteria and the direct methane oxidation in the upper atmosphere). The amount of carbon in ocean sediments of methane hydrates is estimated at no smaller than 10 000 Gt, which is more than ten times larger than the amount of carbon in the atmosphere.

(4) There is a very strong positive feedback between an increase in the atmospheric water vapor concentration and an increase in the Earth's average temperature. Since water vapor is a greenhouse gas, an increase in the water vapor concentration causes a further increase in the Earth's average temperature.

As already noted, a common property of the above potential natural CO_2 sources is the strong positive feedback between the CO_2 concentration and the Earth's average temperature, which can lead to an avalanche-like increase in the CO_2 concentration in the atmosphere even in a case of total abandonment of the use of carbon-containing mineral fuels (coal, oil, gas). In circumstances of destruction of natural biosystems involved in the CO_2 removal from the atmosphere, this can cause an *irreversible* change in the chemical composition of the atmosphere and, consequently, in the Earth's climate. The scenario of such irreversible climatic changes caused by the increase in the CO_2 concentration was called the greenhouse catastrophe [6–10].

In crude summary, one can infer that, at present, there are no efficient mechanisms to limit the increase in the CO_2 concentration in the atmosphere. The relative stability of the climatic parameters is now due mainly to the inertia of the Earth's climatic system, specifically, due to the thermal inertia of the ocean and the existence of capacious reservoirs for greenhouse gases (the atmosphere, the ocean, and the biosphere).

In this context, it was of particular interest to estimate the possible changes in the basic climatic parameters and, first of all, the Earth's average temperature.

RADIATIVE–ADIABATIC MODEL OF THE GREENHOUSE EFFECT

Basing on the above, one can suppose that the increase in the CO_2 concentration in the atmosphere will continue in both near and distant future. This will necessarily lead to an increase in the Earth's average temperature.

Although the first reports on the possible role of greenhouse gases in the formation of the temperature balance of the Earth and other planets came out as far back as almost 150 years ago [11], the estimates of the dependence of the greenhouse effect on a change in the CO_2 concentration still differ almost tenfold (!!!): the increment T as the CO_2 concentration in the atmosphere is doubled is reported to be from T 1°C [12] to T 5°C (according to the Intergovernmental Panel on Climate Change (IPCC)). This difference is largely because of the necessity of making additional assumptions in conventional radiative–convective models [13].

The drawback of early radiative models and later radiative–convective models [13, 14] is the necessity of detailed calculations of the radiative and convective flows both in the atmosphere and in the atmosphere–land–ocean system. Computational difficulties in solving the strongly nonlinear three-dimensional problem are due not only to the limited memory and speed of present-day computers but also to the existence of fundamental (nonalgorithmic) instabilities in the system under investigation. Simplification of the problem, which is inevitable for such systems, leads to uncontrolled loss of accuracy of the final results.

The purpose of this study was to construct an *analytical model* of the greenhouse effect that would give reliable estimates within an accuracy of at least 50% over wide ranges of the concentration of greenhouse gases and the Earth's average temperature. This

model was called the radiative–adiabatic model of the greenhouse effect.

The main difference of this model from conventional radiative–convective models of the greenhouse effect is that the role of convective phenomena is restricted to the formation of the so-called adiabatic temperature gradient T(z) in the lower, radiative atmosphere (the troposphere):

$$T(\mathrm{z}) = T_0 \quad {}_{\mathrm{A}}\mathrm{z}, \tag{1}$$

where T_0 is temperature on the surface of a planet (e.g., the Earth) and z is the altitude above the planet's surface.

This assumption can be considered justified, since the adiabatic temperature gradient, which is due to vertical movements of air masses, depends weakly on specific dynamic parameters of such movements and, over a wide range of these parameters, is determined by the physicochemical composition of the atmosphere and the acceleration of gravity near the planet's surface:

$${}_{\mathrm{A}} = \frac{g}{C_p} = (9.8 \quad 10^{\ 3})\,\mathrm{deg/m} \qquad 0\,\mathrm{deg/km}. \tag{2}$$

Here, g is the acceleration of gravity (for the Earth, $g = 9.8$ m/s^2), C_p is the specific heat at constant pressure of the gas phase of the atmosphere (for the Earth, $C_p = 1.00 \quad 0^3$ J/(kg deg)), and is a coefficient determined by the air humidity and the content of water aerosols in the air. For dry air, $= 1$. In the general case, is always smaller than 1 (tropical deserts) and, as a rule, larger than 0.6 (the equatorial belt). The adiabatic gradient exists on all the planets of the solar system that have atmosphere and is sufficiently accurately described by expressions (1) and (2).

If the distribution of gases in the planet's atmosphere is known and is ${}_i$(z) and if the spectral properties of each of the greenhouse gases are also known ($a_i(\ )$ are the spectral absorptivities (emissivities)), then one can readily write the expression for the power spectrum of the thermal (long-wavelength) radiation of an atmospheric element located at a certain altitude z into the surrounding space:

$$W^{\mathrm{rad}}(\ ,\mathrm{z}) = \widetilde{W}^{\mathrm{rad}}(\ ,\mathrm{z})A^{\mathrm{abs}}(\ ,\mathrm{z}). \tag{3}$$

Here,

$$\widetilde{W}^{\mathrm{rad}}(\ ,\mathrm{z}) = \quad {}_i\, a_i(\ )\ {}_i(\mathrm{z})\ \frac{2 \quad {}^3}{c\exp\dfrac{h}{kT(\mathrm{z})}} \tag{4}$$

is the power spectrum of the "primary" radiation of the atmospheric element located at the altitude z and

$$\mathrm{A}^{\mathrm{abs}}(\ ,\mathrm{z}) = \exp \quad {}_i\, a_i(\ ) \quad {}_{\mathrm{z}}\ {}_i(\ )d \tag{5}$$

is the absorptivity of the overlying atmospheric layers. The coefficient $a_i(\ )$ characterizes both emissivity and absorptivity of the ith greenhouse gas (according to Kirchhoff's radiation law), and h is a coefficient, which depends on the dimensionality of the model (in a three-dimensional spherically symmetrical (quasi-one-dimensional) case, one must additionally perform integration with respect to solid angle over the upper hemisphere). The function ${}_i$(z) describes the change in the density of the ith greenhouse gas with altitude. Under the assumption that the atmosphere is isothermal, the density of most greenhouse gases varies with altitude z according to the barometric formula

$${}_i(\mathrm{z}) = {}^0_i \exp \quad \frac{{}_{\mathrm{air}} m_{\mathrm{H}} g}{kT_{\mathrm{eff}}}\mathrm{z} \tag{6}$$

where ${}_{\mathrm{air}}$ 29 is the average molecular weight of air, $m_{\mathrm{H}} = 1.67 \quad 0^{-27}$ kg is the atomic weight of hydrogen, k is the Boltzmann constant, ${}^0_i$ is the density of the ith greenhouse gas at sea level (on the planet's surface), and T_{eff} is the so-called effective atmospheric temperature.

There are a number of greenhouse gases to which the barometric formula (6) is fundamentally inapplicable. The concentration of some of these gases, e.g., ozone, depends on chemical reactions in the atmosphere and varies with altitude in a complex way. The concentration of the others, among which is such an important greenhouse gas as water vapor, is determined by condensation and evaporation. The variation of the water vapor concentration in the atmosphere is mainly governed by the ambient air temperature, which, in turn (according to the radiative–adiabatic model), linearly depends on the altitude z:

$${}_{\mathrm{H_2O}}(\mathrm{z}) = {}^{\mathrm{H_2O}}(T(\mathrm{z})) = r\,{}^{\mathrm{H_2O}}(T_0 \quad {}_{\mathrm{A}}\mathrm{z}). \tag{7}$$

According to available estimates [4], the largest (95%) contribution to the thermal radiation of the Earth is made by the atmosphere, where the main role is played by two greenhouse gases, carbon dioxide CO_2 and water vapor H_2O. Therefore, virtually without loss of generality, basing on expressions (1)–(7), one can write the expression for the total power of the thermal radiation of the Earth into the surrounding space:

$$W^{\mathrm{rad}}(\ {}^{\mathrm{CO_2}}_{0}, T_0) = \quad dz\,d\ W^{\mathrm{rad}}(\ {}^{\mathrm{CO_2}}_{0}, T_0, \ , \mathrm{z}) =$$

$$= \quad dz\,d\ \frac{2\ h\ ^3}{c \exp \dfrac{h}{kT(\mathrm{z})}}\ a^{\mathrm{CO_2}}(\ )\ {}^{\mathrm{CO_2}}_{0} \exp \quad \frac{{}_{\mathrm{air}}m_{\mathrm{H}}g}{kT_{\mathrm{eff}}}\mathrm{z}\ + a^{\mathrm{H_2O}}(\ )\ {}^{\mathrm{H_2O}}(T_0 \quad g_{\mathrm{A}}\mathrm{z}) \tag{8}$$

$$\exp \quad a^{\mathrm{CO_2}}(\ )\ {}^{\mathrm{CO_2}}_{0}\ \frac{kT_{\mathrm{eff}}}{{}_{\mathrm{air}}m_{\mathrm{H}}g} \exp \quad \frac{{}_{\mathrm{air}}m_{\mathrm{H}}g}{kT_{\mathrm{eff}}}\mathrm{z} \quad a^{\mathrm{H_2O}}(\ )\ d \quad {}^{\mathrm{H_2O}}(T_0 \quad {}_{\mathrm{A}}\ )$$
$$\mathrm{z}$$

The condition for the radiation balance in thermodynamic equilibrium requires that the power of the radiation incident on the planet be equal to the power of the radiation emitted by the planet:

$$W^{\mathrm{inc}} = \frac{(1 \quad)S}{4} = W^{\mathrm{rad}}(\ {}^{\mathrm{CO_2}}_{0}, T_0) = \mathrm{const}, \tag{9}$$

where the solar constant S and the albedo a of the planet are assumed constant.

Thus, the condition that the power of the thermal radiation emitted by the planet into the surrounding space is constant gives a formal analytical solution of the problem on the relationship between small increments in the CO_2 concentration and the Earth's average temperature:

$$dW^{\mathrm{rad}} = \frac{W^{\mathrm{rad}}(\ {}^{\mathrm{CO_2}}_{0}, T_0)}{{}^{\mathrm{CO_2}}_{0}} d\ {}^{\mathrm{CO_2}}_{0} + \frac{W^{\mathrm{rad}}(\ {}^{\mathrm{CO_2}}_{0}, T_0)}{T_0}\mathrm{dT}_0$$

$$0 \quad dT_0 = \quad \frac{W^{\mathrm{rad}}(\ {}^{\mathrm{CO_2}}_{0}, T_0)}{{}^{\mathrm{CO_2}}_{0}} \Big/ \frac{W^{\mathrm{rad}}(\ {}^{\mathrm{CO_2}}_{0}, T_0)}{T_0}\ d\ {}^{\mathrm{CO_2}}_{0}. \tag{10}$$

At first glance, it seems that one has to surmount great computational difficulties to obtain the final analytical expression for $T_0(\ {}^{\mathrm{CO_2}}_{0})$. However, there exists a special translation–dilatation group of transformations of the parameters T_0 and ${}^{\mathrm{CO_2}}_{0}$ under which the function $W^{\mathrm{rad}}(\ {}^{\mathrm{CO_2}}_{0}, T_0)$ is invariant:

$$\begin{aligned} {}^{\sim\mathrm{CO_2}}_{0} &= \quad {}^{\mathrm{CO_2}}_{0}, \\ \widetilde{T}_0 &= T_0 + \ {}_{\mathrm{A}}H_0 \ln(\ ). \end{aligned} \tag{11}$$

Here, ${}_{\mathrm{A}} = g/C_{\mathrm{p}}$ 8 deg/km is the (Earth-)average adiabatic gradient and $\mathrm{H}_0 = kT/(\ {}_{\mathrm{air}}m_{\mathrm{H}}g)$ is the altitude at which the air density decreases by a factor of e. Therefore, actually, the application of this group almost immediately yields the analytical expression for the differential greenhouse effect (furthermore, the expression is directly obtained in an integral form for arbitrarily large changes ${}^{\mathrm{CO_2}}_{0}$ in the carbon dioxide concentration):

$$T = gH_0 \ln \ \frac{{}^{\mathrm{CO_2}}_{0} + \quad {}^{\mathrm{CO_2}}_{0}}{{}^{\mathrm{CO_2}}_{0}}$$

$$59\ \mathrm{K} \ \ln \ \frac{{}^{\mathrm{CO_2}}_{0} + \quad {}^{\mathrm{CO_2}}_{0}}{{}^{\mathrm{CO_2}}_{0}} \tag{12}$$

This result allows a simple and vivid interpretation, which demonstrates the physical meaning of the translation–dilatation symmetry (11) for the power $W^{\mathrm{rad}}(\ {}^{\mathrm{CO_2}}_{0}, T_0)$ (8) of the thermal radiation of the planet. Indeed, one can readily see that transformations (11) are in essence equivalent to the following change of variables in expression (8):

$$\begin{aligned} \mathrm{z} &= \mathrm{z} + H_0 \ln \\ &= \quad + H_0 \ln \end{aligned} \tag{13}$$

which can be interpreted as a shift of the basic characteristics of the atmosphere along the altitude axis by the quantity

$$H_0 \ln \quad = H_0 \ln \ \frac{{}^{\mathrm{CO_2}}_{0} + \quad {}^{\mathrm{CO_2}}_{0}}{{}^{\mathrm{CO_2}}_{0}} \tag{14}$$

To test the validity of the expressions derived, the radiative–adiabatic model was used to evaluate the greenhouse effect on the Venus. Such an application of the model is quite correct, because in constructing this model, no additional assumptions were made that would restrict the applicability of this model to the Earth's atmosphere only. Indeed, it is known that the CO_2 density near the Venus' surface is more than five orders of magnitude higher than that

near the Earth's surface ($^{CO_2}_{0V}/\ ^{CO_2}_{0E}$ 1.2 10^5). From this fact, one can easily calculate the altitude H_{0V} at which the CO_2 density in the Venus' atmosphere equals the CO_2 density in the Earth's radiative atmosphere. Under the assumption that the atmosphere is isothermal, H_{0V} 75 km. Knowing the adiabatic gradient in the Venus' atmosphere ($^{A}_{V} = 8.9$ deg/km), one can estimate the absolute value of the greenhouse effect at

$$T_{0V} = \ ^{A}_{V} H_{0V} = 670 \text{ K}. \qquad (15)$$

The really observed greenhouse effect on the Venus is $T = 500$ K, which is only 25% lower than the calculated value. Such an accuracy can be regarded as a success in view of such large differences in the CO_2 concentrations (10^5), the albedos, and other physicochemical parameters between the Earth and Venus' atmospheres.

Moreover, the radiative–adiabatic model allowed one to analyze the error in the main result (12). This error is an inevitable consequence of the simplifications made. One can easily show that the maximal estimated error in the result for the Earth does not exceed 37% of the differential greenhouse effect:

$$T \quad 59 \quad 22\text{K} \ \ln \frac{^{CO_2}_{0} + \ ^{CO_2}_{0}}{^{CO_2}_{0}} \qquad (16)$$

This error is due to the neglect of the contribution of the Earth's surface to the total thermal radiation of the Earth, the dependence of the Earth's albedo on the Earth's average temperature, the difference of the really observed adiabatic gradient in the Earth's atmosphere from its average, and the contributions of "minor" greenhouse gases. One can demonstrate that taking into account the nonisothermal character of the Earth's atmosphere and also the latitudinal distributions of the temperature and the humidity over a wide range only insignificantly affects the final result.

At the same time, the differential greenhouse effect caused by the anthropogenic increase in the CO_2 concentration in the Earth's atmosphere is estimated by the radiative–adiabatic model at

$$T(30\% \ \ CO_2) = (15.5 \quad 6)\,\text{K}, \qquad (17)$$

where 30% is the said anthropogenic increase throughout the industrial stage of the development of the human civilization. This estimate not only exceeds estimates made in other works but also is almost ten times greater than the really observed increase in the Earth's average temperature for the last 300–400 years. However, there is no contradiction here at all. The estimates made by the radiative–adiabatic model are asymptotic; i.e., they do not take into account the thermal inertia of the Earth's climatic system, first of all, the thermal inertia of the ocean, which decreases the rate of change in the Earth's average temperature. It will be shown below that taking into account the thermal inertia of the ocean not only ensures agreement between the theoretical and observed values of the resultant increase in the Earth's average temperature but also gives a detailed representation of the real temperature variation in the XX century.

MODEL OF THE CHANGE IN THE EARTH'S CLIMATE WITH REGARD FOR THE THERMAL INERTIA OF THE OCEAN AND THE AEROSOL POLLUTION OF THE UPPER ATMOSPHERE

An integral model describing the dynamics of the Earth's average temperature with regard for the results obtained by the radiative–adiabatic model of the greenhouse effect can be written as

$$\frac{dT(t)}{dt} = \frac{1}{\ _{in}} \ T_0 + 37\,\text{K} \ \ln \frac{^{CO_2}_{0}(t)}{^{CO_2}_{0}} \qquad T_A(t) \quad T(t) \qquad (18)$$

Here, $T(t)$ is the time variation of the Earth's average temperature; $_{in}$ is the relaxation time of the Earth's climatic system, which is determined by the total thermal inertias of the ocean, glaciers, and land; T_0 and $^{CO_2}_{0}$ are the initial (preindustrial) values of the Earth's average temperature and the CO_2 density, respectively; $^{CO_2}_{0}(t)$ is the time variation of the CO_2 density; and $T_A(t)$ is the time variation of the thermal forcing due to the aerosol pollution of the upper atmosphere (the stratosphere).

Note that, in expression (18), the temperature forcing

$$T(\ ^{CO_2}_{0}(t)) = 37\text{K} \ \ln \frac{^{CO_2}_{0}(t)}{^{CO_2}_{0}} \qquad (19)$$

due to the greenhouse effect is estimated using the coefficient corresponding to the lower limit of the confidence interval (16).

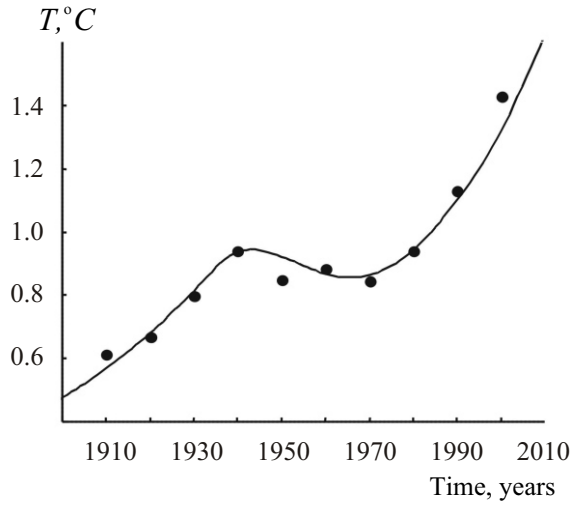

Fig. 3. Results of modeling the increase in the Earth's average temperature in the period 1900–2010. Points represent observed data. Note a good agreement between the observed data and the modeling results.

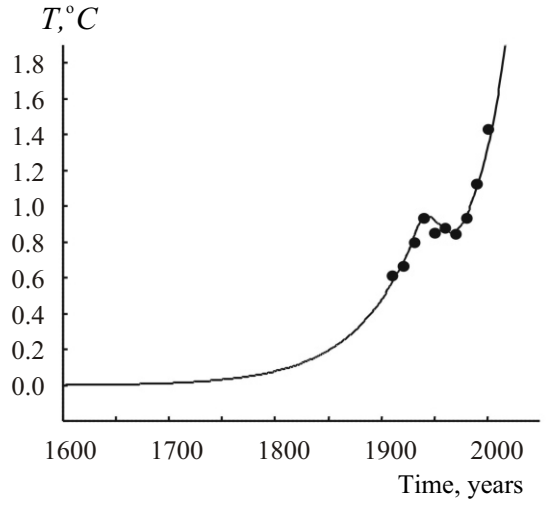

Fig. 4. Results of modeling for the period 1600–2050. Total increment in the Earth's average temperature as compared with the preindustrial age (1600–1700) according to the constructed model is 1.3 K, which agrees well with paleoclimatic data obtained by analysis of the mountain glaciation dynamics and some other methods.

The time variation ${}^{CO_2}_{0}(t)$ of the CO_2 density from the beginning of the industrial age to the present day is well approximated by the exponential function of time:

$$ {}^{CO_2}_{0}(t) = {}^{CO_2}_{0}\ 1 + 0.3 \exp \frac{t - t_{pr}}{t_{CO_2}} \qquad (20) $$

where t_{pr} is the year 2000 and $_{CO_2}$ 45 years, which corresponds to the annual increase in the CO_2 emissions by 2.25%. Possible measures to limit the CO_2 emissions to the atmosphere may lead to replacement of the exponential increase in the CO_2 concentration by a linear increase therein. Let us consider three scenarios of the increase in the CO_2 concentration in the Earth's atmosphere:

(1) the exponential increase in the CO_2 concentration persists (expression (20)),

(2) the CO_2 emissions are stabilized in the year 2000 at the 2000 level (the increase in the CO_2 concentration becomes linear), and

(3) the CO_2 emissions are stabilized in the year 2100 at the 2100 level.

The importance of taking into account the aerosol pollution of the upper atmosphere (the stratosphere) for estimating the change in the Earth's average temperature was noted as early as 1974 by Budyko [15]. Later, interest in this problem has considerably grown in connection with investigation of the "nuclear winter" phenomenon [16].

Let us describe the anthropogenic aerosol pollution of the upper atmosphere by the following function

$$ T(t) = \begin{cases} 0 \text{ before the year 1939,} \\ T_A \text{ before in the year 1939 and after.} \end{cases} \qquad (21) $$

That is, it assumed that the anthropogenic aerosol pollution of the upper atmosphere does not take place before 1939, jumped in 1939, and remains unchanged until now.

This assumption is justified by the fact that carbon black aerosols (which are most optically active) can arrive at the stratosphere only as a result of the formation of a tropospheric channels a powerful upward airflow transferring aerosol particles immediately to the stratosphere (as being condensation nuclei, aerosols entering the lower troposphere are quite rapidly washed down from the atmosphere by rains).

Before 1939, carbon black and dust particles arrived at the stratosphere only due to natural processes, such as volcanic eruptions. After 1939, the situation has changed. During the World War II, fires in towns, oil storage facilities, etc., created conditions for the formation of tropospheric channels and the arrival of carbon black aerosols in the atmosphere. After the end of the World War II, the main source of the aerosol solution of the stratosphere became atmospheric nuclear tests and, after their prohibition, civil flights in the tropopause. Indeed, carbon black particles

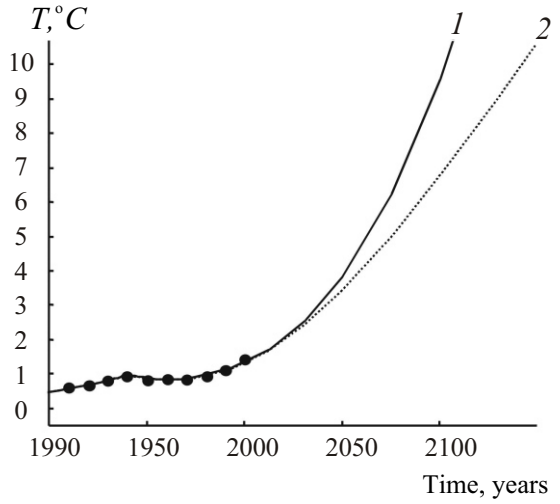

Fig. 5. Prediction of the increase in the Earth's average temperature for the period to the year 2100 (1) if the current increase in the CO_2 concentration in the atmosphere persists and (2) if an international convention of stabilization of the anthropogenic CO_2 emissions to the atmosphere at the 2000 level comes into effect. The modeling results (the increase in the temperature by 5–8 K by the year 2100 as compared with the current value) agree satisfactorily with the results of other studies.

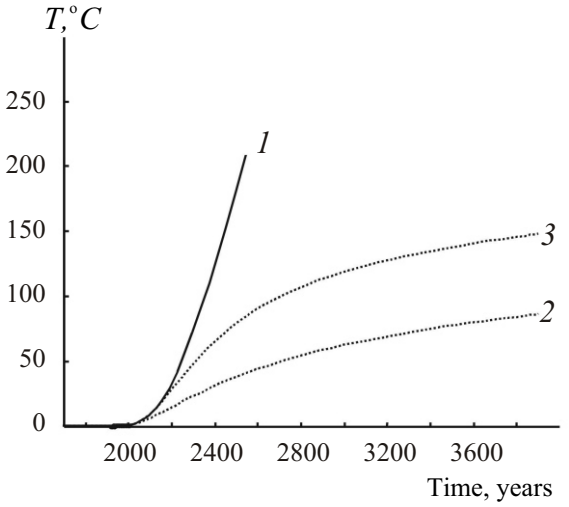

Fig. 6. Results of modeling the change in the Earth's average temperature for the period to the year 4000 (1) if the current increase in the CO_2 concentration in the atmosphere persists and if the anthropogenic CO_2 emissions are stabilized at the (2) 2000 or (3) 2100 level.

forming in the fuel combustion in airplane jet engines directly enter the stratosphere.

Thus, the step form of $T_A(t)$ as a function of time seems to be quite justified. Unfortunately, available information is insufficient to estimate the T_A value, as well as to directly calculate the relaxation time $_{in}$ of the Earth's climatic system, because this requires, in fact, a total reconstruction of the three-dimensional pattern of ocean currents.

Thus, the model involves two free parameters, $_{in}$ and T_A, whose values are fitted by collating the modeling results with the real temperature trend $T_{obs}(t)$ in the instrumental observation period (1900–2000). By minimizing the root-mean-square deviation between the observed [17] and theoretical temperatures:

$$\sum_{t_i=1900}^{2000} (T_{obs}(t_i) \quad T(t_i))^2 = \min, \qquad (22)$$

one can make numerical estimates of the parameters that characterize the inertia of the Earth's climatic system ($_{in}$ 200 years) and the thermal forcing due to the aerosol pollution of the upper atmosphere (T_A 5 K). Note that the relaxation time $_{in}$ 200 years is here a "renormalized" value, which takes into account that two greenhouse gases, CO_2 and H_2O, are considered.

The modeling results are presented in Figs. 3–6 (in all the figures, along the abscissa is the increment in the Earth's average temperature as compared with the preindustrial age (the year 1600)).

One can readily see that the resultant increase in the Earth's average temperature can amount to tens and hundreds of degrees (even if the anthropogenic CO_2 emissions are stabilized). Note that Fig. 6 presents an "optimistic" variant of the change in the Earth's average temperature. Firstly, this is because the modeling uses the asymptotic estimate (19) of the greenhouse effect that corresponds to the lower limit of the confidence interval (16). And secondly, the model does not as yet take into account the positive feedbacks between the temperature and the CO_2 concentration in the atmosphere, which can lead to an avalanche-like increase in the CO_2 concentration in the atmosphere and still more greatly narrow the time limits for the conditions appropriate for the existence of life and the human civilization on the Earth.

CONCLUSION

The results of this work suggested an unprecedented danger related to the increase in the Earth's average temperature because of the greenhouse effect.

The irreversible change in the Earth's climate can be prevented only by taking a complex of measures, such as:

(1) environmental measures, first of all, control and conservation of climate-forming biocenoses (including the use of cryoconservation methods);

(2) limitation and, in the future, total abandonment of recovery and burning of mineral fuels (coal, oil, gas);

(3) "conversion of the power industry"s a gradual transition to renewable energy sources (hydro, wind, and solar power), including wood to be used both as firewood and as a raw material for organic fuel production;

(4) measures aimed at increasing the area (and biomass) of forests to fix the excess of CO_2 in the atmosphere (for a while) and to extend the range of raw materials used in the "forest power" industry;

(5) artificial removal of CO_2 from the atmosphere, e.g., by burial of carbon-containing waste, including household garbage; and

(6) control of the solar radiation incident on the Earth by constructing spaceborne shields in the near-Earth space for protecting the Earth from a part of the solar radiation.

Of course, these measures are far from equivalent both in the strength of their effect on the climate and in the funds required for their implementation. However, in my opinion, only their simultaneous execution will prevent dramatic consequences of the change in the Earth's climate.

The necessity to choose the optimal strategy using incomplete information and to simultaneously perform a wide range of studies and also the insufficiency of time and material resources extremely complicate the planning of measures required to stabilize the Earth's climate.

At the same time, with regard for the extreme degree of danger of the current change in the Earth's climate, the humankind (first of all, industrially developed countries) must as soon as possible agree to pursue a coordinated policy in this field and to allocate necessary funds both for conducting full-scale investigations and for taking a complex of measures aimed at stabilizing the Earth's climate.

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