



РОССИЙСКАЯ АКАДЕМИЯ НАУК
ПЕТЕРБУРГСКИЙ ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ
ИМ. Б.П.КОНСТАНТИНОВА

A. M. Makarieva

Biotically Maintained Stability
of the Earth's Mean Global
Surface Temperature

ГАТЧИНА

RUSSIAN ACADEMY OF SCIENCES
PETERSBURG NUCLEAR PHYSICS INSTITUTE

Preprint 2384

A. M. Makarieva

Biotically Maintained Stability
of the Earth's Mean Global
Surface Temperature

Gatchina - 2000

ТН-41-2000 2384

Поддерживаемая биотой устойчивость среднеглобальной температуры поверхности Земли

Макарьева А.М.

Аннотация

Найдена зависимость парникового эффекта от концентрации парниковых веществ, объясняющая наблюдаемый постоянный тропосферный градиент температуры. Согласно полученной зависимости, парниковый эффект быстро растет с увеличением температуры в том случае, когда облачность закрывает все существующие спектральные окна. На основе полученной зависимости показано, что существует два физически устойчивых состояния земного климата – состояние полного оледенения и состояние полного испарения гидросферы Земли. Наблюдаемое состояние земного климата, в котором сосуществуют все три фазы воды, является физически неустойчивым. Устойчивость наблюдаемой среднеглобальной температуры земной поверхности поддерживается только за счет управляющего функционирования биоты Земли.

Biotically Maintained Stability of the Earth's Mean Global Surface Temperature

Makarieva A.M.

Department of Theoretical Physics, Petersburg Nuclear Physics Institute, 188300, Gatchina, St.-Petersburg, Russia, fax +7-812-7131963, e-mail: elba@infopro.spb.su.

Abstract

The established dependence of greenhouse effect on atmospheric concentrations of greenhouse substances makes it possible to account for the observed constant tropospheric lapse rate. It proves that greenhouse effect grows rapidly with temperature under conditions of substantial cloudiness which “closes” all spectral windows. It is shown on the basis of the established dependence that there are two physically stable states of Earth's climate — that of complete glaciation and that of total evaporation of the Earth's hydrosphere. Modern climate of Earth, where all the three phases of water coexist, proves to be physically unstable. The observed stability of the global mean surface temperature is completely due to regulatory functioning of the natural biota of Earth.

1. Introduction

The orbital position occupied by the Earth in the solar system determines the flux of the solar energy incident upon the planet outside the atmosphere. It is called the solar constant. About one third of this flux is reflected back into space, predominantly by clouds in the atmosphere and by ice cover at the Earth's surface. The relative part of solar radiation reflected back into space is called the planetary albedo. Due to non-zero values of albedo, Earth and other planets of the solar system are visible in space. Solar radiation absorbed by the Earth's surface generates cycling processes in the biosphere and finally converts into heat, that is, thermal radiation. In the atmosphere thermal radiation of the Earth's surface is trapped by the so-called greenhouse gases. Molecules of the greenhouse gases emit thermal photons in all possible directions, so that a considerable part of this radiation returns to the Earth's surface where it is re-emitted to the atmosphere and so forth. This phenomenon is known as the greenhouse effect and can be quantified as the relative part of thermal radiation of the Earth's surface that is effectively reflected back to the Earth's surface by the atmosphere. Modern atmosphere of Earth effectively reflects about 40 percent of the thermal radiation, while on Venus this effect amounts to 99 percent.

Temperature of the Earth's surface is uniquely determined by the cumulative flux of thermal radiation from the Earth's surface, which is proportional to the fourth power of absolute surface temperature T . Irrespective of what orbital position is occupied by the planet, this flux is totally determined by the planetary albedo and greenhouse effect. Thus, the planet's surface temperature can assume almost arbitrary values depending on values of albedo and greenhouse effect, the latter being completely determined by inherent environmental characteristics of the planet. That is why the orbital position does not guarantee a suitable-for-life surface temperature on the planet.

Absorption of thermal radiation of the Earth's surface is performed by greenhouse gases. Gases absorb and emit radiation at frequencies which correspond to transitions between discrete energy levels of their molecules. Transitions between some energy levels of

molecules of greenhouse gases are in resonance with characteristic frequencies of the thermal radiation of Earth. The cumulative mass of all greenhouse gases is less than two thousandths of the total mass of the atmosphere. The major greenhouse gas is the water vapour. Its volume content in the atmosphere is less than 0.3 percent. The second important greenhouse gas is carbon dioxide with a volume content of about 0.03 percent. The remaining part of the greenhouse warming is determined by methane, nitrous oxide and ozone. Their cumulative volume content does not exceed $3 \cdot 10^{-4}$ percent (Mitchell, 1989).

In a stationary state—that is, when the average energy content of the planet remains constant over time—the power of the thermal radiation released by the Earth into space is naturally equal to the power of the solar radiation absorbed by the planet. The latter is totally determined by the solar constant and the planetary albedo. Thus, thermal radiation released by the Earth into space does not depend on the greenhouse effect and is characterised by the so-called effective planetary temperature. This temperature characterises the upper radiative layers of the atmosphere from which the thermal radiation is emitted directly into space. Thus, the effective planetary temperature can be measured from outer space. One cannot judge about the temperature of the planet's surface from the effective planetary temperature.

The greenhouse effect increases temperature of the planet's surface as compared with its effective planetary temperature. It leads to formation of a temperature gradient between the planet's surface and the upper radiative layers of the atmosphere. This gradient, so-called lapse rate, constitutes $5.5^{\circ}\text{C km}^{-1}$ and remains nearly constant up to about 6 km above the sea level. At that altitude the temperature difference between the Earth's surface and the atmosphere equals 33°C , which gives the magnitude of the greenhouse effect measured on a temperature scale. The atmospheric layer at height of about 6 km represents an effective radiating surface that determines thermal radiation of the planet emitted directly into space.

In the absence of greenhouse gases the average temperature of the Earth's surface would be equal to the effective planetary temperature. There would be no temperature gradient present in the atmosphere. The snow cover of high-latitude territories would

gradually spread down over the whole Earth's surface. The planetary albedo would then increase up to the value characteristic of snow and ice, that reflect about 80% of the solar radiation (Mitchell, 1989). As a result, the average global temperature would drop to about -90°C , a state where no life is possible.

Hydrosphere of Earth is sufficient for total glaciation of the Earth's surface. At the same time, Earth's hydrosphere is the main source of the atmospheric water vapour, the major greenhouse gas. Absolute concentration of water vapour in the atmosphere, as well as the relative humidity, vary greatly both in space and time, changing many dozens of times as compared with their average values. However, the average concentration of the water vapour changes proportionally to its saturated concentration (the maximum possible concentration under given conditions). Saturated concentration of water vapour grows exponentially with increasing temperature in accordance with Boltzmann distribution and the Clausius-Clapeyron equation (Landau *et al.*, 1965). The concentration of water vapour is negligibly small at low temperatures. With increasing temperature, concentration of water vapour grows exponentially and causes an increase of the greenhouse effect that leads to further increase of temperature and so forth. At 100°C water vapour pressure becomes equal to the atmospheric pressure and water begins to boil. At higher temperatures the atmospheric pressure is totally determined by the pressure of water vapour, which continues exponential growth with increasing temperature (Landau *et al.*, 1965). The process ends in a state of complete evaporation of the hydrosphere, when processes of evaporation and condensation of clouds occur in the atmosphere and do not pertain to the Earth's surface. As a result, the equilibrium temperature of the Earth's surface jumps up to several hundred degrees Celsius due to catastrophic increase of greenhouse warming, as on Venus. In this state life is not possible either.

The existing positive feedback between the surface temperature and atmospheric water vapour concentration points to the physical instability of the current climate of Earth, where hydrosphere is maintained predominantly in the liquid phase (water of oceans, rivers, lakes). The solid phase (ice of glaciers) constitutes less than 14% and the gaseous phase (atmospheric water vapour) less

than two millionth parts of the total amount of liquid water which is mostly concentrated in the oceans (Lvovitch, 1974; Schlesinger, 1990).

When values of albedo and greenhouse effect are temperature-independent, the surface temperature of the planet $T = T_s$ is stable. It is determined by the balance of the absorbed solar radiation and the emitted thermal radiation. The stability of stationary surface temperature T_s is ensured by the following negative feedback. When the surface temperature accidentally increases, $T > T_s$, the emitted flux of thermal radiation increases as well, according to the Stephan-Boltzmann law. As a result, the planet loses more energy than it receives and cools down back to T_s . When the surface temperature decreases, $T < T_s$, the planet loses less energy than it receives. As a result, temperature increases back to T_s .

There are two physically stable states where values of albedo and greenhouse effect remain constant in a wide temperature interval. These are the state of total glaciation of the Earth's surface at temperatures about -90°C and the state of total evaporation of the Earth's oceans at temperatures close to 400°C . In both states life is impossible. Constancy of albedo and greenhouse effect in these states is determined by the fact that in both states water exists predominantly in only one phase—solid at low and gaseous at high temperatures.

Under modern climatic conditions water exists in all three phases. Values of albedo and greenhouse effect depend on temperature. For example, with increasing temperature the ice shields melt and planetary albedo decreases, while atmospheric water vapour concentration grows and the greenhouse effect increases. Stable existence of life during the last four billion years gives a unambiguous evidence that the modern, suitable-for-life state of the Earth's climate is stable and spontaneous transitions to both lifeless states are forbidden. The degree of stability of the modern climate depends on the rates of changes of albedo and greenhouse effect with temperature.

2. Spectral Characteristics of Thermal Radiation

The main characteristic of any thermal flux is the spectral distribution of energy over radiation wave frequencies (or inverse wave numbers). Those parts of the Earth's surface that are not covered by ice or snow, absorb almost all incident radiation. The absorbed energy is evenly distributed over all degrees of freedom of molecules of the Earth's surface causing uniform heating of the latter. In a stationary state when the surface temperature remains constant, the energy spectrum of thermal radiation emitted by the Earth's surface is close to that of black body radiation described by the Planck function.

Unlike the Earth's surface, atmosphere only absorbs thermal radiation at certain spectral intervals defined by the presence of absorption lines of the greenhouse gases. As far as the greenhouse gases constitute but a minor part of the atmospheric gases, thermal radiation of the atmosphere cannot be reduced to black-body radiation depending on air temperature alone. Rather, thermal radiation of the atmosphere depends on concentrations of greenhouse gases and their height distribution. In order to evaluate temperature dependence of the greenhouse effect, it is necessary to understand how radiating properties of the atmosphere depend on concentrations of the greenhouse gases.

Energy spectrum of thermal radiation of the Earth's surface $q(T)$ over radiation frequencies ω can be written as follows:

$$q(T) = \sum_i \Delta\omega_i I(\omega_i, T) = \Delta\Omega \bar{I}(\bar{\omega}, T) = \sigma T^4 \quad (1)$$

Here $I(\omega, T)$ is the observed spectral density of thermal radiation emitted from the Earth's surface, which is close to the Planck function; T is the observed global mean temperature of the Earth's surface. According to the properties of the Planck function, the effective width of the spectrum $\Delta\Omega$ grows linearly with increasing T , while the maximum and the mean values of $I(\omega, T)$ increase proportionally to the third power of T . Thus, $q(T)$ grows proportionally to T^4 . Proportionality coefficient σ is close to the Stephan-Boltzmann constant characterising black-body radiation. The average frequency $\bar{\omega}$ grows linearly with T , so that with increasing T the whole

distribution moves to the right, i.e. in the direction of greater frequencies.

Unlike the Earth's surface that absorbs most part of the incoming radiation, atmospheric gases absorb radiation at some frequencies but allow radiation at other frequencies to pass through unimpeded. Greenhouse gases absorb thermal radiation in those parts of the spectrum that correspond to their absorption bands. The latter are determined by molecular properties of the gases and only weakly depend on atmospheric temperature and density. In some parts of the spectrum there are no absorbers at all or their concentration is very low, so that the absorption of thermal radiation in the atmosphere in such parts of the spectrum is not complete. Such parts of spectrum may be called spectral windows, either "clear" or "turbid". Thermal radiation of the Earth's surface emitting into space through spectral windows is characterised by spectral intensity $I(\omega, T)$ determined by the surface temperature T . In the modern atmosphere only a minor part (not exceeding 10%) of the terrestrial radiation escapes directly into space through all the spectral windows with different degrees of "turbidity" (Barry and Chorley, 1987). This makes it possible—for simplicity reasons—to consider "clear" spectral windows only. Thermal radiation of the planet measured in the outer space, q_e , can be thus represented as a sum of the radiation emitted from the upper radiating layer of the atmosphere with temperature T_e and spectral window radiation:

$$q_e(T_e) = \sum_{i \neq k} \Delta\omega_i I_e(\omega_i, T_e) + \sum_k \Delta\omega_k I(\omega_k, T) \approx \sigma_e T_e^4, \quad (2)$$

where frequency intervals $\Delta\omega_k$ stand for spectral windows. Here $I_e(\omega, T_e)$ is the observed spectral intensity of the upper radiating layer of the atmosphere. Note that the function $I_e(\omega, T)$ can be substantially different from the Planck function $I(\omega, T)$, because the atmosphere is not a black-body radiator.

Namely the small relative value of the second sum in (2), which determines the contribution of spectral windows, makes it possible to neglect it and consider q_e approximately as a function of T_e only, where T_e represents the observed temperature of the upper radiating layer of the atmosphere. The constant σ_e in (2) may differ from the Stephan-Boltzmann constant by several tens of percent.

3. Traditional Estimates of the Contributions from Different Greenhouse Gases to the Greenhouse Effect

The observed global mean flux of terrestrial radiation $q(T)$, atmospheric radiation $q_e(T_e)$ and their difference $f(T, T_e) \equiv q_e - q$, which represents the absolute value of the total greenhouse effect on the planet, are as follows (Mitchell, 1989):

$$\begin{aligned} q &= \sigma T^4 = 390 \text{ W m}^{-2}, & T &= 288 \text{ K (15 }^\circ\text{C)}, \\ q_e &= 240 \text{ W m}^{-2} \approx \sigma_e T_e^4, & T_e &\approx 255 \text{ K (-18 }^\circ\text{C)}, \\ f &= q - q_e = 150 \text{ W m}^{-2}. \end{aligned} \quad (3)$$

In a stationary state the energy lost by the Earth back into space, q_e , is balanced by the energy received by the Earth from the Sun, i.e., q_e is completely determined by values of I and A , $q_e = (I/4)(1 - A)$. The atmosphere is relatively transparent to the solar radiation, which is transformed into heat predominantly at the Earth's surface. It is therefore q_e that serves as the primer radiation flux. It interacts with the greenhouse gases in the atmosphere and initialises a cascade of absorption-emission processes, the result being the observed greenhouse effect. Introducing relative greenhouse effect $B \equiv f / q$ (Raval and Ramanathan, 1989) we may write:

$$q = q_e + Bq \quad \text{or} \quad q = \frac{q_e}{b}, \quad b \equiv 1 - B \quad (4)$$

Here the relative greenhouse effect B has the meaning of the fraction of terrestrial radiation that is reflected by the atmosphere back to the planet's surface. Function b can be interpreted as the fraction of the surface radiation that passes the atmosphere and escapes to space. It is essential that both absolute, f , and relative, B , values of the greenhouse effect depend on the two temperatures, T and T_e .

As well as the thermal fluxes q (1) and q_e (2), the absolute greenhouse effect f can be represented as a sum of spectral components. Using expressions (1) and (2) and the definition of f (3) we have:

$$f(T, T_e) = \sum_{i \neq k} \Delta\omega_i [I(\omega_i, T) - I(\omega_i, T_e)] \quad (5)$$

Here spectral intervals $\Delta\omega_i$ are the same as in (2). Naturally, spectral windows $\Delta\omega_k$, see (2), have cancelled from (5) and do not make any contribution to the greenhouse effect.

Modern greenhouse effect on Earth is by more than ninety percent determined by atmospheric water vapour and carbon dioxide (Mitchell, 1989). Thus, terms $\Delta\omega_{\text{H}_2\text{O}}$ and $\Delta\omega_{\text{CO}_2}$ are the major contributors to (5):

$$f \approx \Delta\omega_{\text{H}_2\text{O}} \Delta I(\bar{\omega}_{\text{H}_2\text{O}}) + \Delta\omega_{\text{CO}_2} \Delta I(\bar{\omega}_{\text{CO}_2}),$$

$$\Delta I(\omega) \equiv I(\omega, T) - I(\omega, T_e) \quad (6)$$

Using the Planck function $I(\omega, T)$, the observed values of mean surface temperature $T = 288$ K and temperature of the upper radiating layer, $T_e = 255$ K, the spectral widths $\Delta\omega_{\text{H}_2\text{O}}$ and $\Delta\omega_{\text{CO}_2}$ known from spectroscopic measurements and taking into account a few minor correction coefficients of the order of ten per cent, we obtain the following estimates for the greenhouse contributions of the absorption bands of water vapour and carbon dioxide (Mitchell, 1989):

$$f_{\Delta\omega_{\text{H}_2\text{O}}} = \Delta\omega_{\text{H}_2\text{O}} \Delta I(\bar{\omega}_{\text{H}_2\text{O}}) \approx 100 \text{ W m}^{-2},$$

$$f_{\Delta\omega_{\text{CO}_2}} = \Delta\omega_{\text{CO}_2} \Delta I(\bar{\omega}_{\text{CO}_2}) \approx 50 \text{ W m}^{-2}. \quad (7)$$

The cumulative contribution of the two gases is approximately equal to the total value of f (3). This fact determines the overwhelming importance of the absorption bands of these two gases for the greenhouse effect. According to (7) the cumulative contribution of the absorption bands of carbon dioxide is only two times less than that of water vapour.

Values of concentrations of the two gases did not enter the calculations when obtaining (7) from (6) and (5). Nowhere has it been taken into account that the atmospheric CO_2 concentration is more than an order of magnitude less than the average concentration of water vapour. The only assumption used implicitly was that the two gases ensure complete absorption of the surface radiation in the corresponding spectral intervals, so that emission of radiation by these gases in the upper radiating layer is determined by this layer's air temperature, which justifies use of the Planck function.

In the conventional estimate of contributions into greenhouse effect from different gases, concentration dependence is only

considered for the minor greenhouse gases which are present in very small quantities and have absorption bands in spectral windows that transmit thermal radiation of the Earth's surface. Greenhouse contributions of such gases (chlorofluorocarbons mostly) grow linearly with concentration until the latter is high enough to ensure almost complete absorption in the middle of the absorption bands. Further increase of concentration results in a very slow (square root or logarithmic) broadening of the absorption band $\Delta\omega$ and corresponding slow increase in the greenhouse effect due to saturation of the wings of the absorption lines, provided that there are no other saturated gases absorbing at the same frequencies (Mitchell, 1989).

Such a situation is realised for the atmospheric CO_2 . Thus, the widely discussed projected global warming is traditionally calculated on the basis of logarithmic growth with concentration of the greenhouse contribution of the absorption band of CO_2 (Ramanathan *et al.*, 1987; Mitchell, 1989; IPCC, 1994).

The results (7) obtained with use of (5) and (6) do not actually represent contributions of real *concentrations* of the greenhouse gases to the greenhouse effect, but, rather, contributions of those spectral *intervals* that correspond to absorption bands of CO_2 and H_2O . In reality the greenhouse contribution of a mix of several greenhouse gases is not an additive function of contributions of individual greenhouse gases.

The greenhouse contributions from corresponding spectral intervals were calculated in (5) and (6) on the basis of the known values of temperature T_e of the upper radiating layer of the atmosphere and temperature T of the Earth's surface¹. Values of T_e and T entered the calculations as empirical parameters. In reality, however, the difference $T_e - T$ is largely determined by and strongly dependent upon atmospheric concentrations of the greenhouse gases.

¹ To take into account the observed deviations of the radiation of the upper radiating atmospheric layer from that of a black body, one may substitute T_e for the so-called brightness temperature which is frequency dependent. However, such a substitution will have only a minor impact on the result (7).

Real greenhouse contribution of a given greenhouse gas is determined by the flux of energy re-emitted by this gas back to the Earth's surface. Energy absorbed by certain gas *A* in a given spectral interval is partly re-emitted back to the Earth's surface heating it. The Earth's surface emits then more radiation in all spectral intervals due to re-distribution of the absorbed energy over the whole black-body spectrum. In the presence of gas *A* other greenhouse gases have therefore an opportunity of absorbing and, consequently, re-emitting more thermal radiation in their own spectral intervals. As far as energy absorbed by one gas in a given spectral interval can be transmitted to another gas and thus re-distributed over other spectral intervals, greenhouse contributions from different spectral intervals do not give information about real greenhouse contributions of gases.

Note that the observed vertical temperature gradient in the atmosphere means that the life times of the excited states of molecules of greenhouse gases caused by their interaction with thermal radiation, are larger than the average time between successive collisions of air molecules, during which the excitation energy of molecules of greenhouse gases is transmitted to other air molecules. In such a situation thermal energy absorbed by greenhouse gas molecules has the time to be distributed over all energetic degrees of freedom of the molecules (including those of chaotic thermal motion). As a result, thermal equilibrium of gases sets in at each height.

If the energy of radiative thermal excitation of greenhouse gas molecules did not have time to re-distribute over all energetic degrees of freedom of air molecules, the height temperature gradient in the atmosphere could not be formed. Imagine that we decrease the air concentration at the expense of its non-greenhouse components (e.g. oxygen and nitrogen), so that the time between successive collisions of air molecules becomes significantly longer than the life time of the excited states of greenhouse molecules. In such a case energy exchange between different degrees of freedom of molecules of greenhouse gases and other atmospheric gases would be suppressed.

The temperature of the upper radiating layer of the atmosphere would then coincide with that of the Earth's surface T . In other words, the atmosphere would be evenly heated up to the surface temperature T . Meanwhile the greenhouse effect would

remain at the initial level completely determined by the concentrations of the greenhouse gases, as far as other gases do not interact with thermal radiation, and changes in their concentrations cannot influence the greenhouse effect. The cumulative radiation of the planet emitted into space would remain equal to equilibrium black-body radiation with temperature $T_e < T$. However, in the upper radiating layers each greenhouse gas would emit thermal radiation characterised by its own brightness temperature significantly different from the actual gas temperature T .

This suggests that the greenhouse effect (i.e. heating of the Earth's surface above the effective planetary temperature) is not necessarily coupled to the presence of the vertical temperature gradient. Hence, the dependence of the greenhouse effect on the concentrations of the greenhouse gases cannot be calculated on the basis of the observed temperature gradient alone.

Note also that, on the other hand, if the atmosphere contained no greenhouse gases, the vertical temperature gradient would be absent as well. In such a case the atmosphere and the planet's surface would cool down to T_e (instead of being evenly heated up to T , as in the above considered case of rarefied atmosphere with unchanged concentrations of greenhouse gases).

4. Dependence of the Greenhouse Effect on Concentrations of the Greenhouse Gases

Let us now consider the dependence of the greenhouse effect on concentrations of greenhouse gases. We assume that there are N greenhouse gases present in the atmosphere and their N non-overlapping absorption bands cover the whole range of terrestrial radiation frequencies. We take into account the existence of spectral windows by taking zero values of concentrations of greenhouse gases that could absorb radiation in the spectral interval corresponding to the spectral window.

Let δ_l be the relative portion of energy of thermal radiation of the Earth's surface corresponding to the absorption interval of the l -th greenhouse gas ($l = 1, 2, \dots, N$). We obtain from (1):

$$\delta_l = \Delta\omega_l \frac{I(\omega_l, T)}{\sigma T^4}; \quad \sum_{l=1}^N \delta_l = 1.$$

For each greenhouse gas it is possible to determine thickness of such a layer that would absorb in the corresponding absorption band all (within the uncertainty of measurements) radiation that comes into this layer. It is natural to call such a layer for an optically dense layer of the considered greenhouse gas. We denote as n_l the number of the optically dense layers of the l -th greenhouse gas in the atmosphere. The value of n_l is proportional to the optical density of the atmosphere, which is equal to the number of such layers that each of them weakens the incoming radiation by $e = 2.718$ times, see, e.g., (Allen, 1955; Kondratyev, 1999). Each optically dense layer ensures complete absorption of thermal radiation in the corresponding spectral interval and re-radiates in all possible directions, i.e., up and down in the considered one-dimensional atmosphere, Fig. 1. Any layer absorbs radiation emitted from the two neighbouring layers only. Radiation that is emitted from more distant layers does not reach this particular layer being completely absorbed by the intermediate layers.

Let $x_{l,k}$ be the flux of thermal radiation emitted by the k -th layer of the l -th gas in either upward or downward direction (we consider these two fluxes equal). $x_{l,1}$ stands for radiation of the upper radiative layer emitted directly into space. Energy balance equations for Earth as a whole, (8a), each layer of each greenhouse gas, (8b), and the Earth's surface, (8c), can be written in the following form:

$$q_e = \sum_{l=1}^N x_{l,1}, \quad (8a)$$

$$\begin{aligned} 2x_{l,1} &= x_{l,2}, \quad 2x_{l,2} = x_{l,1} + x_{l,3}, \quad \dots, \quad 2x_{l,k} = x_{l,k-1} + x_{l,k+1}, \quad \dots, \\ 2x_{l,n_l} &= x_{l,n_l-1} + q\delta_l, \end{aligned} \quad (8b)$$

$$q = q_e + \sum_{l=1}^N x_{l,n_l}. \quad (8c)$$

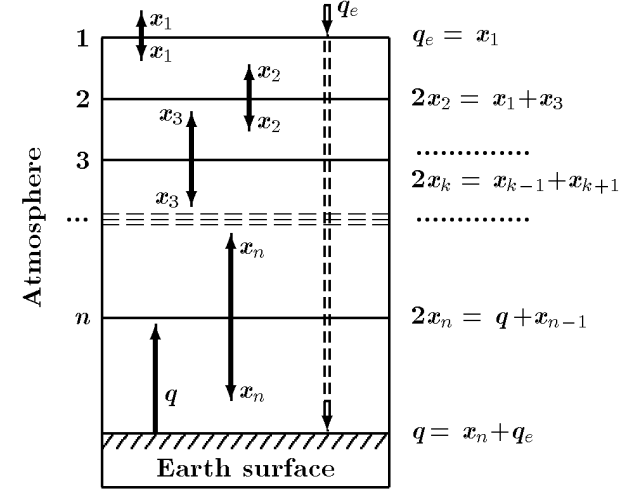


Fig. 1. Dependence of the greenhouse effect on the number of optically dense layers n for the case of one greenhouse gas which ensures complete absorption of thermal radiation over the whole terrestrial spectrum, $\delta_1 = 1$. x_k ($k = 1, 2, 3, \dots, n$) is the intensity of thermal radiation emitted by the k -th layer upwards and downwards; q is the intensity of thermal emission by the Earth's surface; q_e is the intensity of solar radiation absorbed by the Earth's surface, which is equal to the intensity of radiation of the upper radiative layer, x_1 . The atmosphere is considered to be transparent to solar radiation.

Here q and q_e are fluxes of radiation emitted from the Earth's surface and from the upper radiating layers, respectively. q_e is equal to the flux of solar radiation absorbed by the Earth's surface. Equation (8a) and the last equation of (8b) represent boundary conditions at the upper radiating layer of the atmosphere and near the Earth's surface, respectively. Equation (8c) can be deduced from all the other equations.

$$\begin{aligned} \text{Solution of the internal equations of system (8) has the form} \\ x_{l,k} = kx_{l,1}, \quad k = 1, 2, \dots, n_l, \end{aligned} \quad (9)$$

which can be easily tested. Using expression (9) in Eq. (8c) and solving (8c) together with (8a), we arrive at the following expression for the flux of Earth's surface radiation q :

$$q = \frac{q_e}{\frac{\delta_1}{n_1+1} + \frac{\delta_2}{n_2+1} + \dots + \frac{\delta_N}{n_N+1}} \equiv \frac{q_e}{b},$$

$$\text{where } b = \sum_{l=1}^N \frac{\delta_l}{n_l+1} \text{ and } \sum_{l=1}^N \delta_l = 1 \quad (10)$$

Comparing (10) and the definition of the relative greenhouse effect B (4) we obtain for the relative and absolute values of the greenhouse effect B and f :

$$B \equiv 1 - b = 1 - \sum_{l=1}^N \frac{\delta_l}{n_l+1}; \quad f = Bq = \frac{1-b}{b}q \quad (10a)$$

If the number of optically dense layers n_l is of the same order of magnitude for all gases, the flux of terrestrial radiation q and the absolute greenhouse effect f increase infinitely with growing n_l , while b tends to zero and B tends to unity. This is especially clear in the case of one greenhouse gas ($N=1$) with n layers, as shown in Fig. 1. Then $B = 1 - 1/(n+1)$ and $f = q_e n$. Expressions (10) and (10a) make it clear that contributions of different greenhouse gases into the greenhouse effect are not additive.

Let us now consider a situation when one of the N gases is absent, $n_k = 0$. Then there is a spectral window in the frequency interval $\Delta\omega_k$. Terrestrial radiation in this part of the spectrum passes unimpeded through the atmosphere directly into space and is equal to $\delta_k q$. In such a case an increase in the number of optically dense layers n_l and, consequently, in concentrations of the remaining greenhouse gases cannot lead to an infinite increase of the terrestrial radiation q . Increase in q is saturated when all the $(N-1)$ items with non-zero n_l in the denominator of fraction (10) become infinitely small as compared to the finite k -th item corresponding to the spectral window (at $n_k = 0$ it is simply equal to δ_k). The saturated values of q , B and f are then as follows:

$$q = q_e / \delta_k, \quad B = 1 - \delta_k, \quad f = q_e (1 - \delta_k) / \delta_k$$

This saturation effect has a very clear explanation. Higher concentrations enable the greenhouse gases to re-emit more radiation heating the Earth's surface and increasing the surface temperature and terrestrial radiation q . As a result, more and more radiation is released into space through the spectral window while less and less radiation is emitted from the upper radiating atmospheric layers ($x_{l,1} \rightarrow 0$), the total amount of the released radiation being limited by the absorbed solar energy q_e . Saturation corresponds to the case when practically all the radiation passes through the spectral window, $q_e = \delta_k q$.

Let us discuss the physics of this ultimate case in greater detail.

As follows from solution (9) of system of equations (8), the energy flux of radiation of atmospheric layers, and, consequently, their temperature, grow in the downward direction, i.e. when approaching the Earth's surface, see Fig. 1. The difference between temperatures of the surface and the upper radiating layer depends on concentrations n_l of the greenhouse gases. In the ultimate case of very large n_l but with $n_k = 0$, the atmosphere ceases to emit radiation to space ($x_{l,1} \rightarrow 0$), and the temperature of the upper radiating layer approaches absolute zero. It means that the atmosphere returns to the surface all thermal radiation in the spectral interval corresponding to absorption bands of all the l -th greenhouse gases with $l \neq k$. This leads to heating of the Earth's surface. Thermal energy that is directed by greenhouse gases with $l \neq k$ down to the planet's surface, is "pumped" over to the spectral interval corresponding to the absorption band of the absent gas with $l = k$ ($n_k = 0$), which represents a clear spectral window. As a result, the heat flux leaving the planet's surface through the spectral window increases up to the value of the total flux of thermal radiation emitted by the Earth into space. In the absence of an atmosphere, i.e. at zero concentrations of all greenhouse gases, this total flux would be distributed over the whole thermal spectrum.

Equations (8) and their solutions (9) and (10) are obtained under the assumption that each greenhouse gas absorbs and emits radiation in its own spectral interval independent of absorption and emission processes in other spectral intervals. Under this assumption each local site of an optically dense layer of the gas absorbs and emits

energy in upward and downward directions only. That is, it interacts exclusively with the two neighbouring local sites situated along the same vertical on the two neighbouring optically dense layers. In the atmosphere there is no energy transfer “in the horizontal dimension”, i.e., from one greenhouse gas to another and from one spectral band to another.

Obviously, this assumption remains invalid before the thermal equilibrium sets in. When thermal radiation is absorbed by a greenhouse gas molecule, the excitation energy is fairly evenly distributed over all energetic degrees of freedom of molecules, the result being heating of the gas. During collisions this heating is distributed over all air molecules and, consequently, passes over to the spectral intervals of other greenhouse gases. If one placed a screen at the Earth’s surface impeding radiation in some part of the thermal spectrum corresponding to absorption band of certain greenhouse gas, this would not be an obstacle for that gas to absorb and emit radiation in the corresponding spectral interval in accordance with the local temperature. This would be possible—in spite of the fact that no radiation would come to the absorption band of this gas directly from the Earth’s surface—due to energy transfer from absorption bands of other greenhouse gases.

However, as soon as thermal equilibrium sets in for each atmospheric layer, “horizontal” energy transfer between different spectral intervals turns to zero. This becomes clear from the analysis of the constant vertical temperature gradient that is realised in the modern atmosphere. The relative difference between the surface temperature T and the temperature of the upper radiating layer T_e is small, $(T - T_e) / T \ll 1$. Therefore the observed linear growth of temperature with decreasing height corresponds to linear growth of the radiation intensity of the optically dense layers irrespective of what is the actual dependence between the radiation intensity and temperature, including the real case of σT^4 . Linear dependence of radiation intensity on height means that radiation intensity of any intermediate layer, $x_{l,k}$, is equal to the average of radiation intensities of the two vertically neighbouring layers, $x_{l,k+1}$ and $x_{l,k-1}$, see (8) and (9). This means that the intermediate layer absorbs and re-emits only that radiation which is emitted by its vertical neighbours. Hence, in a

state of thermal equilibrium and constant temperature gradient there is no energy exchange between different greenhouse gases (i.e. between different spectral intervals), which justifies the assumption that we made when constructing system (8).

On the other hand, system (8) and its solutions (9) and (10) explain the existence of the constant vertical temperature gradient in the atmosphere and determines its quantitative characteristics in terms of the numbers of the optically dense layers (concentrations) of greenhouse gases.

The above statements are especially evident for the case when the major greenhouse component of the atmosphere, e.g. cloudiness, absorbs thermal radiation over the whole range of thermal frequencies. Obviously, there is no energy transfer between different spectral intervals in such a case. When there are several greenhouse gases with different concentrations and numbers of optically dense layers n_l , relation (9) holds for each optically dense layer of each gas at constant temperature gradient. Each optically dense layer of each greenhouse gas acquires temperature corresponding to its vertical localisation and emits radiation depending on this temperature. While thermal equilibrium and constant vertical temperature gradient persist, there is no energy transfer between different greenhouse gases. After averaging over seasonal and diurnal oscillations, one can assume that both the temperature gradient and thermal equilibrium at each height indeed remain constant.

The suggested approach does not take into account mixing of atmospheric layers due to convection and processes of evaporation and condensation of water. Rather, it describes a situation realised in objects like a fur-coat, where a fixed structure of the material prevents layers of air with different temperatures from convective mixing. Processes of convection, water evaporation and condensation are ordered processes that are generated and maintained above the thermal chaotic level by the solar energy. These processes represent intermediate stages of dissipation of the solar energy into the thermal radiation of the Earth’s surface. The exact mechanisms and localisation of this dissipation are determined by the properties of the environment.

Convection treats all greenhouse gases equally. In the course of convection macroscopic amounts of air from the hotter lower layers of the atmosphere drift upwards to the cooler layers and vice versa. Temperature of different atmospheric layers becomes more uniform. The vertical temperature gradient becomes smaller than it would be in the absence of convection. Processes of evaporation and condensation of the water vapour further enhance this effect. As a result of atmospheric mixing, thermal radiation that is actually absorbed by the lower atmospheric layers, appears to be effectively absorbed by the upper layers due to the upward drift of the lower layers, as if the intermediate layers were partly transparent to the radiation or if there were fewer intermediate optically dense layers than there actually are. Thus, atmospheric mixing can be taken into account if the actual numbers of optically dense layers are substituted for smaller *effective* numbers of optically dense layers. However, the latter remain proportional to the concentrations of the corresponding greenhouse gases, though proportionality coefficients may be very different in the cases of absence/presence of convection, evaporation and condensation of water. Thus, the dependence of the greenhouse effect on concentrations of the greenhouse gases has essentially the same form as its dependence on the number of the optically dense layers n_l in (10a).

Clouds absorb terrestrial radiation rather evenly over the whole thermal spectre contributing to all spectral intervals $\Delta\omega_l$. Thus, the number of optically dense layers of clouds n_0 should be added to the number of layers of every greenhouse gas producing the following expression for b :

$$b = \sum_{l=1}^N \frac{\delta_l}{n_0 + n_l + 1} \quad (11)$$

Note again that, as follows from (10), (10a) and (11), the cumulative contribution of several greenhouse gases into the radiation of the Earth's surface, q , and into the absolute greenhouse effect, b , is not an additive function of individual contributions of these gases, compare to (5), (6) and (7).

In the absence of clouds ($n_0 = 1$) the main contribution to the greenhouse effect comes from the l -th gas that is characterised by the

maximum value of $\delta_l / (n_l + 1)$ in the sum determining the value of b in (10). If the concentration of that gas remains constant, changes in concentrations of the other gases do not have any considerable effect on q and f . When the concentration of this gas and, hence, n_l , increases, the term $\delta_l / (n_l + 1)$ decreases, and values of q and f grow practically linearly with n_l until the diminishing value of $\delta_l / (n_l + 1)$ becomes equal to that of some other gas, $\delta_m / (n_m + 1)$. After that the concentration of the m -th gas becomes the major factor for q and f and so on.

In the terrestrial atmosphere the major greenhouse gases are water vapour and carbon dioxide. The observed spectral window (Mitchell, 1989) remains transparent at clear sky and is "closed" with appearance of clouds. For the terrestrial atmosphere the value of b (11) can be written in the following form:

$$b = \frac{\delta_{\text{H}_2\text{O}}}{n_0 + n_{\text{H}_2\text{O}} + 1} + \frac{\delta_{\text{CO}_2}}{n_0 + n_{\text{CO}_2} + 1} + \frac{\delta_0}{n_0 + 1}, \quad (12)$$

where δ_0 is the share of thermal radiation passing through the spectral window in the absence of clouds. It is easy to see that b (12) diminishes monotonously and f in (10a) grows monotonously with increasing n_0 and $n_{\text{H}_2\text{O}}$. At $n_0 \gg n_{\text{H}_2\text{O}}$ and $n_0 \gg n_{\text{CO}_2}$ we have from (10a) and (12):

$$f \equiv q_e B / b = q_e \{ n_0 + \delta_{\text{H}_2\text{O}} n_{\text{H}_2\text{O}} + \delta_{\text{CO}_2} n_{\text{CO}_2} \} \quad (13)$$

Only in this asymptotic case the contributions of different greenhouse gases are additive, cf. (5)-(7).

Note that in the opposite case, i.e. when $n_0 \ll n_{\text{H}_2\text{O}}$ and $n_0 \ll n_{\text{CO}_2}$, the major term in (12) is the third one, which corresponds to the spectral window that is gradually closed by cloudiness with increasing n_0 . In such a case either b or f practically do not depend on the carbon dioxide concentration, n_{CO_2} . However, along with possible logarithmic dependence of δ_{CO_2} on n_{CO_2} , formulae (10), (11) and (12) contain explicit dependence on concentration n_{CO_2} , which is not taken into account in the conventional estimates.

On Venus the atmospheric pressure is about 93 bars, i.e. the atmosphere of Venus is about hundred times more dense than the

atmosphere of Earth. The temperature of the planet's surface is about five hundred degrees Celsius. The atmosphere of Venus is predominantly built up of carbon dioxide (Kasting *et al.*, 1988). Such values of pressure and temperature are above the critical point of carbon dioxide (31 °C, 73 bars) (Landau *et al.*, 1965). The physical properties of CO₂ above the critical point differ significantly from those of a rarefied (ideal) gas and approach properties of cloudiness. According to observations, the greenhouse effect on Venus is close to 99%. It means that all the thermal radiation of the planet's surface is absorbed by the atmosphere and returned (re-emitted) to the surface. Such an effect can be only produced by thick cloudiness with absorption properties similar to those of a blackbody. Absorption of radiation by clouds occurs practically over the whole thermal spectrum and "closes" all spectral windows.

Clouds consist of a large number of optically dense layers absorbing radiation in all regions of the Venusian thermal spectrum. According to the above-made estimates, the greenhouse effect grows proportionally to the number of optically dense layers and, consequently, proportionally to the concentration of the substances forming cloudiness in the atmosphere of Venus. Increase of water cloudiness in the terrestrial atmosphere caused by an increase in the mean surface temperature should bring about the same effect, when formulae (10), (11), (12) and (13) give a correct quantitative description of the greenhouse effect which grows then proportionally to the cumulative water content of the atmosphere.

5. Possible Climates on Earth and Their Stability

Energy balance for a unit of the Earth's surface area consists in the fact the rate of energy content change per unit area is equal to the difference between the average flux of solar radiation absorbed by the Earth's surface and the average flux of thermal radiation emitted by the Earth's surface.

Energy content is equal to CT , where C is the average heat capacity per unit area of the Earth's surface and T is its absolute temperature. Due to rotation of the Earth, the solar flux I incident

upon the Earth's cross section area πr_E^2 , where r_E is the Earth's radius, is distributed over the whole planet's surface area, $4\pi r_E^2$. As a result, the average flux of solar radiation per unit of the Earth's surface area is equal to $I/4$. The absorbed solar radiation is equal to $aI/4$, where $a \equiv 1 - A$, A is the planetary albedo, that is, the fraction of solar radiation reflected by the planet back to space. The net flux of heat from the Earth's surface is equal to σT^4 (Stephan-Boltzmann law) multiplied by the coefficient $b \equiv 1 - B$, where B is the relative greenhouse effect and describes the part of terrestrial radiation effectively re-emitted by the atmosphere back to the Earth's surface.

The energy balance equation for a unit area of the Earth's surface can be written as follows:

$$C \frac{dT}{dt} = \frac{I}{4} a - \sigma T^4 b \equiv - \frac{dU}{dT} \quad (14)$$

We introduced in (14) the potential Liapunov function U characterising stability of the energy balance equation. The only variable in (14) is the temperature T . Coefficients a and b are temperature-dependent, as well as the potential function U . The potential function is chosen so that the negative value of its first temperature derivative is equal to the rate of energy content increment. Equation (14) is based on the law of energy conservation and does not contain any approximations. Its accuracy is determined by the accuracy of characterisation of the whole Earth's surface by a global mean temperature. Minor deviations of the thermal radiation of Earth from blackbody radiation in some parts of the thermal spectrum are taken into account in coefficient b . Coefficients a and b are global averages of the well-measured parameters. Strictly speaking, the whole temperature dependence of the Earth's surface radiation, i.e. its values at different temperatures can be in principle determined empirically. Isolation in the second term of (14) of the physically reasoned multiplier σT^4 describing blackbody radiation leads to considerable simplification of finding the rest of temperature dependence of the surface radiation, which is then confined to function $b(T)$.

In a stationary state, when the energy content does not change, $C \frac{dT}{dt} = 0$, the derivative of U turns to zero, and,

consequently, U has an extreme—maximum or minimum. The central part of (14) also turns to zero, and this equality determines a stationary temperature $T = T_S$:

$$\frac{I}{4}a(T_S) - \sigma T_S^4 b(T_S) = 0, \quad \text{or} \quad T_S = T_0 \left(\frac{a(T_S)}{b(T_S)} \right)^{1/4},$$

$$\text{where } T_0 \equiv \left(\frac{I}{4\sigma} \right)^{1/4} = 278 \text{ K} \quad (15)$$

Here the following numerical values of σ and I were used: $\sigma = 5.67 \cdot 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ and $I = 1367 \text{ W m}^{-2}$. At $a = b = 1$, which means that both the planetary albedo A and greenhouse effect B are equal to zero, the stationary temperature of the Earth's surface would be equal to $T_0 = 278 \text{ K}$ (5°C). This temperature, which is totally determined by I , that is, by the planet's location in the solar system, can be called planet's orbital temperature, see below Table 1.

Note that here and below we imply that the notion of stationary state describes a state where the *average* energy content CT does not change with time. Here all oscillatory processes after averaging over time periods longer than periods of oscillation are included, as well as chaotic fluctuations that do not change the average energy content.

When the first derivative of U is equal to zero, the sign of its second derivative $U'' \equiv \frac{d^2 U}{dT^2}$ determines the character of the extreme.

It is a minimum, when U'' is positive, and maximum, when U'' is negative.

The sign of U'' allows one to judge about stability of stationary solutions of (14). In the neighbourhood of the stationary point $T = T_S$ the first derivative $U' \equiv \frac{dU}{dT}$ can be expressed as a Taylor power series in terms of a small deviation $x \equiv T - T_S$:

$$U'(T) = U'|_{T=T_S} + U''|_{T=T_S} (T - T_S) = U''|_{T=T_S} (T - T_S) = U''|_{T=T_S} x,$$

as far as $U'|_{T=T_S} = 0$.

Equation (14) can be then re-written as follows:

$$\frac{dx}{dt} = -kx, \quad \text{where } k \equiv \frac{1}{C} U''|_{T=T_S}$$

Heat capacity C is positive, so that the sign of coefficient k coincides with that of U'' . Solution of the above equation looks like $x = x_0 e^{-kt}$, where x_0 is an arbitrary constant, t stands for time. Thus, when $k > 0$ (U has a minimum), any initial deviation of temperature T from the stationary value T_S exponentially damps out, which means that the stationary state is stable. In such case k can be interpreted as coefficient of relaxation, while the reciprocal value k^{-1} characterises the time of recovery of the stationary state after a perturbation. On the contrary, when $k < 0$ and U has a maximum at $T = T_S$, any deviation exponentially grows with time. In such case the stationary state $T = T_S$ is unstable.

We have seen therefore that stability of stationary states of (14) can be readily illustrated by the character of function U in very much the same manner as the gravitational potential of Earth can be described by relief of the surface. Stable stationary states correspond to minima (pits) of function U , see below Fig. 2. The degree of stability depends on a pit's depth. Unstable states correspond to maxima (hills) of function U . Any deviation from the stationary state leads to sliding along the hill down to one of the two nearest pits located to the left and to the right of the hill.

Values and signs of U'' and relaxation coefficient k are unambiguously determined by temperature dependence of functions $a(T)$ and $b(T)$ in (14), and, consequently, by temperature dependencies of albedo A and greenhouse effect B . Expanding functions a and b in Taylor power series with respect to small deviations $x \equiv T - T_S$ and using relation (15), we obtain the following expression for U'' in the stationary point T_S using temperature derivatives of a and b , a' and b' :

$$U''|_{T=T_S} = \frac{I}{4} \frac{a}{T_S} (4 + \beta - \alpha) \Big|_{T=T_S}, \quad \text{where } \alpha \equiv \left(\frac{a'T}{a} \right)_{T=T_S},$$

$$\beta \equiv \left(\frac{b'T}{b} \right)_{T=T_S}. \quad (16)$$

As far as $a > 0$ and $T_s > 0$, it is evident from (16) that a stationary state is stable when $\alpha - \beta < 4$ and unstable when $\alpha - \beta > 4$.

It is convenient to seek solution of (15) in a graphical form drawing the curve $y_1(T) = T_0 \left(\frac{a(T)}{b(T)} \right)^{1/4}$ and looking for intersections of this curve with the line $y_2(T) = T$. Temperature derivatives of functions $y_1(T)$ and $y_2(T)$ have the form:

$$y_1' \Big|_{T=T_s} = \frac{\alpha - \beta}{4}, \quad y_2' = 1 \quad (17)$$

In a stationary state the stability condition $\alpha - \beta < 4$ is equivalent to the condition $y_1' \Big|_{T=T_s} < 1$. Similarly, the instability condition $\alpha - \beta > 4$ corresponds to $y_1' \Big|_{T=T_s} > 1$. Which of the two conditions is realised in the point of intersection of y_1 and y_2 can be determined visually comparing the slopes of the two curves. Such graphical analysis of the stability of stationary solutions of (14), in addition to the graphical analysis of the potential function $U(T)$, is convenient, because function y_1 directly reflects the temperature-dependent behaviour of the albedo and greenhouse effect, and, consequently, of functions $a(T)$ and $b(T)$.

6. Physical Stability of the Earth's Climate

Let us now consider the physical behaviour of the greenhouse effect and albedo and functions $a(T)$ and $b(T)$ when the temperature T changes from the state of total glaciation **1** to the state of complete evaporation of the hydrosphere **3**, Table 1.

The stationary steady state of an ice-covered Earth lies in the interval of temperatures lower than -80°C . In this state all the major components of the environment including atmospheric CO_2 are present in the solid phase. As soon as the solid phases of most components persist over a broad interval of low temperatures, one can assume that in the vicinity of the stationary state **1** neither the greenhouse effect nor albedo depend on temperature. Albedo of the ice-covered Earth should be equal to that of snow cover, i.e. to 80% (North *et al.*, 1981; Mitchell, 1989) making the value of $a(T)$ equal to

Table 1. Thermal characteristics of the planets.

Planets	Solar constant	$A = B = 0$ (Orbital temperature)	$A > 0, B = 0$ (Thermal radiation into space)		$A > 0, B > 0$ (Average values at planetary surface)		
	$I, \text{W m}^{-2}$	$t, ^\circ\text{C}$	$A, \%$	$t, ^\circ\text{C}$	$B, \%$	$t, ^\circ\text{C}$	p, bar
Mars	589	-48	15	-56	7	-53	0,01
Venus	2613	+58	75	-41	99	+460	93
Earth, modern climate 2	1367	+5	30	-18	40	+15	1
Earth, complete glaciation 1	1367	+5	80	-90	7	-85	1
Earth, total evaporation of hydrosphere 3	1367	+5	75	-80	99	+400	300

Notes to Table 1:

I is the solar constant, i.e., the power of solar radiation incident upon unit of perpendicular area outside the planet's atmosphere. A is the planetary albedo, i.e. fraction of solar radiation reflected by the Earth back to space. B is the relative greenhouse effect, i.e., the fraction of the planet's heat radiation that is reflected by the atmosphere back to the planet's surface. p is the atmospheric pressure. In the state of complete glaciation of the Earth (**1**), the value of planetary albedo is taken equal to the albedo of ice and snow sheets, the value of greenhouse effect was taken as on Mars. The state of complete glaciation lies below the CO_2 melting point (-78°C , 1 bar). In the state of total evaporation of the hydrosphere of the Earth (**3**), the values of albedo and greenhouse effect are taken as on Venus. On Venus where the atmosphere is composed of CO_2 to the extent of 96%, this gas find itself above its critical point (31°C , 73 bars). State **3** of complete evaporation of the Earth's hydrosphere is also above the critical point of H_2O , the main terrestrial greenhouse gas (its critical point is 374°C , 219 bars). Sources: Landau *et al.*, 1965; Pollack *et al.*, 1980; McKay, 1983; Kasting *et al.*, 1988; Mitchell, 1989.

0.2. The relative greenhouse effect on Mars where the mean surface temperature is higher than -80°C and gaseous carbon dioxide is relatively abundant, is about 7% (Pollack, 1979; Kasting *et al.*, 1988; Mitchell, 1989). Thus, for the ice-covered Earth the relative greenhouse effect $B(T)$ does not presumably exceed 1–5%, and the value of $b(T)$ is not more than 0.95. We use below $b(T) = 0.95$ for the maximum temperature leading to complete glaciation of the planet.

The stationary steady state of complete evaporation of the hydrosphere corresponds to global mean surface temperature higher than 400°C (Table 1) and atmospheric pressure exceeding the present one by a factor of several hundred. As soon as all the hydrosphere is evaporated, the atmospheric concentration of water does not further change with temperature. Thus, it is reasonable to assume that in state **3** neither albedo nor greenhouse effect change considerably with temperature, similarly to the situation in the stationary state **1**. On Venus the surface temperature is about 460°C , while the planetary albedo (which is completely due to the cloudiness) is approximately equal to that of the ice-covered Earth (Table 1). Thus we may take the value of albedo in state **3** equal to 80% and value of $a(T) = 0.2$, as in state **1**. The relative greenhouse effect on Venus can be uniquely calculated from the difference between the temperature T on the planet's surface and the effective temperature T_e of thermal radiation of the planet measured from the outer space. The effective thermal radiation of Venus is equal to $q_e = \sigma T_e^4 = Ia / 4 = 163 \text{ W m}^{-2}$, $T_e = 232 \text{ K}$, see Table 1. Thermal radiation of the planet's surface is calculated as $q = \sigma T^4 = (Ia / b) / 4 = 16000 \text{ W m}^{-2}$, $T = 730 \text{ K}$ (Table 1). From these values we obtain

$$b \equiv 1 - B = (T_e / T_s)^4 = 163 \text{ W m}^{-2} / 16000 \text{ W m}^{-2} = 0.010 \quad (18)$$

It is reasonable to accept the obtained value of $b(T) = 0.010$ for the stationary state of the totally evaporated hydrosphere on Earth.

The atmosphere of Venus consists of carbon dioxide to the extent of 96% and has a pressure of about 93 bars² (Kasting *et al.*, 1988). On Earth the cumulative mass of the oceans exceeds mass of the modern atmosphere by 300 times (Allen, 1955). In the state of total

² The global mean atmospheric pressure on Earth is equal to 1.013 bar, 1 bar = 10 N m^{-2} (Allen, 1955).

evaporation of the hydrosphere the atmospheric pressure would be about 300 bars. In such a case, the terrestrial H_2O would find itself, similarly to CO_2 on Venus, above the critical point (Landau *et al.*, 1965). Thus it is reasonable to assume, with allowance made for the cloudiness, that in the state of total evaporation of the hydrosphere the relative greenhouse effect B on Earth would be at least not less than it is on Venus making the value of $b \equiv 1 - B$ not greater than 0.010.

The chosen values of $a(T)$ and $b(T)$ in states **1** and **3** completely determine the mean global temperature of the Earth's surface in these two states, see (15) and Table 1.

Let us now consider possible physical mechanisms of transition from the stable state of the ice-covered Earth **1** to the stable state of total evaporation of the hydrosphere **3**.

The major part of the modern greenhouse effect on Earth is determined by atmospheric concentration of water vapour, which is proportional to the number of the optically dense layers of H_2O , see (10)-(12). Atmospheric concentration of water vapour varies greatly in space and time. However, the average concentration of the water vapour changes proportionally to its saturated concentration (Ramanathan *et al.*, 1987; Raval and Ramanathan, 1989). Saturated concentration of water vapour, as well as the saturated partial pressure, $p_{\text{H}_2\text{O}}$, grows exponentially with increasing temperature in accordance with the Clausius-Clapeyron formula (Landau *et al.*, 1965) and the Boltzmann distribution. According to this formula, the temperature dependence of partial pressure of saturated water vapour, $p_{\text{H}_2\text{O}}$, and, consequently, temperature dependence of the number of the optically dense layers, $n_{\text{H}_2\text{O}}$, has the form (Landau *et al.*, 1965; Raval and Ramanathan, 1989):

$$n_{\text{H}_2\text{O}}(T) = ce^{-\frac{T_{\text{H}_2\text{O}}}{T}} \equiv e^{-\frac{T_{\text{H}_2\text{O}} + \epsilon}{T}}, \quad T_{\text{H}_2\text{O}} \equiv \frac{Q_{\text{H}_2\text{O}}}{R} = 4871 \text{ K} \quad (19)$$

Here $Q_{\text{H}_2\text{O}}$ is the latent heat of evaporation of 1 mole of water vapour, R is the gas constant, $T_{\text{H}_2\text{O}}$ is the effective temperature characterising

the energetic of evaporation process, $c \equiv e^\varepsilon$ is a temperature-independent constant.

Function $b(T)$ that enters formulae (14) and (15) and determines the relative fraction of thermal radiation passing through the atmosphere ($b(T)$ may be called the transmissivity coefficient), is given by expression (12). We take the following values for modern contributions δ_l of different spectral intervals: $\delta_{\text{H}_2\text{O}} = 0.6$; $\delta_{\text{CO}_2} = 0.3$; $\delta_0 = 0.1$ (within uncertainty limits these values agree with (7)). At present cloudiness is responsible for about one third of the total greenhouse effect (Raval and Ramanathan, 1989; Kondratyev, 1999) and for about one third of the greenhouse effect determined by water vapour. Assuming that this relation holds within a broad temperature interval, we take $n_0(T) = 0,3 n_{\text{H}_2\text{O}}(T)$. Further, taking into account that atmospheric CO_2 concentration constitutes at present about 10% of the average water vapour concentration and only changes slowly with temperature, we take a constant value of $n_{\text{CO}_2} = 0,1 n_{\text{H}_2\text{O}}(288 \text{ K})$. Setting the condition of complete glaciation of the Earth's surface in the form $b(238 \text{ K}) = b(-35^\circ\text{C}) = 0.95$, one may determine constant ε in (19), which proves to be equal $\varepsilon = 17.1$. The fact that the Earth's hydrosphere has a finite mass (and, consequently, the greenhouse effect on Earth cannot grow and b cannot diminish infinitely) can be taken into account by specifying the limiting value of $b_{\min} = 0.01$ and adding this value to the right-hand part of (12).

The character of dependence of the planetary albedo on temperature remains to a large extent unknown. Its basic features, however, can be taken into account if the unknown function $a(T)$ is approximated by a Gaussian curve. The limiting value of $a_{\min} = 0.2$ at high and low temperatures corresponds to the states of the total glaciation and total evaporation of the hydrosphere, where the planetary albedo $A \equiv 1 - a$ is at its maximum due to the high reflectivity of ice cover and clouds, respectively. The observed modern value of a is 0.7 ($A = 0.3$). We assume that the maximum value $a_{\max} = 0.75$. It corresponds to the state of already totally melted ice-cover but still predominantly liquid hydrosphere, when the albedo of the Earth's surface equals zero (at present it is equal to 5% due to ice shields (Schneider, 1989)). We thus obtain for $a(T)$:

$$a(T) = 0.20 + 0.55 \exp\left[-\frac{(T - T_m)^2}{(\Delta T)^2}\right];$$

$$T_m = 298 \text{ K } (25^\circ\text{C}); \quad \Delta T = 50 \text{ K } (50^\circ\text{C}) \quad (20)$$

Maximum of the albedo is chosen at a global mean temperature $T_m = 298 \text{ K } (25^\circ\text{C})$. Proportionality coefficient near the exponential term and the effective width of the curve ΔT are retrieved from the condition that at the modern mean global temperature $T = 288 \text{ K}$ the value of $a(T)$ given by (20) is equal to the observed value, $a(288) = 0.70$ (Table 1), and the condition that Earth is totally covered with ice at -25°C , i.e. the temperature value produced when subtracting the distribution width ΔT from the temperature T_m corresponding to the maximum value of albedo: $T_m - \Delta T = 25^\circ\text{C} - 50^\circ\text{C} = -25^\circ\text{C}$. Variations of parameters b_{\min} , T_m and ΔT within physically reasonable limits do not change the results to be obtained.

Note that transition from the state of complete glaciation of the Earth's surface to the state of complete evaporation of the hydrosphere is accompanied by a hundredfold change in the absolute greenhouse effect as compared to a two- to threefold change in the planetary albedo at maximum. Hence, the temperature dependence of the albedo is unlikely to have a major impact on the solutions of (15) and their stability.

Fig. 2 shows the graphical solution of equation (15), Fig. 2a, and the continuous potential function $U(T)$ which was obtained by integrating (14), Fig. 2b. The integration constant was chosen such that the potential function $U(T)$ turns to zero in the stationary state of total evaporation of the hydrosphere. As becomes clear from Fig. 2, there are three stationary states of the Earth's climate. The stationary states of total glaciation and total evaporation of the hydrosphere are, as could be expected, stable, while the stationary state corresponding to the modern climate proves to be unstable.

7. Biotic Stability of the Modern Climate of Earth

In order to account for the observed stability of the suitable-for-life modern climate, it is necessary to change the physical temperature

dependencies of functions $a(T)$ and $b(T)$. This can be done by introducing non-physical, biotically controlled singularities in the temperature-dependent behaviour of albedo and greenhouse effect within the temperature interval from 5°C to 25°C . According to the available paleodata, the biota has been existing within this temperature interval during billions of years. The degree of stability of a stationary state is characterised by the depth of the corresponding potential pit. In particular, stability of the modern value of the global mean surface temperature could be ensured if functions $a(T)$ and $b(T)$ remained temperature-independent within the considered temperature interval. However, the appearing potential pit would then be too shallow, and the potential barriers separating the modern climate from states of complete glaciation **1** and complete evaporation of the hydrosphere, **2**, would be too low.

The maximum possible stability of the stationary state **2** can be retrieved from the condition of the maximum physically possible negative feedback in the temperature interval $5^{\circ}\text{C} < T < 25^{\circ}\text{C}$. The maximum physically possible feedback can be illustrated by a hypothetical situation when the relative greenhouse effect B increases linearly with decreasing temperature up to the maximum possible value, which is realised at the lower boundary of the considered temperature interval, while the albedo A decreases linearly with decreasing temperature and attains there the minimum possible value, $B(5^{\circ}\text{C}) = 1$, $A(5^{\circ}\text{C}) = 0$. The same situation is realised when the limiting values of albedo and greenhouse effect correspond to the upper boundary of the considered temperature interval, $B(25^{\circ}\text{C}) = 0$, $A(25^{\circ}\text{C}) = 1$. In such a case the potential pit depth in the vicinity of $T = 288\text{ K}$ (15°C) appears to be an order of magnitude higher than the depths of potential pits in states **1** and **3**.

Fig. 2 shows the graphical solution of equation (15) and the potential function U (14) for a model example of weaker negative feedback:

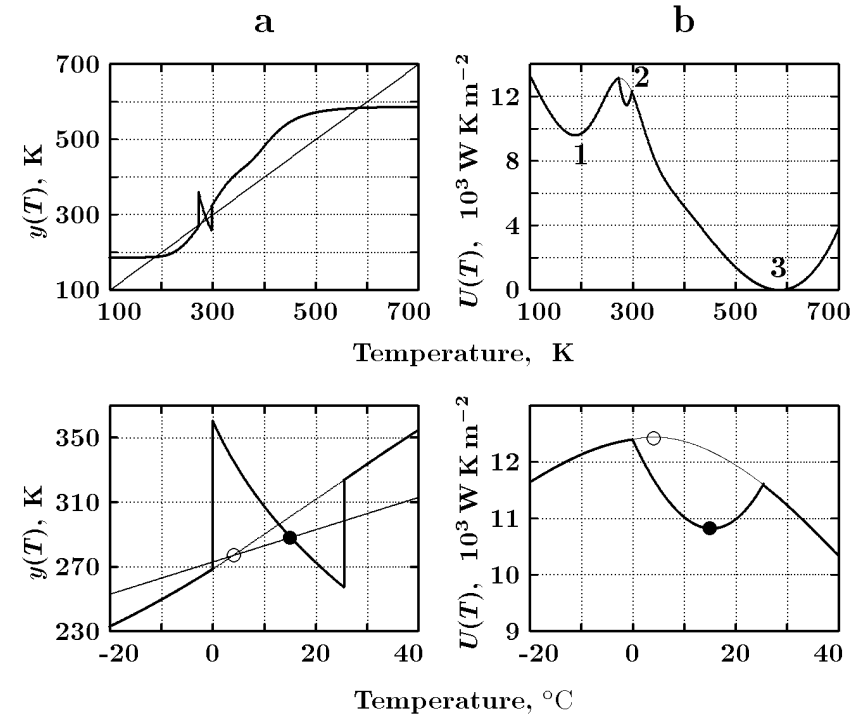


Fig. 2. Physical and biotic stability of the global mean surface temperature.
a: graphical solution of equations (15), (17).
b: potential function $U(T)$, see (14). **1** — physically stable state of complete glaciation of the planet, **2** — modern biotically stable but physically unstable state; **3** — physically stable state of total evaporation of the hydrosphere. Biotic singularities of the temperature-dependent behaviour of albedo and greenhouse effect correspond to thick lines in the centre of the diagrams. Thin lines correspond to the physical thermodynamic behaviour which contains no singularities and corresponds to physically unstable state **2**. Filled circles stand for the currently observed mean global surface temperature. Empty circles correspond to the temperature of the unstable equilibrium on a lifeless Earth or after complete destruction of the regulatory biotic potential (i.e. elimination of the biotic singularities (2a) and the biotic pit (2b)).

$$a(T) = 0,7 - (t - t_2) 0,02, \quad 0 \text{ }^\circ\text{C} < t < 25 \text{ }^\circ\text{C}, \quad t_2 = 15 \text{ }^\circ\text{C} \quad (21)$$

$$b(T) = 0,6 + (t - t_2) 0,02, \quad 0 \text{ }^\circ\text{C} < t < 25 \text{ }^\circ\text{C}, \quad t_2 = 15 \text{ }^\circ\text{C}$$

Outside the considered temperature interval the temperature-dependent behaviour of functions $a(T)$ and $b(T)$ remains to be governed by physical thermodynamic regularities (19) and (20).

The real behaviour of albedo and greenhouse effect in the life-compatible temperature interval can be presumably deduced only empirically on the basis of detailed studies of paleodata, which is not our goal here. We aim at demonstrating that it is impossible to account for the observed stability of the suitable-for-life global mean surface temperature on the basis of thermodynamic physical regularities. The observed stability of modern climate provides a unambiguous evidence that the real temperature-dependent behaviour of functions $a(T)$ and $b(T)$ deviates significantly from the thermodynamic behaviour (19) and (20).

Note that the biota not only changes the character of the extreme of $U(T)$ (from maximum to minimum), but also shifts the very location of the stable equilibrium state. Determining the constant ε in (19) from the condition that complete glaciation sets in at $T = -35^\circ\text{C}$ (i.e. $b(T) = 0.95$ when $T = -35^\circ\text{C}$), we obtain a physical maximum of the potential function (Fig. 2b, thin lines) at $T_{\max} = 277 \text{ K}$, i.e. to the left of the observed mean global surface temperature $T_S = 288 \text{ K}$. This means that the biota shifts the equilibrium in the direction of higher temperatures. The biotically stable equilibrium in the form of a potential pit, Fig. 2b, thick lines, is then situated on the right slope of the physical potential hill (Fig. 2b, thin lines) leading to complete evaporation of the hydrosphere. There is no shift in the equilibrium temperature (the physical hill is precisely above the biotic pit), if we choose that complete glaciation sets in at $T = -26^\circ\text{C}$, $b(-26^\circ\text{C}) = 0.95$. Finally, if we state that $b(T < -26^\circ\text{C}) > 0.95$ (i.e. complete glaciation occurs at temperatures higher than -26°C) the biotic stable minimum will find itself to the left of the physical maximum. Since glaciation at higher temperatures is less probable than at lower ones, the situation shown in Fig. 2b is more probable. This means that when the humankind completely destroys the natural biota, the regulatory biotic potential degrades and the biotic pit

vanishes, we will find ourselves rapidly sliding down the physical slope in the direction of complete evaporation of the hydrosphere. In other words, after human-induced degradation of the natural biota on a global scale, we will be boiled rather than frozen.

In the performed analysis of the stability of the global mean surface temperature we have only taken into account temperature-dependent changes in concentrations of atmospheric water vapour and cloudiness. Concentrations of the remaining greenhouse gases, CO_2 in particular, were assumed to remain constant, i.e. temperature-independent. This assumption is justified in natural Earth's environment undisturbed by anthropogenic activities. The fact that CO_2 freezes out from the atmosphere at low temperatures practically does not affect the result obtained without taking into account this effect. However, formula (12) contains an explicit dependence of the greenhouse effect on the atmospheric CO_2 concentration. This makes it possible to analyse changes in temperature stability under conditions of anthropogenic growth of the atmospheric CO_2 concentration caused by industrial and agricultural activities of humans.

To perform such an analysis let us express the carbon dioxide term in (12), n_{CO_2} , in terms of concentration of water vapour, $n_{\text{CO}_2} = 0,1\gamma n_{\text{H}_2\text{O}}$ (288 K). Coefficient γ describes the relative amount of CO_2 in the atmosphere. The value $\gamma = 1$ corresponds to the initial undisturbed (preindustrial) state. It can be easily shown that with growing γ the location of the two physical minima of the potential function $U(T)$ corresponding to the states of complete glaciation and complete evaporation of the hydrosphere, Fig. 2b, practically does not change. However, the physical maximum **2** corresponding to the physically unstable stationary state begins to move to the left, i.e. in the direction of lower temperatures.

This becomes evident from the graphical solution of Eq. (15) with use of functions $y_1(T)$ and $y_2(T)$, see (17) and Fig. 2a. Indeed, $y_1 = T_0(a/b)^{1/4}$. When the value of γ and, consequently, n_{CO_2} , grow at a fixed temperature, the greenhouse effect B increases while function b (12) decreases monotonously, so that y_1 increases as well. As a result, the corresponding curve in Fig. 2a moves upwards, which means that

the point of intersection of y_1 and line $y_2 = T$ moves to the left. Fig. 3 shows value ΔT of the shift of the physically unstable stationary state 2 with respect to growing γ , $\Delta T = T - 277$ K.

Biotic stability is characterised by the depth of biotic potential pit at $T = 288$ K. This depth is dependent upon the character of intersection of the biotic pit with the physical potential function $U(T)$ constructed without taking into account the biotic control of albedo and greenhouse effect. The nature of this intersection changes substantially only at very large values of γ of the order of $\gamma \sim 100$, which corresponds to a hundredfold increase of CO_2 as compared to its modern value. The widely discussed projected twofold increase in atmospheric CO_2 concentration (IPCC, 1994) does not impose any considerable impact on the degree of stability of the modern climate, provided that the natural biota of Earth continues to perform its regulatory functions on a global scale. We conclude that the anthropogenic growth of atmospheric CO_2 concentration does not play any role when considered against the background of those changes in the greenhouse effect that are caused by human-induced global-scale degradation of the regulatory biotic potential, i.e. anthropogenic shallowing of the biotic pit.

Changes of the biotic pit in response to growing CO_2 cannot be predicted without a detailed analysis of the biotic response. It follows from the above consideration that without studying the nature and degree of stability of the modern climate it is impossible to make any forecasts about possible changes of the mean global surface temperature related to changes in the atmospheric CO_2 concentrations.

8. Biotic regulation of climate and global circulation processes

We have shown so far that the observed stability of the Earth's climate with regard to the mean global surface temperature points to the complex nature of the temperature dependencies of albedo and greenhouse effect within the life-compatible temperature interval. We have shown that, on the basis of the known physical atmospheric

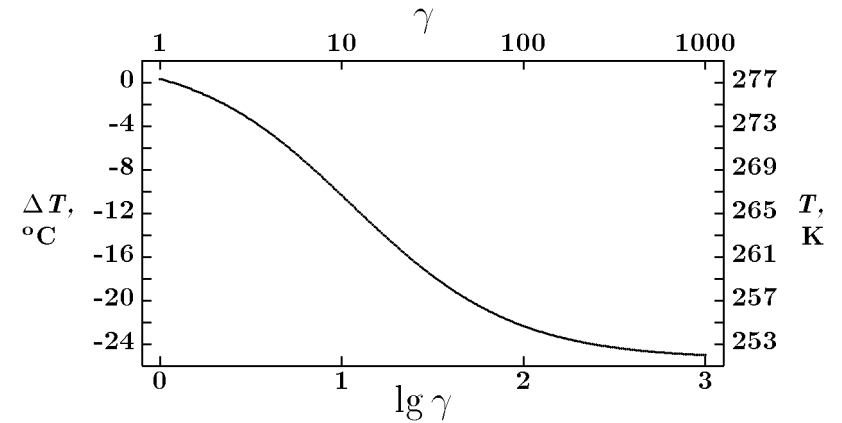


Fig. 3. The temperature shift ΔT of the physically unstable state 2 (see Fig. 2b) with respect to the relative change in the atmospheric CO_2 concentration, $\gamma \equiv \frac{[\text{CO}_2]}{[\text{CO}_2]_0}$. $\Delta T = T - T_0$, where $T_0 = 277$ K is the position of the physically unstable state as described in Fig. 2b. With growing γ the potential hill 2, Fig. 2b, moves to the left at a distance equal to $|\Delta T|$.

properties alone, there are no grounds to expect such anomalies in temperature-dependent behaviour of either albedo or greenhouse effect. This, in its turn, points to existence of a biotic mechanism of climate control within the interval of life-compatible temperatures. Such control can be only based on highly ordered non-equilibrium processes that are generated by solar radiation due to large difference between temperatures of solar radiation (short-wave radiation of the Sun) and terrestrial thermal radiation (long-wave radiation of the Earth).

The main quantitative characteristic of orderliness of processes generated during any type of energy transformation is the difference between temperatures of the initial and final states. The final state of all processes taking place in the environment

corresponds to chaotic thermal energy of the Earth's surface, which is characterised by global mean surface temperature $T_E \sim 300$ K. Solar energy is characterised by temperature $T_S \sim 6000$ K. The relative difference between these temperatures constitutes

$$\eta_S = \frac{T_S - T_E}{T_S} \sim 0.95 \quad (22)$$

In thermodynamics the variable η_S has the meaning of the efficiency of energy transformation (Landau *et al.*, 1965). This is the maximum possible work efficiency of a reversible heat machine based on a succession of equilibrium thermodynamic processes. The same variable characterises the efficiency of highly-ordered non-equilibrium processes generated by solar energy in the Earth's environment.

All processes of global circulation in the ocean and atmosphere are due to the temperature difference between the equator and the poles, which is of the order of $\Delta T_E \sim 30^\circ\text{C}$. The efficiency of ordered processes generated by global circulation is characterised by

$$\eta_E = \frac{\Delta T_E}{T_E} \sim 0.1, \quad (23)$$

which is an order of magnitude lower than the value of η_S (22). It means that a unit energy of global circulation generates in the Earth's environment ten times less energy of ordered processes than the same unit of solar energy. (The amounts of solar energy consumed by the global biota and by the global circulation processes are of the same order of magnitude, Gorshkov *et al.*, 2000).

As shown above, the observed stability of the modern climate can be only explained taking into account highly ordered processes generated by solar energy in the global biota. Ordered processes that are due to global circulation make an order of magnitude lower contribution and may be neglected. There are no grounds to expect that detailed elaboration of global circulation models yield reliable predictions of climate change under anthropogenic impact.

Until now studies devoted to the climate stability problem have been based on quantitative characteristics of energy fluxes, while the degree of orderliness of corresponding processes has never been

taken into account (North *et al.*, 1981; Ramanathan *et al.*, 1987; Tang and Weaver, 1995; Li *et al.*, 1997). This is predominantly due to the fact that most processes generated at the Earth's surface by solar energy go through stages that are very far from thermodynamic equilibrium, for which no general theory exists. However, the parameter η , (22) and (23), is valid for all processes, including non-equilibrium ones, and can be used when estimating their orderliness. Note also that all models concerned about climate stability are based on empirical characteristics of the modern climate that enter the models as parameters, see, e.g. (Li *et al.*, 1997). It is not surprising that in all such models the modern climate proves to be stable. The question *why* the observed characteristics of climate ensure its stability is rarely—if ever—addressed.

Highly-ordered processes generated by solar energy with efficiency close to (22) are of biological nature and take place only in the biota. That means that the climate stability on Earth can be only due to the regulatory function of the natural biota. Ordered processes aimed at maintenance of climate stability should be necessarily characterised by strictly defined succession, direction and duration, i.e., fluxes and stores of information.

Such information is contained in the genetic programme of biological species combined into ecological communities of the global biota. Natural ecological communities are characterised by strictly specified population densities of all species that undergo directional changes in response to environmental perturbations. Anthropogenic perturbation of natural ecological communities is manifested in artificial change of the natural population density distribution of species and violation of genetic programs of natural species due to creating new sorts of plants and breeds of animals. This leads to degradation of the stabilising environmental potential of the biota.

The natural biota operates with processes far out of thermodynamic equilibrium. In physics, development and dynamics of similar processes have been recently successfully described with use of non-linear equations of the Fokker-Planck type (Cross and Hohenberg, 1993; Ginzburg and Pustovoit, 1998). However, using the genetic information of biological species, the biota is able to stop the physically prescribed development of non-equilibrium processes and

correct it in accordance with changing environmental conditions. It is impossible to construct a mathematical model of a non-equilibrium process controlled by the biota without detailed decoding of the genetic programme of interaction of living organisms with their environment. It is impossible to describe this ultra-complex interaction with use of elementary physico-chemical processes in an arbitrary set of non-correlated living organisms, where the complexity of the existing genetic programmes remains uninvolved.

During large-scale natural perturbations of the environment of the past (e.g., glaciations, volcanic eruptions, meteorite fall etc.) the regulatory potential of the biota decreased in proportion to reduction of areas occupied by the natural biota, but remained substantial. For example, were the area occupied by the global biota to reduce by half, the global regulatory potential would halve as well. That means that the rate of biotic compensation of external perturbations would be reduced twofold. Estimates of relaxation coefficients of the nonperturbed biota show that the characteristic time of complete recovery of the initial stable state of the environment after natural external perturbations is of the order of 10 years for the non-perturbed biota (Gorshkov and Makarieva, 1998). Were the global biota reduced by half, that time would only double, which may not have any drastic consequences to the environmental stability.

In contrast, anthropogenic cultivation of territories occupied by natural biota has a catastrophic impact on environmental stability. The perturbed biota loses information necessary for correct regulation of the environment, but retains the absolute huge value of environmental impact. The destabilising impact of the perturbed biota may be larger than stabilising impact of the remaining intact territories.

Hence, we are forced to the conclusion that in order to ensure long-term stability of climate on Earth natural biota should be restored and protected on most part of the continental surface, rather than in tiny reserves and national parks. As one of the immediate measures, one can name considerable reduction and ultimate abandonment of forest use on a global scale.

Acknowledgements. This preprint is published on the basis of the lecture given by A.M. Makarieva at the XXXIVth Winter School of PNPI, February 2000. Original results were obtained together with V.G. Gorshkov (Gorshkov *et al.*, 2000). The work was supported by the Russian State Ecological Committee and a Research Support Scheme grant of Soros Foundation for A.M. Makarieva.

References

- Àcs F., Hantel M. (1998) The land-surface flux model PROGSURF. *Global and Planetary Change*, **19**: 19-34.
- Allen C.W. (1955) *Astrophysical Quantities*. Athlone Press, London.
- Barry R.G., Chorley R.J. (1987) *Atmosphere, Weather and Climate*. New York: Methuen.
- Cross M.C., Hohenberg P.C. (1993) Pattern formation outside of equilibrium. *Rev. Mod. Phys.*, **65**, 851-1111.
- Ginzburg S.L., Pustovoit M.A. (1998) Noise-induced hypersensitivity to weak alternating signals. *JETP Letters*, **67**: 627-632.
- Gorshkov V.G., Makarieva A. M. (1998) Impact of terrestrial and oceanic biota on the modern carbon and oxygen cycles. *Ecological Chemistry*, **7**: 129-137.
- IPCC (1994) *Climate Change 1994: Radiative forcing of climate change and an evaluation of the IPCC IS92 Emission Scenarios*. J.T. Houghton, L.G. Meira-Filho, J. Bruce, Hoesung Lee, B.A. Callander, E. Haites, N. Harris and K. Maskell (Eds.). Cambridge Univ., Cambridge.
- IPCC (1996) *Climate Change 1995: The Science of Climate Change*. J.T. Houghton, L.G. Meira-Filho, B.A. Callander, N. Harris, A. Kattenberg and K. Maskell (Eds.). Cambridge Univ., Cambridge.
- Kasting J.F., Toon O.B., Pollack J.B. (1988). How climate evolved on the terrestrial planets. *Sci. Amer.*, **258**, 90-97.
- Kondratyev K.Ya. (1999) *Climatic effects of aerosols and clouds*. Springer-Praxis Series in Atmospheric Physics and Climatology, Chichester, UK.
- Landau L.D., Akhiezer A.I., Lifshitz E.M. (1965) *General Physics. Mechanics and Molecular Physics*. Nauka, Moscow. (in Russian)
- Li Z.-X., Le Treut H., Ghil M. (1997) Atmospheric radiative equilibria in a simple column model, *Climate Dynamics*, **13**, 429-440.
- Lvovitch M.I. (1974) *World Water Resources and their Future*. Mysl, Moscow. (in Russian)

- McKay C. (1983) Section 6. Mars. In: R.E.Smith and G.S.West (eds), *Space and Planetary Environment Criteria Guidelines for Use in Space Vehicle Development*. Huntsville, AL: Marshall Space Flight Center.
- Mitchell J. (1989) The “greenhouse” effect and climate change. *Rev. Geophys.*, **27**, 115-139.
- North G.H., Cahalan R.F., Cookley J.A. (1981) Energy balance climate models. *Rev. Geophys. and Space Phys.*, **19**, 91-121.
- Pollack J.B., Toon O.B., Boese R. (1980) Greenhouse models of Venus' high surface temperature, as constrained by Pioneer Venus measurements. *J.Geophys.Res.*, **85**, 8223-8231.
- Ramanathan V., Callis L., Cess R., Hansen J., Isaksen I., Kuhn W., Lacis A., Luther F., Mahlman J., Reck R., Schlesinger M. (1987) Climate-chemical interactions and effects of changing atmospheric trace gases. *Rev. Geophys.*, **25**: 1441-1482.
- Raval A., Ramanathan V. (1989) Observational determination of the greenhouse effect. *Nature*, **342**, 758-761.
- Schlesinger W.H. (1990) Evidence from chronosequence studies for a low carbon-storage potential of soils. *Nature*, **348**, 232-234.
- Schneider S.H. (1989) The greenhouse effect: science and policy. *Science*, **243**, 771-781.
- Tang B., Weaver A.J. (1995) Climate stability as deduced from an idealized coupled atmosphere-ocean model. *Climate Dynamics*, **11**, 141-150.

Работа поступила в Издательство ПИЯФ РАН 18.08.2000 г.

Ответственный за выпуск *А.М. Макарьева*

Отпечатано в типографии ПИЯФ РАН
188300, Гатчина Ленинградской обл., Орлова роща
Зак. 337, тир. 100, уч.-изд. л. 2,5 ; 30.08.2000 г.