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The climate of the Earth
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A scientific session of the Physical Sciences Division of the Russian Academy of Sciences (RAS) on the climate of the Earth was held in the conference hall of the Lebedev Physical Institute, RAS, on 12 April 2011.

The following reports were put on the session agenda posted on the web site www.gpad.ac.ru of the Physical Sciences Division, RAS:

(1) **Nigmatulin R I** (Shirshov Institute of Oceanology, RAS, Moscow) "Ocean and climate";

(2) **Byalko A V** (Landau Institute for Theoretical Physics, RAS, Chernogolovka, Moscow region; journal *Priroda* of the Presidium of RAS) "Relaxation theory of climate."

A paper written based on report 2 is published below.

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Relaxation theory of climate

A V Byalko

1. Introduction

An analysis of data obtained from antarctic ice cores allows developing a simple theory that explains the physical processes of the past climate and quantitatively predicts the future climate.

From the physical standpoint, there is not the slightest doubt about the reality of the greenhouse effect. The balance of energy falling on Earth from solar radiation and the microwave radiation leaving Earth into space indicates that the Earth's surface temperature is 32 K warmer than the equilibrium temperature that would be in the absence of the greenhouse effect. The theory of the greenhouse effect is also sufficiently well developed. The absorption spectra of the greenhouse gas molecules carbon dioxide (CO_2), methane (CH_4), and water vapor (H_2O) and their absorption band widening as pressure increases are well known, and the radiation convection theory, although quite complex, is nevertheless sufficiently developed for reliable computer modeling of Earth's atmosphere [1].

The increasing combustion of fossil fuels (coal, oil, and gas) in the last century and a half has led to a substantial 40% increase in the main greenhouse gas (CO_2) in the atmosphere. The global warming resulting from this has been calculated by several world climate centers. Their results for the predicted temperature increase by the end of the 21st century over that at the beginning of the 20th century are in the range from 3 to 5.5 K. Such divergences arouse certain doubts in general society. One reason for such differences, the most obvious, is different model representations of the dynamics of further industrial development and, consequently, of future CO_2 emissions. On the other hand, there are also difficulties with the physical understanding of climate processes.

For example, it is necessary to specify the cloud fraction in the model. Clouds cover approximately half Earth's surface on the average. This follows from the symmetry of convection: the vertical flows in cloudy cyclones and in cloudless anticyclones are equal. But we pose a qualitative question: Was the cloud fraction during glacial periods more or less than the contemporary cloud fraction? The factual answer is unknown. Current measurements, which correspond to a very narrow temperature range, give the sign of the trend inside the error limits [2]. Meanwhile, the quantitative dependence is necessary for modeling the climate: the cloud fraction effect on the planet albedo is stronger than the effect of the glacial cover. The schoolhouse notion of the dew point is unfortunately inapplicable for describing cloudiness in a turbulent atmosphere [3].

Another, more substantial difficulty for computer climate modeling is related to the need to predict the mass and heat exchanges between the upper layers of the ocean and its depths. The average temperature of the ocean surface is about 14 °C, and the ocean depths are substantially colder, 3 °C in all. Such a temperature distribution (seemingly contradicting thermodynamics) is maintained by the system of global thermohaline currents, called the Great Conveyor, which was discovered only in the 1980s as a result of research by Soviet and American oceanologists [4, 5]. The Great Conveyor begins with the sinking of cold saline waters near Greenland, flows in the depths of the Atlantic, curves around Antarctica, and surfaces near India and in the north Pacific Ocean. The time of the entire journey is about 1.5 ky. This means that the speed of the Great Conveyor current is two orders less than the speed of the ordinary wind-driven currents. Nevertheless, because of the large heat capacity of water, the influence of the Great Conveyor on climate is quite substantial.

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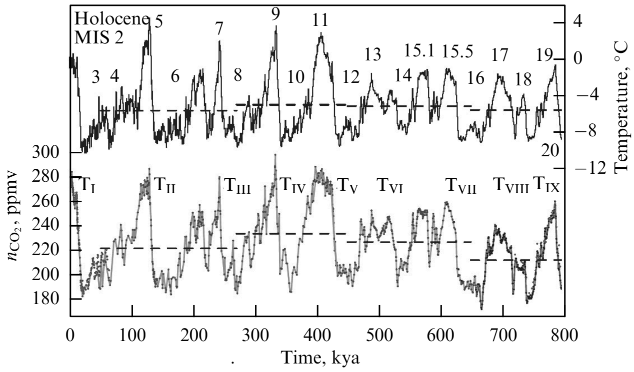

Figure 1. Variations of temperature (upper curve) and CO_2 concentration (lower curve) for the last 800 ky obtained from the results of analyzing ice cores from Antarctica (from [6]). The marine isotope stages (MIS) are shown by numbers; $T_I - T_{IX}$ are the glacial period terminations (ppmv is parts per million by volume).

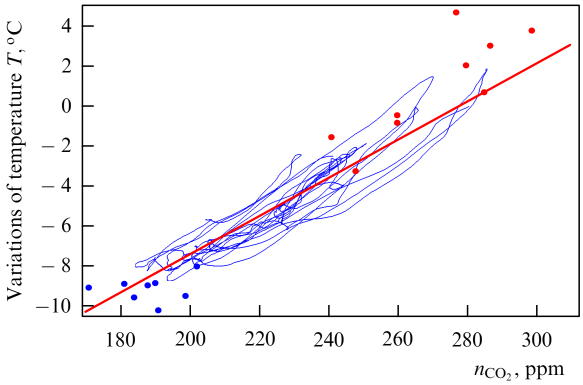

Figure 2. Dependence of the Paleocene temperature on CO_2 concentration shifted by 3 ky and the regression line. The time dependence is smoothed by a sliding average with a 10 ky window. Temperature extremes in the original data are shown by circles.

Both these difficulties can be partially overcome if the antarctic ice core data on the historical climate is used for forecasting.

2. Analysis of climate data

Climate changes during the last 800 ky can be judged from the time dependences of the temperature T and carbon dioxide concentration n_{CO_2} [6] (Fig. 1). Immediately after [6] in the same issue of *Nature*, data on the methane concentration was published [7]. A standard mathematical analysis of those dependences [8] showed the following:

(1) The autocorrelation functions of the dependences $T(t)$, $n_{CO_2}(t)$, and $n_{CH_4}(t)$ are similar to each other. The decrease in the temperature autocorrelator at small times is slower than for the correlation functions. In contrast, the methane correlator decreases sharply, which indicates that methane is less predictable. The correlators become negative when the time shift reaches 20 ky. There is a wide minimum in the range from 40 to 60 ky, then maximums appear at about 90 ky, and there is also one more maximum for the greenhouse gases close to 120 ky. The minimum around 40 ky is somewhat surprising, because a maximum should appear here according to the Milankovitch theory. That maximum indeed arises, but in the time period from 2.7 to 1.3 mya [9]. In the intervals 1.3–0.7 and 3.2–2.7 mya, both climate oscillation modes are present.

(2) The mutual correlations (covariances) contain information about which function is leading and by what characteristic times. The temperature and n_{CO_2} dependences turn out to be closely related to a maximum covariance of 0.88 attained with temperature leading $n_{CO_2}(t)$ by approximately 2 ky. Unfortunately, the accuracy of calculating lags and leads is not very high, about 0.5 ky. Temperature and methane concentration turned out to be almost synchronous; the maximum covariance is slightly lower, equal to 0.82. Finally, the CO_2 concentration lags n_{CH_4} an average of 1.5 ky with a maximum covariance of 0.74.

(3) The correlations and covariances exhaustively describe random dependences if the variations of the variables are distributed according to a normal (Gaussian) law. The normalized rank distributions of the three variables T, n_{CO_2}, and n_{CH_4} were constructed and then approximated by a tenth-degree polynomial, which was then differentiated. With this method, the decaying tails of the distribution turn out to be unreliable, but the position of the maximums are determined with sufficient accuracy. The statistics of the methane concentration turned out to be close to normal: it has one maximum at $n_{CH_4} = 440$ ppb. The temperature distribution has two maximums, at -7.8 °C and at 3.3 °C. The carbon dioxide concentration is distributed with three maximums equal to 202, 236, and 282 ppm.

(4) The mean statistical interdependences (regressions) were not published in [8], because it remained unclear how to relate the data for the last 800 ky of climate history to the contemporary warming.

The regression $T - n_{CO_2}$ constructed with the observed lag of the carbon dioxide concentration taken into account [10] is shown in Fig. 2. The planet geography has been almost unchanged for a million years, and the relations between the climate variables characteristic for the past should consequently also be manifested in our times. The CO_2 concentration today has reached a level of 390 ppm, which is unprecedented for the last million years. If the regression line $T(n_{CO_2})$ is extrapolated to that value, then it turns out that the temperature should increase by 9 to 12 °C. Warming is occurring, but today it does not exceed 1 °C compared with the temperature of the preindustrial era when the CO_2 concentration was equal to 280 ppm. Explaining this discrepancy is the main goal of this paper.

The generally accepted approach to understanding climate variations does not allow understanding the reason for this imbalance. The Intergovernmental Panel on Climate Change (IPCC) uses the concept of 'climate forcing,' which unfortunately lacks an adequate physical justification. Its applicability is admissible, for example, for describing the cloud fraction, which changes very slowly. But forcing applied to greenhouse gases without taking the dynamics of their concentrations into account is a characteristic that is useless for describing the contemporary climate. Below, we propose a different concept that takes heat inertia (the heat capacity of the ocean and, in particular, its upper layer) into account.

3. Climate equilibrium curve

The domain of climate variation in the variables (T, n_{CO_2}) turned out to be strongly stretched out. We can therefore assume that an equilibrium curve $T_{eq}(n_{CO_2})$ exists. The data from the antarctic drilling allows finding its linear approximation, which is just the linear regression

$$T_{eq} = (0.098 n_{CO_2} - 27.1)\ [^\circ C]\,,$$

where the equilibrium CO_2 concentration is expressed in ppm. Taking a moving average of the original data has practically no effect on the slope of the line. Calculating quadratic corrections to it would apparently exceed the accuracy. The standard deviation of the temperature is 0.98 °C, but the extrapolation error in the region of contemporary concentrations can reach several degrees, as is shown by a comparison with the quadratic approximation. The CO_2 concentration in the preindustrial era (280 ppm) corresponds to a temperature T_{eq} equal to 0.3 °C.

The climate equilibrium is determined not only by carbon dioxide and methane but also by other factors, in particular, solar activity. The influence of these other factors 'smears' the equilibrium curve into a certain region; the width of that region is small, whence it follows that their combined action is relatively small. The influence of water vapor is not small, but it is already taken into account automatically in $T_{eq}(n_{CO_2})$ because the atmospheric content of water vapor itself depends on temperature. In principle, the equilibrium curve can be found using the methods of atmospheric theory, but it seems simpler for now at least to use its linear approximation from the 'climate experiment' conducted by Nature herself for the last million years.

We consider the applicability of this approximation of the equilibrium curve in the limit cases. We present a thought experiment: we deprive Earth's atmosphere of all carbon dioxide. At $n_{CO_2} = 0$, we obtain $T_{eq} = -27\,^\circ C$, in other words, the average temperature of Earth's surface decreases to $-13\,^\circ C$ (the possible extrapolation error is a few degrees). Even if the entire ocean is covered with ice, a weak greenhouse effect would be supported by the remaining water vapor, which would yield a certain increase over the radiation equilibrium temperature of Earth, equal to 255 K ($-18\,^\circ C$). With the extrapolation error taken into account, we can consider that the thought experiment has concluded satisfactorily.

In contrast, we consider whether the proposed equilibrium is suitable for a period when the planet would be 10 to 15 °C warmer than today. The estimates of the CO_2 concentration in the Eocene Epoch (50 mya) are not very reliable: its upper bound is high, but the minimal magnitude, around 600 ppm, with a stretch falls into the region of possible error [11]. Moreover, it cannot be excluded that at high temperatures, the cloud fraction noticeably increases, thus increasing the albedo. In that case, the equilibrium curve $T_{eq}(n_{CO_2})$ should pass through noticeably below its linear approximation.

4. Relaxation equation

We suppose that the climate equilibrium exists. Then small deviations from the equilibrium should approach it during some time τ, which is characteristic for the described system:

$$\frac{dT}{dt} = \frac{T_{eq}(n_{CO_2}) - T}{\tau} + w(t)\,.$$

Here, $w(t)$ is a function corresponding to a perturbation of the climate system. The linear differential equation is easily integrated:

$$T(t) = T(t_0) + \exp\left(-\frac{t}{\tau}\right) \int_{t_0}^{t} \left[w(t') + \frac{T_{eq}\left(n_{CO_2}(t')\right)}{\tau} \right] \exp\left(\frac{t'}{\tau}\right) dt'\,.$$

We turn to the physical interpretation of these equations. The basic climate characteristic, the average temperature of Earth's surface, almost coincides with the average temperature of the ocean surface. This follows not only because the area of the ocean surface exceeds the area of dry land, but also because the heat capacity of water is significantly greater than the heat capacity of mountain rock and of soil. The distribution of temperature over Earth's surface differs from the normal distribution at large deviations [12], but it is sufficiently close to it in the region of the single maximum. If the lowered temperatures of dry-land mountain regions are brought to sea-level temperatures adiabatically, then the temperature contrast between dry land and the ocean turns out to be insignificant. The surface layer of the ocean is warmer than the deep layers and the atmosphere because it is the ocean surface layer that absorbs the largest part of the solar energy. Air convection transports the absorbed influx upward to the boundary of the troposphere, where the energy is radiated into space in the microwave region of the spectrum, and the height of the radiation is determined by the small concentrations of greenhouse gases.

Both the atmosphere and the ocean depths influence Earth's climate. As is shown in Section 6, the energy flux in the atmosphere, i.e., the insolation power, is three orders greater than the heat exchange in the Great Conveyor; nevertheless, the influence of the latter on the climate is not small. The reason for this is that the insolation is quickly compensated by the planet heat radiation, and the time scale of heat exchange with the ocean depths (relaxation time) is much larger than that of the atmosphere. It is easy to show that the heat capacity of the 100-meter surface layer of the ocean is 30 times greater than the heat capacity of the entire atmosphere of Earth; the same also relates to their relaxation times. The slow current maintaining the cold of the depths ensures the positive balance of the surface temperature. On the contrary, weakening of the Great Conveyor leads to a gradual cooling of the climate.

5. Heat balance of the Pleistocene climate

Returning to the relaxation equation, we note that it takes the action of greenhouse gases into account by the equilibrium function $T_{eq}(n_{CO_2})$. The influence of the Great Conveyor is described by the term $w(t)$. To calculate the heat flux between the surface of the ocean and its depths, we multiply that flux by the heat capacity of the ocean layer above the thermocline:

$$C = 0.71 c_{H_2O} 4\pi R^2 h = 1.5 \times 10^{23}\ \mathrm{J\ K^{-1}}.$$

Here, the coefficient 0.71 is the ocean surface fraction, R is the radius of Earth, c_{H_2O} is the specific heat of water, and $h \sim 100$ m is the estimate of the thermocline depth. The heat capacity of the ocean surface layer is 30 times greater than the heat capacity of the atmosphere, but 40 times less than the heat capacity of the whole ocean. The relation between their relaxation times should also be about the same.

We apply the temperature relaxation equation to data obtained from antarctic ice cores. During the last 780 ky, the temperature and the CO_2 concentration completed eight

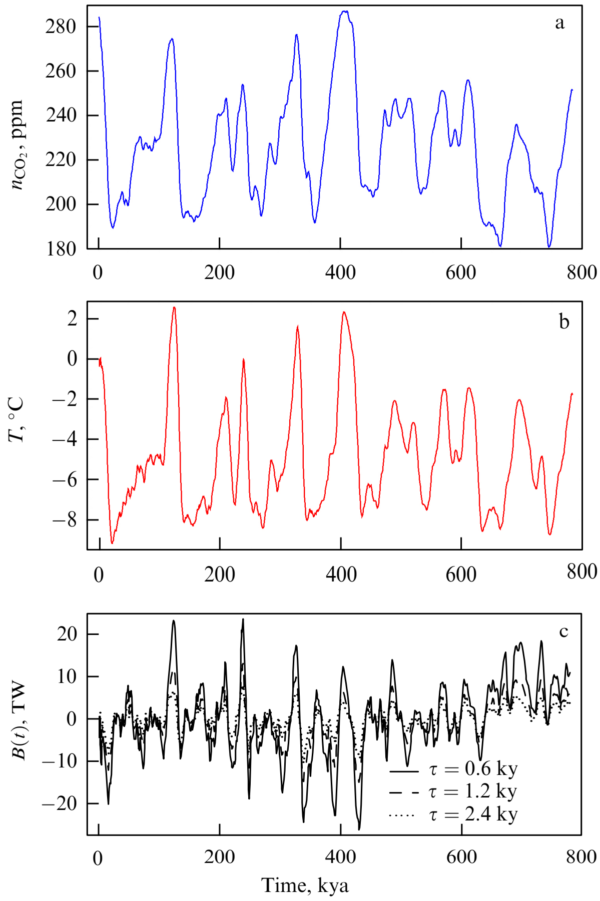

Figure 3. Paleocene climate dependences: smoothed variations of (a) CO_2 concentration, (b) temperature, and (c) heat exchange power $B(t)$ calculated for three relaxation times.

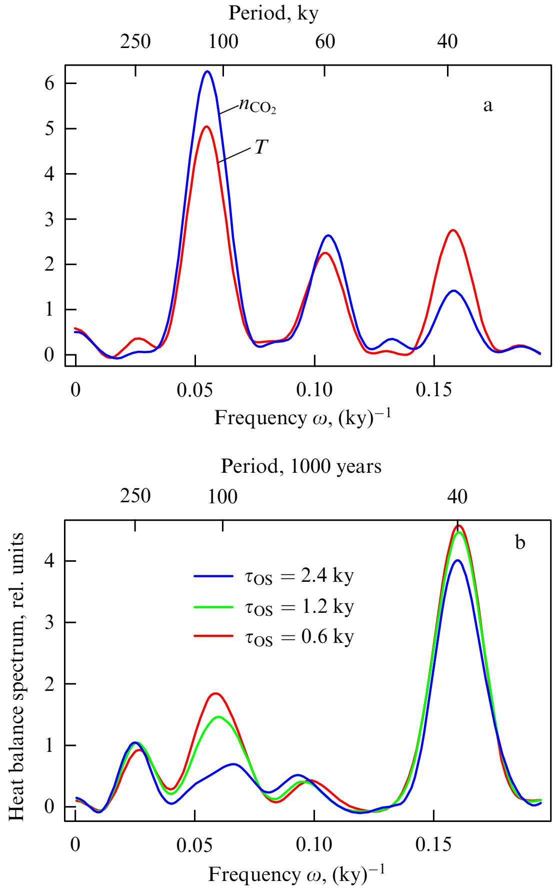

Figure 4. Spectra of climate variables: (a) temperature and CO_2 concentration; (b) power of the heat exchange between the surface layer of the ocean and its depths for different relaxation times.

100 ky cycles and entered the Holocene at about the initial levels. Consequently, the heat balance of the ocean surface was zero on the average over those eight cycles. Using the temperature relaxation equation, we calculate the power of the heat exchange between the surface and the deep waters:

$$B(t) = Cw(t) = C\left[\frac{T - T_{eq}(n_{CO_2})}{\tau} - \frac{dT}{dt}\right].$$

The relaxation time τ most likely is of the order of the turnover time of the Great Conveyor, 10^3 years. For greater confidence, we calculate for three different relaxation times: 0.6, 1.2, and 2.4 ky. In the initial data, the dependence of temperature on time is a nondifferentiable curve. To calculate the derivative, we therefore used data smoothed with a sliding window of 10 ky. This procedure eliminates high frequencies and random measurement errors but does not affect information about slower processes.

In Fig. 3, we present the results of calculating the heat exchange power $B(t)$ together with the smoothed temperature and CO_2 concentration. The temperature extremes correspond to the largest extremes of the heat flux. Moreover, the energy balance manifests a cyclicity with a characteristic period of 40 ky, which was not in the initial T and n_{CO_2} data, where only the 100 ky periodicity was observed.

This unexpected result is more clearly manifested in a spectral analysis. Using standard methods, we found the correlation functions $K(t)$ of all dependences and then their oscillation spectra:

$$S(\omega) = \frac{1}{\sqrt{2\pi}}\int_0^\infty K(\tau)\cos(\omega\tau)\,d\tau,$$

which is the Fourier transform of the correlation functions (Fig. 4). Analyzing them leads to several physical consequences.

(1) In the temperature and n_{CO_2} spectra, we observe a frequency corresponding to a period of 60 ky. This should be understood not as the difference between the 100 ky and 40 ky periods (frequencies, not their periods, are subtracted or added), but as a resonance between frequencies inverse to the periods of 120 ky and 40 ky: $60 = (120 \times 40)/(120 - 40)$. Periods of 120 ky and 90 ky are present in the spectrum of Earth's eccentricity.

(2) In the power spectrum calculated with the 2.4 ky relaxation time, the maximum at the frequency $2\pi/97$ turned out to be unjustifiably low. It seems that the possible relaxation time is limited to the range from 0.5 ky to 1.5 ky.

(3) The maximums of the two other power spectra correspond to periods of 39.3 ky and 106–108 ky, which are sufficiently close to the Milankovitch periods of 40–41 ky and 90–120 ky. The difference between the small periods is perhaps a consequence of a mismatch between the glacial and the astronomical time scales.

(4) The resonance frequency $2\pi/60$ is generally absent from all the heat exchange power spectra. We may interpret this fact as follows: the heat exchange of the Great Conveyor

is the primary physical phenomenon reacting directly to the variation in the astronomical parameters, and the dependences of the temperature and greenhouse gases are secondary.

We return to the energy balance of the Pleistocene climate. The average value of the power variations over the last 780 ky is close to zero; this is as it should be, because a whole number of climate cycles occurred during that time. The root mean squared deviation, i.e., the characteristic amplitude of the energy balance, is equal to 8.9 TW with $\tau = 0.6$ ky and 4.5 TW with $\tau = 1.2$ ky. These values are approximately inversely proportional to the relaxation time. This power is comparable to the total heat flux from the core through the ocean bottom of 4 TW, which corresponds to a flux density of 0.1 W m^{-2} [13]. The heat balance of the Great Conveyor has not yet been measured. Judging from the fact that the climate has been almost constant for the last 6 ky, the contemporary power of the Great Conveyor should compensate the heat flow from the ocean bottom. We note one more circumstance that is essential for understanding the Pleistocene climate: the reaction time of the whole ocean to the competition between the Great Conveyor and the core heat flux is approximately 40 times greater than τ; this time is therefore close to the small Milankovitch period.

The qualitative conclusion from this analysis of the spectra and amplitudes of the heat exchange can be formulated as follows: the physical cause of the climate cycles is the quasiperiodic variation in the cooling power of the Great Conveyor competing with the constant heat flux from Earth's core. The periodicity of these variations coincides with the small Milankovitch cycle. Milankovitch proposed that a glacial period starts with long, cold winters in the northern hemisphere and is caused by a substantial increase in the planet's albedo. But a decrease in the intensity of the Great Conveyor during the glacial periods [14] with such orientations of Earth's axis with respect to the perihelion is also completely logical. The perennial floating ice is unable to melt during the short summer; during the long winter, its thickness insulates the saline waters brought by the Gulf Stream, limiting their cooling and subsequent sinking. Investigations of the age of the deep waters formed in the North Atlantic during the Holocene [15] qualitatively confirm this conclusion. Investigations of the paleotemperature of the deep ocean waters [9] show that, for the last 900 ky, their warming led the termination of glacial periods by 11 ± 5 ky. Such a warming of the deep waters supports the idea, apparently first advanced by Chumakov [16], that namely the decomposition of methane hydrates was the initiator of the terminations. Data from the ice cores also indicate that at the end of the glacial periods, the separation of methane leads the increases in temperature and carbon dioxide concentration [8]. The further development of these ideas should resolve the difficult climate problem concerning the physical mechanism of the terminations.

6. Contemporary warming

The temperature relaxation equation describes the heat exchange of waters through the thermocline, the lower boundary of the upper ocean layer. We attempt to use the analogue of this equation, the gas relaxation equation

$$\frac{\mathrm{d}n_{CO_2}}{\mathrm{d}t} = \frac{n_{CO_2}^{eq}(T) - n_{CO_2}}{\tau_{atm}} + P(t),$$

to describe the gas exchange through the interface of the ocean and atmosphere. Here, τ_{atm} is the sought gas relaxation time of the atmosphere and $P(t)$ is the global source of CO_2 in units of ppm y^{-1}.

It is known with sufficient accuracy how much coal, oil, and gas was extracted and consumed annually by the world energy sector since the beginning of the 20th century. These data are easily converted (see the table) into the potential increase $P(t)$ (i.e., that which would be in the absence of absorption) in the carbon dioxide concentration. This increase for the period 1960–2009 is shown by the solid broken lines in Fig. 5a. Beginning in 1958, the atmospheric CO_2 concentration has been measured on Mauna Loa on the island of Hawaii and is published monthly on the Internet [17].

Table. CO_2 emissions from combustion of extracted fuels.

Fuel	Carbon fraction, %	Combustion heat, MJ kg^{-1}	CO_2 emissions to the atmosphere, ppm (y TW)$^{-1}$
Coal	89	27	0.74
Oil	81	46	0.39
Gas	75	55	0.30

The variations of the average temperature T for this period are also known [18], but they are still insignificant and do not play any special role in the gas relaxation problem. As the equilibrium concentration, we can take its preindustrial value of 280 ppm or the equilibrium value at the contemporary temperature $n_{CO_2}^{eq}(1\,^{\circ}C) = 286$ ppm. Their difference characterizes the error in further calculations. Thus, the data from the antarctic ice cores is, in fact, generally not used in determining the contemporary response of the atmosphere to anthropogenic emissions.

All the functions of time in the gas relaxation equation are known. It remains to fit the only numerical parameter, the atmospheric relaxation time τ_{atm} with respect to the time of dissolving the gas by the ocean. The optimal values of τ_{atm} turn out to be in the range 25.1–27.5 y. As can be seen from Fig. 5b, the solution agrees well with the observations to the end of the year 2010.

This fact allows attempting to extrapolate climate tendencies into the future. Of course, the possible errors increase in this case. The CO_2 concentration today is already 40% higher than its equilibrium concentration; its further increase will inevitably take the gas relaxation equation out of the linear region. We therefore consider two limit scenarios such that the true scenario would be between them. The first, inertial scenario assumes a uniform increase in the extraction of all fossil fuels; moreover, the total CO_2 emissions increase at the same rate as during the last decade, at approximately 3% per year. The second, the radical scenario, stems from a gradual rejection of the use of fossil fuels. We assume a reduction in the extraction of coal (the worst for the atmosphere) beginning from 2015 down to a total prohibition by 2050. Further, the extraction and, most importantly, the use of oil and its products for heating and transportation is reduced by 2060. The extraction of gas only increases for now, but it may then even become necessary to reduce it. The increase in energy as a whole might be compensated by an accelerated development in the nuclear sector, the production of biofuels, and electrical energy from solar batteries.

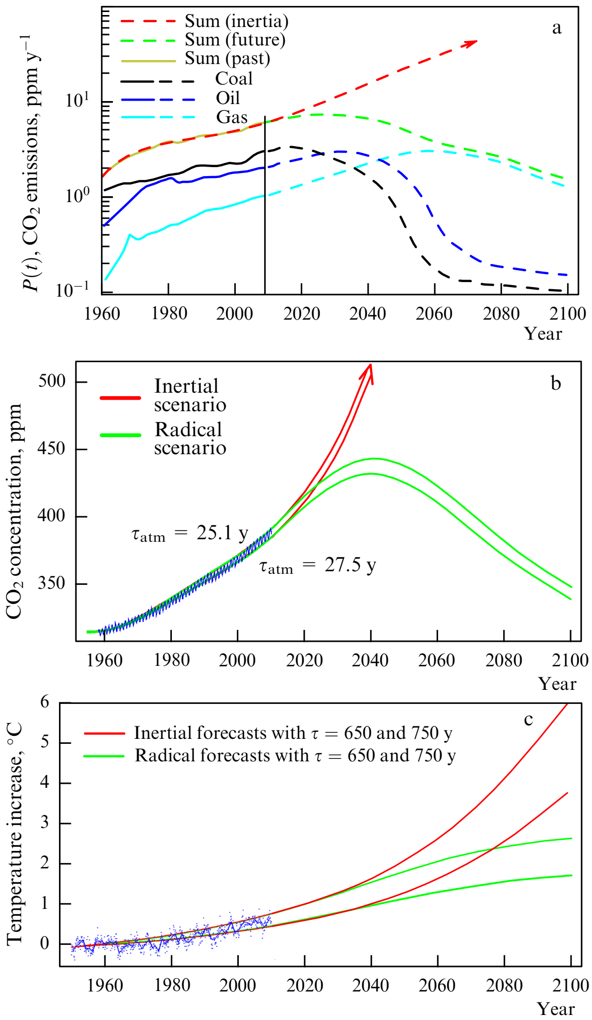

Figure 5. Comparison of the theoretical results and actual data for the contemporary greenhouse effect. (a) Potential annual increase in CO_2 concentration as the total result of coal, oil, and gas combustion together. (b) Monthly variation of n_{CO_2} together with the results of integrating the gas relaxation equation. (c) Change in the average global temperature according to meteorological data together with the results of integrating the temperature relaxation equation: the average annual temperature is shown by the broken line, and the average monthly temperature is shown by the points. The theoretical forecasts are given for two scenarios of fuel industry development, the inertial and the radical scenarios.

We use the obtained solutions of the gas relaxation equation in the two scenarios to solve the temperature relaxation equation. Climate variations, with the exception of those in recent decades, have been small, and we therefore assume that the heat exchange of the Great Conveyor with the ocean depths is balanced in the contemporary era and will remain so in the course of the century, $w(t) = 0$.

We vary the relaxation time such that the solutions of the temperature relaxation equation encompass the dispersion of the observations of the average surface temperature [18] for the period 1960–2010 (Fig. 5c). The obtained optimization of the range $\tau = 0.65-0.75$ ky agrees with the estimate previously made for the Pleistocene climate.

The practical consequences of the forecasts of the energy sector and the corresponding solutions of the relaxation equations are quite substantial. The main conclusion is as follows: all actions to 'correct' the atmosphere begin to affect the average temperature of the planet with a noticeable delay. Thus, in the radical scenario, the maximum CO_2 emission occurs in 2030, but its maximum concentration is attained only in 2042, and the temperature reaches some limit (possibly, a maximum) only by the end of the 21st century.

The warming leads to one more unpleasant consequence, which is that climate perturbations increase proportionally to the time derivative of temperature [19]. A qualitative conclusion hence follows: weather anomalies will become maximal by the middle of the 21st century, when the CO_2 concentration passes its maximum. This statement relates to the radical scenario, while the inertial scenario is completely catastrophic both for temperature and for weather anomalies. The humanitarian consequences of global warming cannot be evaluated in the framework of a physical approach to climate problems.

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