Paleoclimate: Supplements to the Milankovitch Theory

A.V. Byalko

Alexey Byalko, Associate Fellow, L.D. Landau Institute of Theoretical Physics, Russian Academy of Sciences; First Deputy Editor-in-Chief, *Priroda*

In 1920–1940 the Serbian astronomer Milutin Milankovitch developed a daring theory (the geological data at that time was insufficient), explaining the nature of climate cycles [1]. This theory was based on the Earth's asymmetry, the predominance of land masses in the northern hemisphere compared with the southern hemisphere. These land masses give rise to vast glaciers during cooling periods, increasing the Earth's albedo, i.e., the reflected fraction of sunlight. But the amount of solar radiation received at high northern latitudes varies significantly because the Earth's orbital parameters vary. The eccentricity of the Earth's orbit, now equal to 0.0167, was 0.06 in the past with (nonperiodic) changes due to planetary perturbations with a characteristic time of about 100 ky. These perturbations also cause oscillations of the Earth's axis relative to the perihelion of its orbit with a period of 41–42 ky. When the Earth slowly passes through the aphelion during the northern hemisphere winter, its insolation (average solar irradiation) is low, and glaciers grow significantly. During the short summer near perihelion, they cease to melt away because of the increased albedo. When the aphelion coincides with the northern hemisphere summer 20 ky later, glaciers do not expand significantly in the southern hemisphere, because there is little land for them except Antarctica.

Computer climate modeling has undoubted successes, especially for the recent time period. But modeling climate cycles based on the Milankovitch theory was not very successful. It seems that reason for this is that the physical mechanism based only on the albedo variation is insufficient to drive climate cycles. Moreover, it has been impossible to overcome the main deficiency of the Milankovitch theory: it lacks a mechanism for exiting from ice ages.

During the last 70 years, our knowledge about the climate system has expanded sunstantially. The current climate has warmed noticeably, and we clearly understand that this is happening under the action of the greenhouse effect from surplus carbon dioxide (CO_2), which is discharged into the atmosphere from burning coal, oil, and gas. In addition, a comprehensive database containing not only temperatures but also concentrations of greenhouse gases in the atmosphere of past epochs has been gathered by drilling sedimentary layers and glaciers. We can now supplement the Milankovitch theory with the results of current studies of paleoclimates.

But before proceeding to these supplements, we need to expound some well-known propositions describing the Earth's climate system.

Heat Balance of the Earth

The flux of solar radiation incident on the Earth, $W_0 = 1362$ W·m^{-2}, can be considered constant up to the last digit. Part of this energy is reflected by clouds and the surface without a frequency change: the current value of the Earth's albedo according to brightness measurements of the new moon is $A_0 = 0.297 \pm 0.005$. A small part of the solar flux is absorbed by the ozone layer and atmospheric gases, and the largest share is absorbed by the surface, which heats the atmosphere from below. This heat flow is transferred up by convection and is irradiated into space in the microwave frequency range with a spectral density close to the spectrum of a black body. The mean temperature of the outgoing radiation in the thermal frequency range (radiation temperature T_{rad}) can be easily calculated from the equality of incoming and outgoing energy flows:

$$T_{rad} = [W_0(1 - A_0)/4\sigma]^{1/4} = 255 \text{ K},$$

where $\sigma = 5.6705 \cdot 10^{-8}$ W·m^{-2}K^{-4} is the Stefan–Boltzmann constant. The error due to uncertainty of the current albedo is less than 0.5 K. The spectrum of this radiation has a maximum at wave lengths around 10 micrometers.

In the past, the Earth's albedo A_0 varied in a significantly larger range. Vast areas of the land were covered by ice sheets, reflecting sunlight well, but the ocean area not covered by ice varied not so dramatically, and the albedo did not increase substantially. On the other hand, the radiation temperature depends weakly on the albedo, the dependence being proportional to $[(1 - A)/(1 - A_0)/]^{1/4}$. Hence, a 10% variation of the albedo results in only a 1% variation of the temperature, less than 3 K.

In the past, as we will see below, the mean temperature T_0 of the Earth's surface varied in the range of more than 12°, always being higher than $T_{rad,}$ for two main reasons: the greenhouse effect and energy exchange between the atmosphere and ocean.

The greenhouse effect was predicted in the beginning of the past century by S. Arrhenius. It is caused by the presence in the atmosphere of gases absorbing radiation in the microwave range: carbon dioxide CO_2, water vapor H_2O, and methane CH_4.

These three gases have different distributions in the atmosphere. Carbon dioxide is mixed almost evenly in the entire troposphere and stratosphere. The saturation density of water vapor falls exponentially as the temperature decreases, falling by half when the temperature decreases 10°. Water vapor concentrations are therefore unevenly distributed across the Earth's surface. They drop sharply above cloud layers, and water droplets do not absorb in the microwave range.

Methane molecules absorb microwave radiation one to two orders of magnitude more strongly than CO_2 and H_2O, but the atmospheric concentrations of methane are usually 400 to

600 times lower. The methane cycle is very complicated: methane is discharged into water from the ocean bottom; it is produced by bacteria in course of organic decomposition and is consumed by other bacteria; it is oxidized to CO_2 in seawater containing dissolved oxygen and is also oxidized in the atmosphere under the action of solar ultraviolet radiation. It is very important that the modern ocean at depths from 300 to 600 m contain significant deposits of methane hydrate $CH_4 \bullet H_2O$ under a thin layer of sediments. This solid compound is in equilibrium with water-dissolved methane; its deposits grow when the temperature lowers and fall when the temperature rises or the pressure falls.

The atmosphere emits radiation at altitudes of 9–12 km, where the troposphere becomes the stratosphere; the ambient temperature there is equal to the radiation temperature. The difference between the surface and radiation temperature increases with the concentration of greenhouse gases. Unfortunately, a precise calculation of the greenhouse effect is not yet possible. The quantum transition spectra for all the mentioned molecules are known and consist of many narrow lines. As a result of frequent collisions with other air molecules, the energies of these transitions became fuzzy because of the uncertainty principle, and this collection of lines coalesces into absorption bands. For gases at a constant pressure and temperature, the absorption spectra are calculated using complex programs [2], but the complete problem of radiation heat transfer in the real atmosphere is not solved. This fact gives many well-educated and less-educated people an excuse to deny the greenhouse effect altogether. But experimental measurements of absorption unambiguously demonstrate the significance of the greenhouse effect.

Thermohaline circulation. Systems with a heat flow, as a rule, are not in thermal equilibrium. The ocean, whose heat capacity is about a thousand times larger than that of the atmosphere, plays a substantial role in the Earth’s heat balance. In principle, it can be either a heat source or a heat sink for the atmosphere, and this depends on a complex pattern of ocean currents. The mean ocean temperature in the modern epoch (276 K) is noticeably lower its surface temperature (288 K = 14°C). This indicates that ocean was a heat source for a long time, warming the atmosphere. There are three regions on Earth where cool salty water sinks from the surface into the ocean depths. One region is south of Greenland, and the other two regions are near the coasts of Antarctica. For example, Gulf Stream in the Atlantic carries warm salty water to the north. This water cools during the polar winter but does not have enough time to mix with the ambient fresher waters and sinks.*

* There is no analogous process for Kuroshio Current in the Pacific Ocean, which indicates that a certain pattern of coastlines and bottom topography is needed for sinking to occur.

There is indeed an example of the opposite process: relatively cool fresh water from the Atlantic enters the Mediterranean Sea through the Straits of Gibraltar, flows to the east on the surface becoming more and more salty because of evaporation along the way. Between Crete and Cyprus it sinks, flows to the west, and finally returns to the Atlantic as a warm but very salty near-bottom current through the same Straits of Gibraltar. It obviously follows from this that the Mediterranean pumps heat into the ocean at the expense of cooling the regional atmosphere. But the ocean as a whole is cooler than the atmosphere, and this means that the whole system of slow thermohaline currents gives a positive contribution to the heat balance of the near-surface layer of the atmosphere. That is why a global heat balance, which was a basis for our estimate of the radiation temperature, cannot be exact for the atmosphere at any given instant; it will be correct only on average for a time period needed for the ocean to relax to the astronomically varied planet insolation and the atmospheric concentrations of greenhouse gases.

This description of the climate system can be confirmed by analyzing data on Pleistocene climates from ice cores obtained by drilling ice sheets in Greenland and Antarctica. These data also allow a series of far-reaching conclusions.

Pleistocene Climate Variations

Ice sheet deposits in Antarctica and Greenland carry important information on past climates. The seasonal lamination of ice allows determining its age. The atmospheric concentrations of carbon dioxide and methane at the time of ice deposition are established by analyzing air bubbles and gases dissolved in ice. The annual average temperature is calculated from deviations of water deuterium concentrations (heavy water DHO has a different dependence of vapor density on condensation temperature compared with H_2O). Detailed results of such analyses by different research groups were recently published in *Nature* [3, 4].

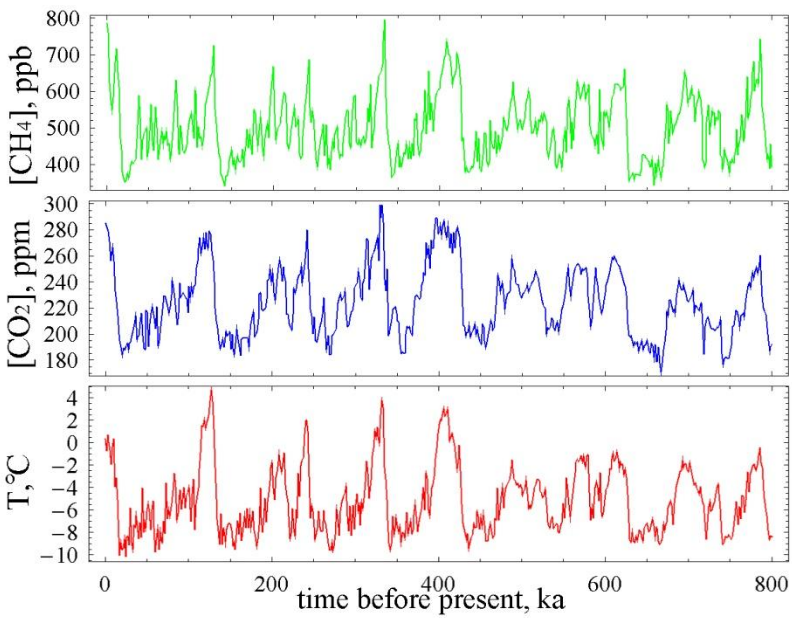

Fig. 1. Results of drilling the Antarctic ice sheet: history of climate for the last 800 ky. Red curve, temperature anomaly relative to the present; blue curve, CO_2 concentrations in parts per million (ppm); green curve, CH_4 concentrations in parts per billion (ppb).

It can be seen from the graphs in Fig. 1 that

— first, the interdependence of the three variables (T, [CO_2], [CH_4]) is rather significant (a chemical formula in square brackets denotes the atmospheric concentration of that gas);

— second, eight climate cycles lasting nearly 100 ky each are generally similar, beginning with a fast rise, having a sharp maximum followed by an intermittent decrease usually ending with low stagnation level for temperature and carbon dioxide concentration but with drop to a deep minimum for methane concentration;

— third, the range of variation relative to the mean is maximum for [CH_4] and minimum for [CO_2];

— finally, the conclusion that temperature variations are determined by changing concentrations of greenhouse gases is naturally tempting but, as we shall later see, at least premature and possibly wrong.

The average temperature of Antarctica during 800 ky turned to be 5.1°C lower than its current value, and its maximum temperature was 4°C higher. In our opnion, this variation is a consequence of a varying heat exchange between the ocean and the atmosphere, and the role of albedo is secondary.

The publication of these data in *Nature* summarized the results of tremendous work on drilling ice sheets and a vast amount of chemical and isotope analyses. But a standard mathematical analysis of these dependences was not published for some reason, although we are sure that the analysis was known to the authors of those works. Perhaps, the reason is certain strangenesses in the results; they do not yield an obvious interpretation. We perform a mathematical analysis of the three time dependences.

Analysis of the Climate Data

The graphs of temperature and greenhouse gas concentrations in [3, 4] were digitized, and the obtained series were analyzed mathematically (Fig. 2).

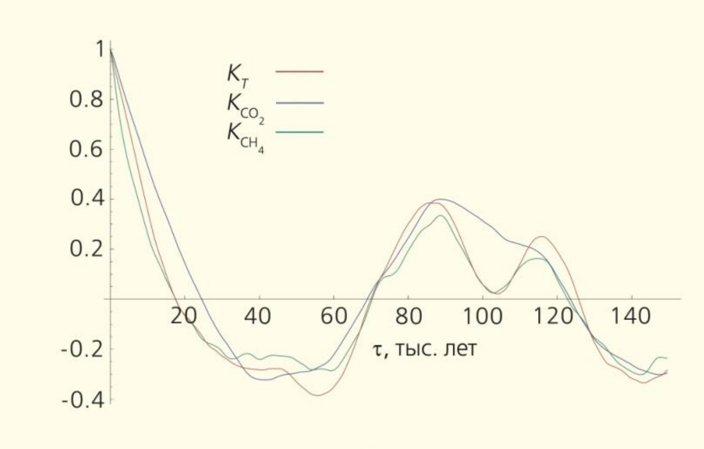

Fig. 2. Autocorrelations of temperature (red curve), carbon dioxide (blue curve), and methane (green curve).

The autocorrelation functions for the variables $T(t)$, [CO2](t), and [CH4](t) look similar to each other. Their derivatives are negative at $t = 0$, which means that they are not differentiable with respect to time. The autocorrelator decreases more slowly for carbon dioxide than for the other variables at small time values, i.e., [CO2](t) is the “smoothest” of the three variables. The reason for this becomes clear in what follows: carbon dioxide has three different possible sources: ocean, land, and oxidation of methane. The correlator for methane, in contrast, drops sharply, and this indicates that it is more unpredictable. The correlators became negative around 20 ky, have wide minima in the range 40–60 ky, and then have maxima around 90 ky. Each greenhouse gas has one additional maximum near 120 ky. A minimum near 40 ky is somewhat surprising because there should be a maximum there according to the Milankovitch theory. Such a maximum indeed occurred but during the time period 2.7–1.3 million years ago [5]. Both modes of climate cycles are present during the time periods 1.3–0.7 and 3.2–2.7 million years ago.

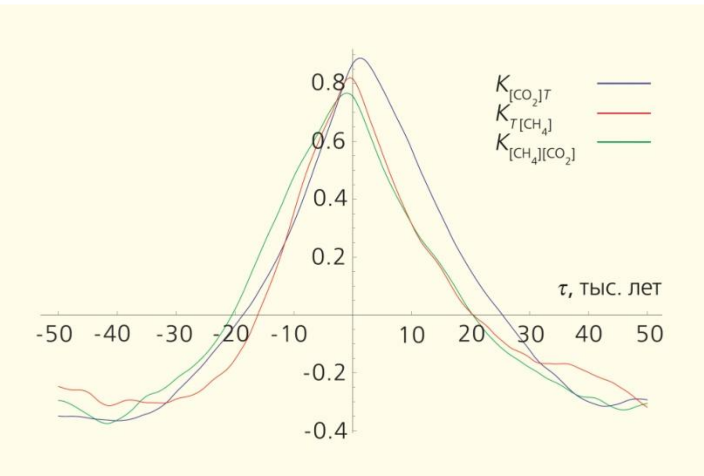

Fig. 3. Cross-correlations: carbon dioxide/temperature (blue curve), methane/temperature (red curve) and methane/carbon dioxide (green curve).

The cross-correlations (covariances) of these variables give even more information. They are presented with a higher time resolution because the shift of the maxima of these functions forward or backward from zero indicates which variable is leading, which is lagging, and with what characteristic time. As Fig. 3 shows, temperature and [CO_2] are closely coupled at small times with a maximum covariance equal to 0.88 reached with the temperature leading by about 2 ky relative to [CO_2](t). The accuracy of calculating lags and leads, regrettably, is not yet good, being around 0.5 ky. The temperature and methane concentration turned out to be almost synchronous, but their maximum covariance is lower, equal to 0.82. Finally, CO_2 concentration lags behind [CH_4] with a 1.5 ky average lag; their maximum covariance is equal to 0.74. The logic of this time lag can be explained by the process of oxidizing methane into carbon dioxide. But the fact that atmospheric CO_2 concentration largely follows behind the temperature is a paradox, contradicting the whole idea of the greenhouse effect as the main regulator of the surface temperature. Theoretically, the opposite should be true: the thermal inertia of the ocean requires some amount of time for its surface to achieve a temperature value corresponding to a concentration of the main greenhouse gas that has changed for some reason. We temporarily defer an exposition of hypotheses clarifying this paradox.

Differential distributions. The correlation and covariance exhaustively describe the relations between random variables if the variations of these variables have Gaussian (normal) distributions. We check if the paleoclimate has statistics sufficiently close to Gaussian. For this, the rank distributions of the three variables T, [CO_2], and [CH_4] were plotted; normalizing them gives the integral distributions. They were approximated by tenth-degree polynomials that were than differentiated (Fig. 4). Using this method makes the tails of the distributions unreliable, but the locations of the maxima are recovered with sufficient accuracy.

The normalized differential distribution of temperature reveals two maxima: at –7.8°C and at +3.7°C. From the low-temperature end, the distribution is close to a threshold one, which can be reasonably explained by the fact that the annual average temperature cannot be lower than the radiation temperature. The differential distribution of carbon dioxide concentration is even more impressive (and also non-Gaussian), having three maxima at concentrations equal to 202, 236, and 278 ppm. We note that the temperature distribution also has a “bulge” between the two maxima. We recall that the functions $T(t)$ and [CO_2](t) turned out to be closely correlated. This indicated a possibility of the presence of the three different mechanisms leading to dominant temperatures and CO_2 concentrations. Finally, the distribution of methane concentrations turned out to be the closest to normal (but still asymmetric); it has a single maximum at [CH_4] = 460 ppb.

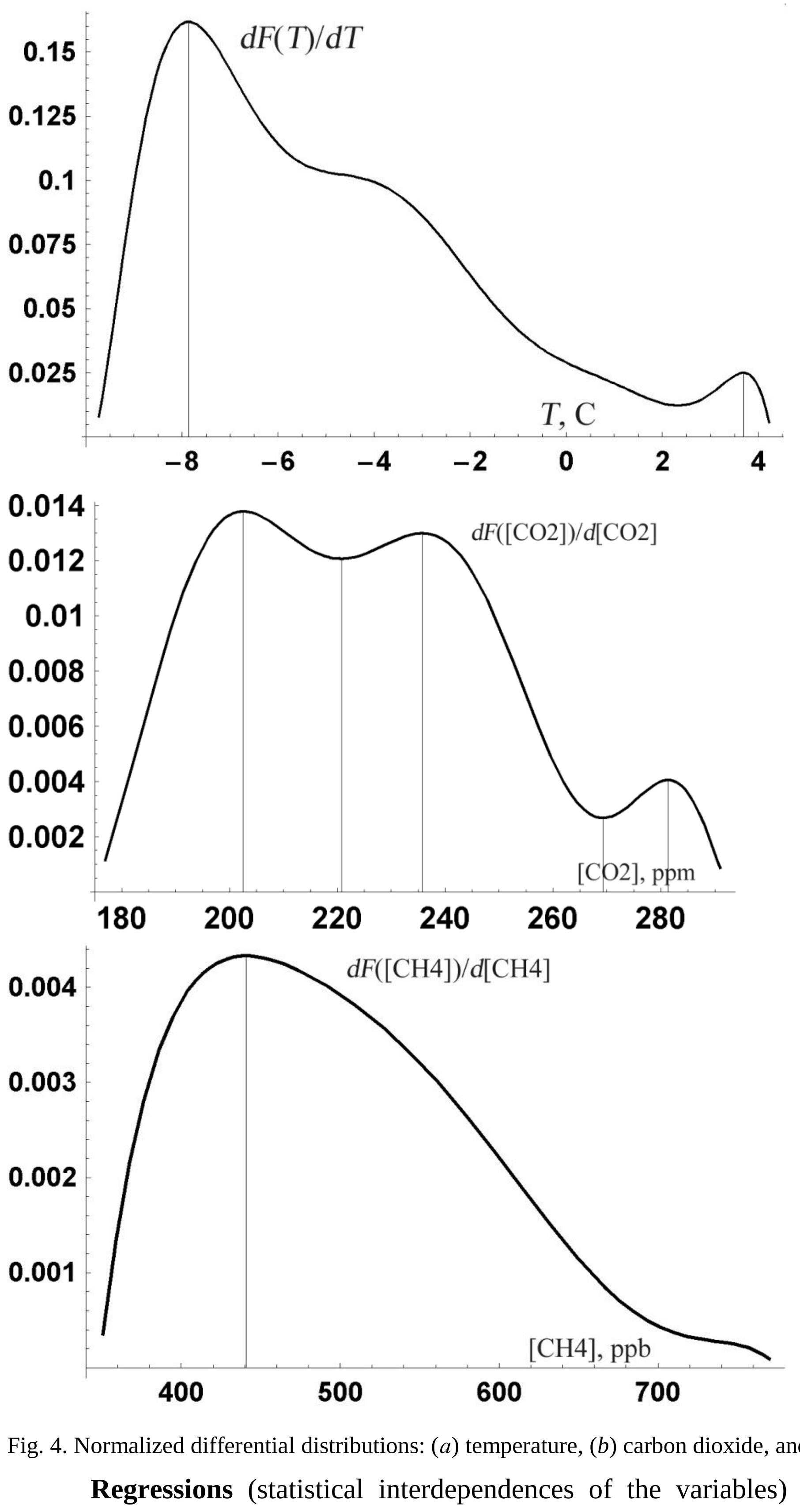

Fig. 4. Normalized differential distributions: (*a*) temperature, (*b*) carbon dioxide, and (*c*) methane.

Regressions (statistical interdependences of the variables) were also calculated. But because significant deviations from normalcy of distributions were found, the regression coefficient values cannot reliably reflect actual relations. The regressions would be better calculated separately for each of the processes leading to the formation of the three maxima of the distributions.

Summarizing the results of the standard statistical analysis allows suggesting some preliminary conclusions. It seems that a state of the Earth's climate system simultaneously depends on several geological and biological processes whose actions differ principally at low and high temperatures. During climate change, the behavior of all three variables seem most peculiar in the periods of rapid rise, attainment of maxima, and subsequent fall. The unpredictability of these surges seems mysterious. To gain a better understanding of the course of such events, we plot three-dimensional diagrams on the axes {T, [CO_2], [CH_4]} separately for each termination, i.e., transition from ice age to interglacial period.

"Cosmic" Dryas

We begin with the last ice age, which terminated 20 ky ago, and trace how the transition to the current climate proceeded. Figure 5 gives the three-dimensional projection of the event and shows how greenhouse gases concentrations and temperature varied in time. There is a sharp kink in the middle of the diagram.

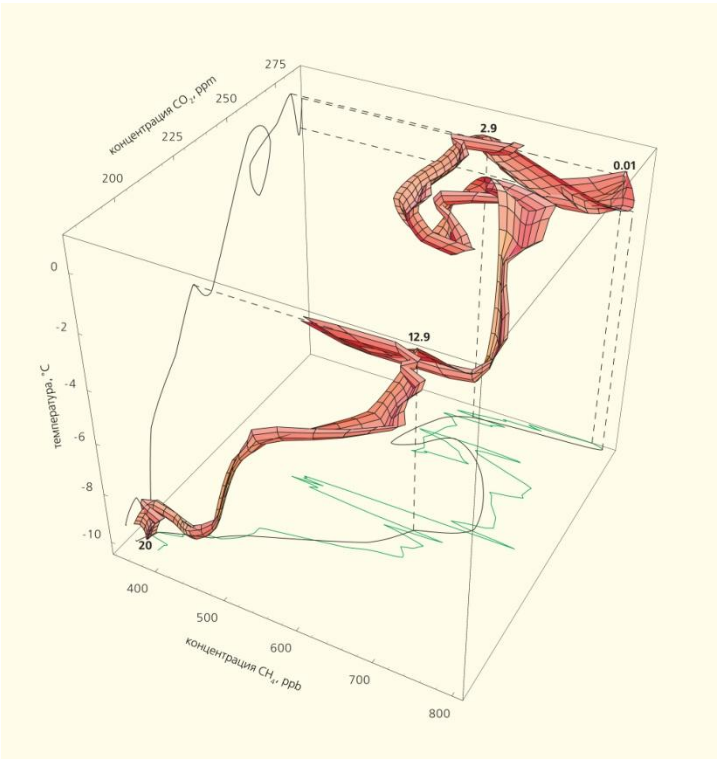

Fig. 5. Holocene warming. The three axes correspond to methane concentration, carbon dioxide concentration, and temperature. The sequence of events in time can be traced by the time tags (in ky before 1950) of the critical points and also by segmentation of trajectory: each small linear segment corresponds to 0.2 ky. Temperature and CO_2 concentrations are given with measurement errors; CH_4 concentrations are represented by combined data from Greenland and Antarctic ice cores. For better visualization of the three-dimensional diagram, the warming trajectory is projected onto the two planes {T, [CO_2]} and {[CO_2], [CH_4]}. The Greenland variation of methane and carbon dioxide is presented by a green curve on the latter plane.

The history of the last warming contains a special event that occurred about 13 ky ago and is named the Younger Dryas. It is represented on our diagram by a reverse path of temperature and a powerful disturbance of the Greenland methane concentration. It has long been thought that around 12.6 ky, a huge lake in the middle of the ice sheet covering a large part of North America thawed through an ice dam and discharged quickly into the Atlantic Ocean, making the wide, deep estuary of the Saint Lawrence River. This was followed by a noticeable cooling that lasted about a thousand years, after which the climate warming continued.

Another (not yet fully confirmed) explanation of the Younger Dryas recently appeared. Excavations have allowed suggesting a hypothesis that a comet with a mass a dozen times larger than that of the Tunguska meteorite exploded above North America 13.9 ky ago [6]. The explosion energy ignited a short lived but extensive conflagration of grasslands south of the glacier, and ash from this fire together with dust from the comet led to accelerated melting of the glacier. A large meteorite explosion pollutes the atmosphere with dust, which is immediately washed from the troposphere by rains but hovers in the stratosphere for years. An analogous manifestation is observed after powerful volcanic eruptions when ejected ash reaches the stratospheric altitudes. This dust disperses solar light and increases the albedo, which leads to a short (2–3 year) global cooling but has a negligible impact on the planet’s climate, at least when the cooling does not result in major extinctions, i.e., a mass destruction of part of the biosphere.

This event led to a large lake forming and later discharging its fresh water, which spread above the Atlantic salt water. For our goals, it is important that we can suggest some logical explanation of the cooling that followed this event. The fresh water that covered the northern part of the Atlantic Ocean with a layer about a meter deep also covered the warm salty water of the Gulf Stream. This prevented their cooling during polar winters and thus made their sinking impossible. As explained above, exactly this sinking of cold water into the depths of the world ocean brings about a relative warming of the North Hemisphere. That is why a cooling occurred during the approximately thousand years of the Younger Dryas. It terminated when the freshened surface waters had been mixed by winds and partly frozen into ice on the Arctic Ocean.

We now discuss the striking behavior of the Greenland methane concentration during the Younger Dryas, its abrupt drop at the beginning and no less abrupt surge at the end. We must first explain that methane concentrations in the northern and southern hemispheres can differ greatly. The reason is that in order to equalize these concentrations, some methane must cross the equator. But trade winds diverging from the equator prevent air mixing in the lower atmosphere, and methane is rapidly oxidized in the upper atmosphere because of solar ultraviolet radiation. In the beginning of the Younger Dryas, the fresh oxygen-rich waters of the melted glacier prevented the discharge of methane from the ocean into the atmosphere. An unusually rapid growth of carbonate deposits is registered at medium depths of the Atlantic Ocean during the same period [7]. After the termination of the Younger Dryas, the sinking of cooled salt waters of the Gulf Stream resumed, the surface temperature began to rise, and the methane concentrations jumped back to the continuation of the previous curve.

On the whole, the Younger Dryas cooling episode lasted about two thousand years; it delayed but did not stop the general Holocene climate warming.

Exits of the Climate from Ice Ages

We compare three-dimensional diagrams of the nine global warmings that occurred during last 800 thousand years. In common geological notation these intervals correspond to the terminations T_I through T_{IX} and the marine isotope stages (MIS) 1, 5, 7, 9, 11, 13, 15, and 17. We note some common features of these events (Fig. 6).

They begin with a rapid rise of all the variables (T, $[CO_2]$, and $[CH_4]$), and their concurrent growth (sometimes with reversals) then continues for 8 to 20 ky. Methane concentration reaches its maximum first, and temperature and carbon dioxide concentration reach their maxima several thousand years after that. The time lags between these maxima are given in the table. Most of these lags are small, some are zero, but negative values were not found. Of course, the validity of this assertion is not established rigorously, because the accuracy of the measurements and data processing is about 0.5 ky, but this regularity can still be considered statistically significant.

Table. Time lags (ky) of maximum temperatures and greenhouse gases concentrations for eight terminations of ice ages.

	T_{II}	T_{III}	T_{IV}	T_V	T_{VI}	T_{VII}	T_{VIII}	T_{IX}	Average
$\Delta t([CH_4] - T)$	1	1	2	3	1	9	3	1	3.5
$\Delta t(T - [CO_2])$	2	0	3	0	0	3	4	0	1.5

A detailed analysis of the processes of the climate exiting from ice ages confirms the feature noted in our analysis of cross-correlations: the methane concentration leads the temperature dependence, and the carbon dioxide concentration lags it somewhat. The observation that $[CO_2]$ follows behind $[CH_4]$ during the sharp rise stage can in principle be explained by oxidation of methane, but the logic of the greenhouse effect requires temperature to lag concentrations of gases during their rise. The paradox is obvious.

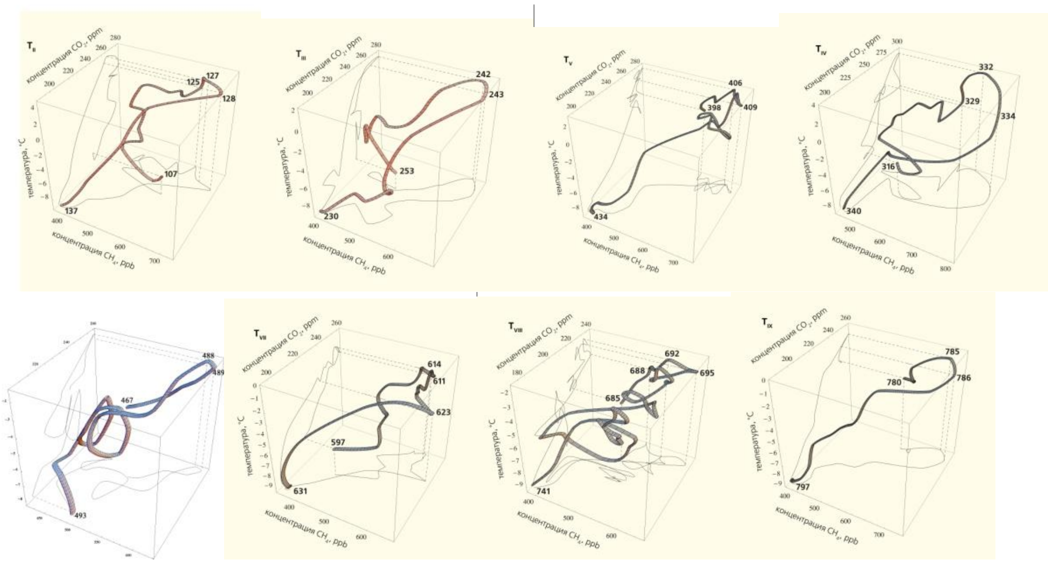

Fig. 6. Terminations of ice ages T_{II} through T_{IX}. The notation is the same as in Fig. 5 except that the curve width is proportional to the measurement errors of the variables.

The final stages of warm periods (interglacials) seem to proceed more logically: high temperatures and carbon dioxide concentrations stimulate increased photosynthesis, which transfers carbon from the atmosphere to humus and the peat in bogs. Reduction of the greenhouse effect begins to lower the surface temperature. But as we shall see below, not every warming ended so innocuously.

What kind of mechanisms can lead to such a sequence of events?

Mechanisms of Climate Transitions

We begin by describing the climate system during maximum glaciations, at times immediately preceding the terminations (bottom left positions on the graphs in Figs. 5 and 6). Because of the massive accumulation of ice on land, the ocean level dropped at these times by 100–120 m. The average salinity of the ocean consequently increased from the present value of 3.5% to 3.6%. A low surface temperature led to decreased evaporation, which dropped to only half its present intensity. The rainfall and snowfall volumes on land were also small; in addition, precipitation accumulated in glaciers. River runoff from the land into the ocean during ice ages was substantially lower than the current value. The whole system of convection in the atmosphere and ocean was less intensive than now; it could be said to be stagnant.

The heat flow from the Earth interior to the surface is negligibly small compared with the power flow of solar radiation incident on the Earth surface, $W_0(1-A) \sim 10^3$ W·m^{-2}. But the atmosphere rapidly transfers this flow away from the surface and radiates it back to space, while the ocean bottom is far from the surface. That is why the heat flow from the Earth's interior through the ocean bottom should not be ignored in the studies of the ocean dynamics. Averaged across the ocean, it amounts to $W_1 = 0.1$ W·m^{-2} [8] and has not changed during the last tens of millions of years. We estimate the time needed for this heat flow to raise the temperature of the entire ocean bulk (average depth H = 3730 m) by ΔT = 1°C for example. A simple estimate gives $\Delta t_1 = c\rho H\Delta T/W_1$ (where c is specific heat capacity and ρ is water density). The answer is five thousand years, which is not very long but is comparable to the ice age durations. This means that a decreased sinking of cold water into the ocean depths can radically change the ocean structure: the ocean water can be rapidly warmed by the heat flow from the Earth’s interior, locally if not globally. The essence of the proposed hypothesis is that this in fact happened. A study of paleotemperatures of ocean bottom waters showed that their warming during last 900 ky indeed led surface warming by 11±5 ky [5].

A pressure decrease in the ocean due to a sea level decrease and a concurrent water temperature increase disturbs the equilibrium of the solid gas hydrates (Fig. 7). The discharge of methane from its deposits currently results in its dissolution in water followed by oxidation, and the methane escaping from the ocean depths makes it to the surface almost nowhere. But in the stagnant ocean of the ice ages, a rapid warming could provoke the ascent of methane to the surface in a flow of bubbles. Such a “boiling up” could rapidly replenish atmospheric methane concentrations and, moreover, could bring warm bottom water to the surface. Every kilogram of methane transferred from gas hydrates to the atmosphere brings about 1400 kg of bottom water to the surface. With a concurrent compensating sinking of cold surface waters in other regions of the ocean, a massive boiling up of methane can provoke an abrupt global warming. The cold ocean surface had absorbed carbon dioxide from the atmosphere during the ice ages, and the bubbling discharge of methane therefore enriched the atmosphere with all greenhouse gases at once.

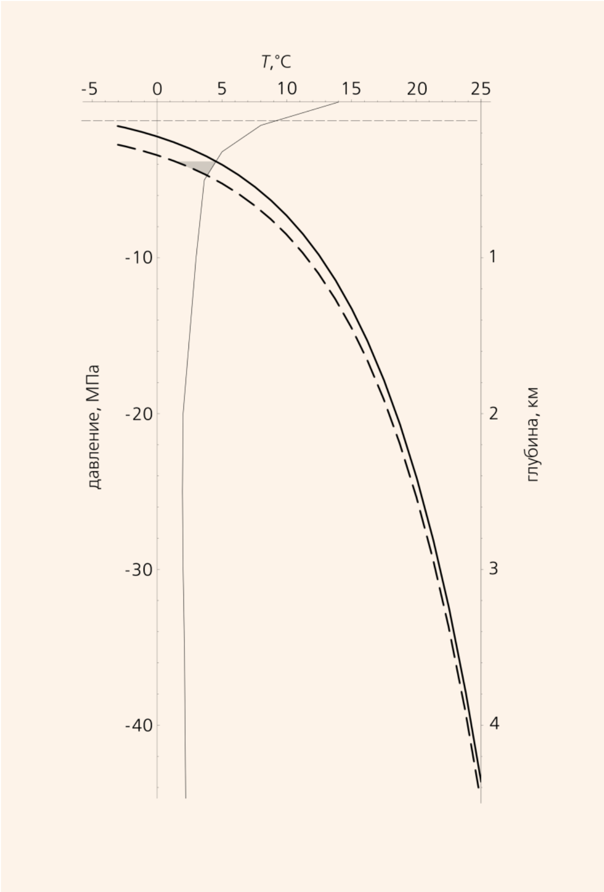

Fig. 7. Equilibrium curve of dissolved methane/methane hydrate (bold line) and the typical dependence of temperature on depth (thin line). During ice ages (ocean level and equilibrium curve shown by the dashed line), the methane hydrate deposits became unstable.

This concept explains the observed sequence of maxima during termination events T_I through T_{IX}: indeed, after the rise of methane, the temperature rises, and the carbon dioxide maximum occurs last in this time sequence. The atmospheric methane concentration drops rapidly after its maximum: first, because the melting of glaciers raises the ocean level, increases the pressure, and stops the gas hydrate decomposition; second, atmospheric methane oxidizes into CO_2. But what causes the sharp decrease after maxima (close in time) of the temperature and carbon dioxide concentrations? It seems that at maximum values (2–4° and 280–300 ppm), the ocean biomass increased rapidly, and this blossoming absorbed excess CO_2 and reduced the greenhouse effect. But why did it occur only in the ocean and not on land?

We return to Fig. 4. As noted above, the probability distribution for carbon dioxide concentrations revealed three maxima (temperature has two and a half of them): two high maxima at low and medium values, and one low maximum at a high value. The first two maxima obviously correspond to exits from ice ages. The second maximum of [CO_2] distribution and the “bulge” of the temperature correspond to upper states of the frequently occurring oscillations between ice ages and moderate warming (note the two and a half turnabouts during the termination T_{VI}; such excursions are common during transitions into ice ages). The only reasonable explanation of simultaneous maxima at high values of the temperature and [CO_2] is that a massive burnout of peat and wood occurred on land and the resulting carbon dioxide could not be dissolved in the ocean sufficiently rapidly. We need not necessarily imagine this process as a forest fire; it could be bacterial decomposition, a fast rot. After the burnout, the mineral components of the decomposed organic matter are washed by rains into the sea, immediately stimulating an explosive growth of biomass.

At this point, the reader is perhaps contemplating to what extent the Milankovitch theory now looks valid on the background of these supplements. The answer is that it is valid statistically, i.e., the climate indeed varies with periods close to 41 or 100 ky. But the mechanism of influence on the climate exerted by the planets probably differs somewhat. Jupiter and Venus perturb the Earth orbit and change its eccentricity, but there is another celestial body influencing our climate, the Moon. Possibly, Milankovitch understood that it should also be taken into account, but unlike planetary motions, which he could calculate for millions years into the past, the position of the lunar orbit can be calculated only for much shorter periods of time.

The lunar influence on terrestrial processes is significant. To begin with, the precession of the Earth's itself axis is in large part due to the Moon. The Chandler motion of planet axis is in resonance with oscillations of the lunar orbit eccentricity. Statistics confirms the influence of the Moon on oscillations of El Nino type and directly on the weather [9]. During those time periods when planetary disturbances cause an increase in the eccentricity of the Earth's orbit, the eccentricity and inclination of the lunar orbit also increase. And if lunar motions currently influence the weather, then the effects of a larger eccentricity applied for a longer time span could trigger an overturn of the ocean. Such an interaction of the Moon with the terrestrial ocean would enhance the planetary perturbations studied by Milankovitch. Of course, such considerations require a detailed investigation.

What Can We See in the Nearest Future?

The history of the paleoclimate is instructive but, unfortunately, does not provide robust foundations for a reliable prediction of even the immediate future. The atmosphere during the last million years was never in a state close to the contemporary state; CO_2 concentrations as high as those that accumulated during the last 100 years because of industrial development have never been observed. The greenhouse effect will inevitably increase for at least the next 20 years simply because of the inertia of economies using fossil fuels. Climate warming will continue, and the next generation will see the Arctic Ocean completely free of ice at the end of the summer season. Whether warming of the Arctic Ocean will provoke a massive release of methane from the gas hydrate deposits on its bottom is unknown.

It seems still too early to predict the climate further than 2040–2050. The unprecedented increase of the carbon dioxide concentration does not allow the ocean to find a new equilibrium sufficiently rapidly. The peculiar feature of the current state is that the climate instability increases faster then the warming itself. The surface temperature has increased less than 1°C over the preindustrial level, but the frequency of hurricanes, floods, and fires during the same period has approximately doubled. It is very hard to predict what climate state will be stable after the ocean stabilizes.

Literature

1. Milankovitch M. Kanon der Erdbestrahlungen und Seine Anwendung auf das Eiszeitenproblem. Belgrade, 1941 (Canon of Insolation and the Ice Age Problem. Alven Global, 1998).
2. HITRAN (**Hi**gh Resolution **Tran**smission), open-access database of Harvard-Smithsonian Center for Astrophysics, USA (www.cfa.harvard.edu/hitran).
3. Lüthi D. et al. High-Resolution Carbon Dioxide Concentration Record 650.000–800.000 Years Before Present // Nature. 2008. V.453. P.379–382.
4. Loulergue L. et al. Orbital and Millennial-Scale Features of Atmospheric CH_4 Over the Past 800.000 Years // Nature. 2008. V.453. P.383–386.
5. Sosdian S., Rosenthal Y. Deap-Sea Temperature and Ice Volume Changes Across the Pliocene-Pleistocene Climate Transition // Science. 2009. V.325. P.306–309.
6. Kennett D. J. et al. Nanodiamonds in the Younger Dryas Boundary Sediment Layer // Science. 2009. V.323. P.94.
7. Lein A.Yu., Ivanov M.V. Methane Cycle in the Ocean [In Russian]. Moscow, 2009.
8. Hofmeister A.M., Criss R.E. Earth’s Heat Flux Revised and Linked to Chemistry // Tectonophysics. 2005. V.395. P.159–177.
9. Sidorenkov N.S. Nature of the Earth Rotation Instabilities, “Priroda” 2004. №8. P.8–18.

Published in Russian in “Priroda”, 2009, №12, pp.18-28. Translated by Bill Everett.