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Insolation Cause of Long-Period Climate Changes

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Abstract—In the middle of the 19th century, insolation oscillations at high latitudes, which are due to the precession of the Earth's axis of rotation, were put forward as the cause of the Ice Ages. A quarter of a century later, the eccentricity of the orbit was proposed as an additional factor. In the first third of the 20th century, M. Milanković developed the astronomical theory of climate change, which determines insolation fluctuations depending on three parameters of the Earth's orbit. However, the insolation oscillations were small, and the extremes did not coincide with warming and cooling of the paleoclimate. At the end of the 20th century, this theory was analyzed by me; the problems included in it had been solved in a new way. Later, I additionally solved the problem of the evolution of the Earth's rotation axis. Taking it into account, insolation fluctuations increased 7–8 times, and extremes coincided with cooling and warming of the paleoclimate. This article considers insolation periods of climate change over 20 million years and the epochs of their onset and their duration. Insolation periods are compared with paleoclimate fluctuations over 250000 years, and their coincidence is established. Changes in annual insolation and average annual temperature are considered. Based on various characteristics of insolation, the main properties of insolation periods are formulated. Annual and summer temperatures vary within such limits that can lead either to glaciations of territories almost to the middle latitudes or to the complete melting of polar ice. In the process of climate fluctuations, certain territories are flooded, both within the continents and on the shores of the seas. As a result, alternating layers of deposits and soil are formed. They capture the frequency of changes in insolation.

Keywords: Ice Ages, paleoclimate, insolation, orbit and rotation axis of the Earth, evolution, insolation periods, properties, temperature, layers

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INTRODUCTION

For a long time, people have wondered how the world around us was formed and what are the reasons for the changes occurring on Earth. For example, 2500 years ago, Herodotus (2009) drew attention to the coastal protrusion in the Mediterranean Sea on which the Nile Delta is located. Having studied the data on the annual sediment load of the Nile, he came to the conclusion that it was formed by the river with its sediments over 20000 years. And, once upon a time, in its place and in the place of the delta and the lower part of the river valley, there was a sea bay.

Another example: in the Alpine valleys, as well as in other places in Europe, there are large stone blocks and boulders, the material of which is not typical of the surrounding area. The reason for their appearance was explained by the transfer of powerful streams of water during the Great Flood. This cause of catastrophism was rejected in 1795 in J. Hutton's book *The Theory of the Earth* (John et al., 1982), in which the author proposed to explain all the changes taking place on Earth not by biblical, but by natural processes. Hutton concluded that in the past the glaciers in the Alps were large, and then they melted, leaving behind boulders "captured" from other places. In 1829, Swiss engineer I. Venetz-Sitten supported and developed the ideas of Hutton, suggesting that the territory of Europe north of the Alps, including Northern Europe, was under the influence of ice (John et al., 1982).

This conclusion was supported by a statement from J. Esmark (1824) about the more extensive glaciers of Norway in the past. Esmark's results became known to the German professor R. Bernhardi, who in 1832 put forward the idea of an ice sheet covering Northern Europe and reaching Central Germany (Imbrie, J. and Imbrie, K.P., 1988). In 1834, J. de Cherpentier supported Venet-Sitten's conclusions with the results of field observations.

In 1837, at the annual conference of the Swiss Society of Naturalists in Neuchatel, its president, J.L. Agassiz, gave a report on the boulders that are found in abundance on the slopes of the Jura mountain range. The presence of glacial striations on them and their distance from bedrock of similar composition confirmed the existence of an ice age in the history of the Earth.

In 1848, French scientist E. Colomb reported the discovery of two layers of moraines separated by a thickness of river sediments (Imbrie, J. and Imbrie, K.P., 1988). In 1863, A. Geikie showed that the composition of plant remains found in deposits between moraines in Scotland indicated a warm period that separated the glacial epochs. In the 1870s, American scientists J. Newberry and W.J. McGee found the remains of trunks and roots of an ancient forest between two moraine horizons. During these same years, traces of repeated glaciations were discovered in Western Europe and in European Russia (Imbrie, J. and Imbrie, K.P., 1988). In the second half of the 19th century, Russian scientists studied glacial deposits in the Asian part of Russia (see the Afterword by G.A. Avsyuk and M.G. Grosswald to the book (Imbrie, J. and Imbrie, K.P., 1988)).

In 1842, in his book *Revolutions de la mer: Deluges Periodiques* (in English, *Revolutions of the Sea: Periodic Floods*), French mathematician A.J. Adhemar was the first to name the precession of the Earth's rotation axis as the cause of glaciation periods (Imbrie, J. and Imbrie, K.P., 1988). As a result of precession, the line of intersection of the plane of the equator and the Earth's orbit, i.e., the line of equinoxes, rotates along the Earth's orbit in the direction opposite to the Earth's movement, and the seasons of the year "move" along the orbit. In modern times, winter in the Northern Hemisphere occurs when the Earth is at the perihelion of its orbit, i.e., at its shortest distance from the Sun. That's why winter in the Northern Hemisphere is warmer than in the Southern Hemisphere. It was assumed that, when the Earth was at perihelion, when winter would occur in the Southern Hemisphere, an ice age would begin in the Northern Hemisphere. Since this theory was not supported by rigorous calculations, it was not developed.

In 1849, the French astronomer U. Le Verrier proposed a comprehensive theory that made it possible to calculate changes in the parameters of planetary orbits as a result of their disturbance by other planets. However, the real beginning of the astronomical theory of climate change comes from the research of the Scottish scientist J. Croll, who, being fascinated by the theory of A.J. Adhemar, used the theory of Le Verrier and calculated the change in the eccentricity of the Earth's orbit over 3 million years (Bolshakov, 2003). This allowed him in 1875 to calculate the change in the distance between the Earth and the Sun at the onset of winter in the Northern Hemisphere. When this distance became greatest due to changes in eccentricity, it was assumed that an ice age was beginning in the Northern Hemisphere.

In 1920, in his book *Mathematical Theory of Thermal Phenomena Caused by Solar Radiation*, the outstanding Serbian researcher M. Milanković presented a theory that made it possible to calculate the distribution of solar heat over the Earth's surface, i.e., its insolation, depending on the eccentricity of the orbit of e; the angle of inclination of the orbital plane to equatorial plane ε; and the perihelion angle $\varphi_{p\gamma}$, counted from the moment of the equinox. To determine these orbital parameters, Milanković (1939) used the theory of J. Stockwell, who completed it in 1872. It was assumed that Stockwell's theory was more accurate than Le Verrier's theory.

To confirm his theory, Milanković needed more precise calculations of the changes in these parameters. Based on the theory of Le Verrier, they were calculated for 600000 years by the director of the Astronomical Observatory in Belgrade at the time, V. Mišković. Thus, Milanković created an astronomical theory of climate change, in which climate change was explained by fluctuations in the amount of solar heat reaching the Earth (Milanković, 1939). This theory substantiated the insolation cause of long-term climate changes both in the past and in the future.

Milanković's solutions were consistently repeated by several generations of researchers (Brouwer and Van Woerkom, 1950; Sharaf and Budnikova, 1969; Berger and Loutre, 1991; Edvardsson et al., 2002; Laskar et al., 2004). In this case, the problem of the interaction between the bodies of the Solar System was solved and changes in the parameters of the Earth's orbit were determined. Therefore, this theory is often called the Milanković theory, or the orbital theory of paleoclimate (Bolshakov, 2003).

However, fluctuations in insolation were small, and the periods of its maxima and minima did not coincide with known fluctuations in paleoclimate. For example, according to Milanković's theory, insolation of the Earth's surface increased to a maximum 10000 years ago. However, according to paleogeographic studies, a slight warming (the Holocene optimum) occurred 6000 years ago, preceded by an era of cooling, and, 8000–20000, years ago there was an Ice Age.

We have created a new astronomical theory of climate change (Smulsky, 2018, 2021) in which, unlike the previous theory, the problem of the evolution of the Earth's rotational motion was additionally solved (Smulsky, 2020a). The variations in the angle of inclination of the Earth's equatorial plane to the plane of its orbit ε turned out to be 7–8 times greater than in Milanković's theory. These variations had a more significant impact on the climate than variations in orbital eccentricity e and the perihelion angle $\varphi_{p\gamma}$. According to our calculations, fluctuations in insolation coincided with changes climate in the past (Smulsky, 2016a). That is, previous solutions incorrectly represented the evolution of the Earth's insolation, due to which fluctuations in insolation did not coincide with the fluctuations in paleoclimate that took place.

Thus, the astronomical theory of climate change that we propose proves that the cause of long-term climate fluctuations is a change in insolation. That is, astronomical factors are the main factors of climate change, and other factors, if they exist, have little effect on long-term climate change.

CHANGES IN EARTH'S INSOLATION OVER THE PAST 20 MILLION YEARS

Main period of insolation fluctuation. When creating a new astronomical theory, all the foundations of the previous theory were analyzed and the problems included in it were solved in a new way. The problem of the evolution of the Earth's orbital motion has been solved by us over a time interval of 100 million years (Melnikov and Smulsky, 2009), and the Milanković insolation theory was translated into another mathematical algorithm (Smulsky and Krotov, 2014). These two problems give more accurate results on insolation, but do not differ significantly from the results of the previous theory.

Then the problem of the evolution of the Earth's rotational motion over the last 20 million years was solved (Smulsky, 2020a). During this time interval, the evolution of the Earth's insolation was also determined. In Fig. 1, insolation changes are presented at four millionth time intervals for the 1st, 5th, 10th and 20th million years ago.

In Fig. 1a, the change in summer insolation is shown Q_s^{65N} (curve *1*) over the last 1 million years at 65° N. This value is a characteristic of the climate in high latitudes. Over the interval of 200000 years ago, 13 insolation periods of climate change were introduced: O_I, 1_I, 2_I, ..., 12_I (Smulsky, 2016a).

It is clear that insolation Q_s^{65N} changes unevenly. Maximum warming and cooling periods follow irregularly: they can occur in 30000 or 300000 years (Smulsky, 2018). However, almost all insolation fluctuations are consistent with the course of the harmonic Q_{shar}^{65N} (curve *2* in Fig. 1), which is defined as follows:

$$Q_{shar}^{65N} = Q_0 + Q_a \sin(\varphi_0 + 2\pi T / P_{prm}), \qquad (1)$$

where $Q_0 = (Q_{s\,max}^{65N} + Q_{s\,min}^{65N})/2 = 6.099$ GJ/m^2; $Q_a = (Q_{s\,max}^{65N} - Q_{s\,min}^{65N})/2 = 1.2711$ GJ/m^2; $\varphi_0 = 0$; T is time, thousands of years, which is negative for time ago; and $P_{prm} = -25.7478$ thousand years, average period of precession of the Earth's rotation axis over 20 million years. The dash means that the Earth's axis rotates clockwise, i.e., opposite to the planet's daily and orbital motions.

Parameter values Q_0 and Q_a in formula (1) are given for the interval 0–5 million years ago. (see Figs. 1a, 1b). At other intervals they differ in the 3rd–4th digit. In the interval 0–5 Ma, the precession period is $P_{pr} = -25.3262$ thousand years.

Since the period of precession P_{pr} fluctuates, then its value depends on the time interval over which it is defined. At intervals of 26000 years, the maximum and minimum values of P_{pr} were determined over the last 20 million years. Their modules are equal to 26574 years in the epoch $T = 16.5$ million years ago and 24977 years in the era $T = 7$ million years ago.

There are two periods of oscillation of P_{pr}: approximately 26000 years and 18.5 million years. Harmonic Q_{shar}^{65N} with constant period P_{prm} represents the passage of time in these periods. In the graphs in Fig. 1, the units of this time change from 1*h* up to 777*h*. A comparison of insolation extremes with harmonic extremes allows us to identify some time characteristics of insolation changes.

In Fig. 1, all harmonic maxima are numbered. First, max 1*h* comes at the moment $T_1 = 6.4 \times 10^{-3}$ million years ago. Since the period of change of maxima is equal to P_{prm}, the number of the maximum harmonic at the end k millionth interval will be

$$n_h = \mathrm{INTEGER}\left((k + T_1)/P_{prmM}\right), \qquad (2)$$

where INTEGER is the integer part of the expression in brackets; T_1 is the time ago, negative value; and P_{prmM} is period P_{prm} in millions of years.

Changes in insolation Q_s^{65N} are shown for the 10th million years ago in Fig. 1c, and they are shown for the 20th million years ago in Fig. 1d. A comparison of the change in insolation at these intervals with the harmonic Q_{shar}^{65N} shows that the extremes of insolation in most cases coincide with the extremes of the harmonic or are close to them. Therefore, the period of precession P_{prm} of the Earth's rotation axis is the main period of climate change on Earth.

In the analysis, three gradations of warm climate (moderately warm, warm, and very warm) and three gradations of cold climate (moderately cold, cold, and very cold) were also introduced (Smulsky, 2016a). In Fig. 1b (interval 5 million years ago), the boundaries between gradations are shown by dotted lines. These boundaries are separated by the same value $\Delta Q_s = 0.5127$ GJ/m^2 from the average summer insolation over 20 million years Q_s^{65N} equal to $Q_{sm}^{65N} = 6.055$ GJ/m^2 (line *3* in Fig. 1b).

Over the past 200000 years (see Fig. 1a), there were two very cold and two very warm periods. There were three cold periods and two warm ones. The remaining periods were moderately cold and moderately warm. Overall, over the last 20 million years, there have been 67 very warm periods and 55 very cold periods; i.e., there have been a total of 122 very significant climate changes (Smulsky, 2018).

The sequence of onset of very warm periods, such as 2_I, and very cold periods, such as 3_I, are extremely uneven. With a total of 122 over the last 20 million years, the average period of their alternation is 164000 years. During this time there were 777 harmonic oscillations Q_{shar}^{65N}, caused by the period of pre-

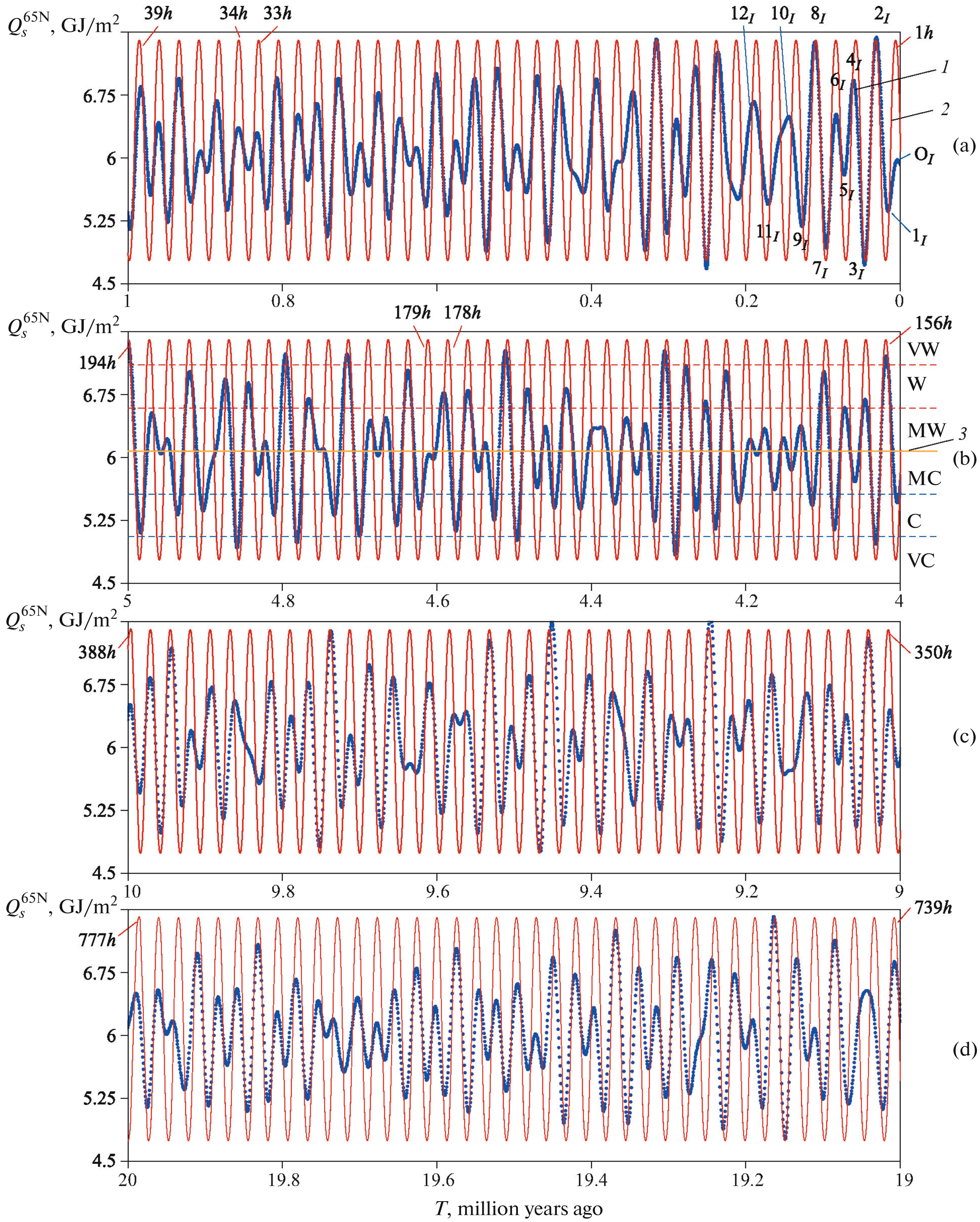

Fig. 1. Summer insolation oscillations $Q_s^{65\,N}$ (*1*) at four millionth time intervals over the last 1 million years (a) and for the 5th (b), 10th (c), and 20th (d) million years ago. (*2*) Harmonic $Q_{shar}^{65\,N}$ according to Eq. (1) with a period of oscillation equal to the average period of precession of the Earth's axis over the last 20 million years $P_{prm} = -25.75$ thousand years; (*3*) average summer insolation over the last 20 million years $Q_s^{65\,N} = 6.055$ GJ/m^2; O_I, 1_I, 2_I, ... 12_I, extremes of insolation periods of climate change over the past 200000 years; 1*h*, 39*h*,..., 739*h*, 777*h*, numbers of harmonic maxima (1). (b) Dotted line shows the boundaries between the warm and cold climate gradations: VW, very warm; W, warm; MW, moderately warm; MC, moderately cold; C, cold; and VC, very cold. See text for the rest of the explanation.

cession P_{prm}. Therefore, on average, very cold periods are replaced by very warm ones in 6.4 harmonic oscillations $Q_{\text{shar}}^{65\text{N}}$. Warm periods such as 4_I and cold periods such as 1_I occur 4 times more often.

From the data shown in Figs. 1a and 1b, as a rule, a very cold period comes after a very warm one, or vice versa. Therefore, in most cases, their change occurs in one period P_{prm} of harmonics.

Moments of the Onset of Insolation Periods

Very warm and warm periods, such as 2_I and 4_I, correspond to the moments of harmonic maxima $Q_{\text{shar}}^{65\text{N}}$ (see Fig. 1). Very cold and cold periods such as 3_I and 1_I, accordingly, occur at the moments of harmonic minima. Sometimes insolation periods can be 3000–4000 years ahead of the harmonic extremum or lag behind it. Taking this time difference into account, all significant insolation periods are tied to the maxima and minima of the harmonic $Q_{\text{shar}}^{65\text{N}}$.

In Fig. 1, at the beginning and end of each millionth interval, the numbers of the harmonic maxima $Q_{\text{shar}}^{65\text{N}}$ are given: 1*h*, 39*h*, 156*h*, 194*h*, 350*h*, 388*h*, etc. All very warm and warm periods coincide with harmonic maxima, for example 2_I from 2*h*, 4_I from 3*h*, 8_I from 5*h*, and 12_I from 8*h*. Similarly, all very cold and cold periods 1_I, 3_I, 7_I, 9_I, and 11_I coincide with the harmonic minima $Q_{\text{shar}}^{65\text{N}}$. Moderately warm and moderately cold periods such as 10_I and 13_I may correspond to the minimum or maximum of harmonics, respectively.

Not every maximum or minimum of the harmonic is realized by the insolation period of climate change. Often in two adjacent maxima of the harmonic (for example, in harmonics 33*h* and 34*h* in the era of 0.84 million years ago), the magnitude of insolation $Q_{\text{s}}^{65\text{N}}$ decreases at the intermediate minimum of the harmonic. In this case, the interval between adjacent insolation minima increases to two periods P_{prm}.

Something similar happened in the era 4.6 million years ago. At maximum harmonic 179*h*, insolation $Q_{\text{s}}^{65\text{N}}$, after the minimum, almost reaches the average value Q_{sm}, then decreases slightly in the adjacent minimum of the harmonic. After this, insolation increases and reaches a maximum near the maximum of harmonic 178*h*.

A similar situation occurs in the modern era ($T = 0$). Insolation maximum O_I is at the maximum of harmonic 1*h*. Then, at the minimum of the harmonic, which will come in the future era T = 1640 years (Smulsky, 2021), insolation also decreases slightly and then reaches a maximum at the epoch of 16760 years near the maximum of the harmonic (these extremes are not shown in Fig. 1).

The same small changes in insolation can occur at harmonic minima. There are other oscillations $Q_{\text{s}}^{65\text{N}}$ that lead to the fact that, during the extremum of harmonics, insolation extremes are not observed.

Duration of Insolation Periods

The duration of insolation periods of climate change is measured by the interval between average changes in insolation Q_{sm}, which limits its extremum (Smulsky, 2016a). Since insolation periods are related to the course of the harmonic, their nominal duration is determined by its half-period $\Delta T_{\text{in}} = 0.5(-P_{\text{prm}})$ = 12870 years.

The boundaries of insolation periods for the last 200000 years are given in Table 1. It is evident that very warm and very cold, as well as warm and cold insolation periods, can be 2000–4000 years longer than ΔT_{in}. In the case of moderately warm and moderately cold insolation periods, their duration can be 2000–4000 years less than ΔT_{in}. However, in the case of periods of 10_I –12_I, when there is a mismatch between their peaks and harmonic oscillations (see Fig. 1), insolation periods can have a duration 1.5–2 times greater than ΔT_{in}.

It is worth noting the peculiarity of the O_I period—the Holocene optimum. Since the insolation value at this time is less than the average insolation value Q_{sm}, the duration of the period is determined by the value of insolation in the modern era (Smulsky, 2016a), which is what distinguishes this period from the others.

Differences between the New Theory and the Previous One

As already noted, the Earth's insolation depends on three parameters: the eccentricity of its orbit e; the angle of inclination of the orbital plane to the equatorial plane ε; and the angle of perihelion, measured from the moment of equinox, $\varphi_{p\gamma}$. The evolution of the tilt angle ε is similar to the evolution of insolation $Q_{\text{s}}^{65\text{N}}$, shown in Fig. 1 (Smulsky, 2020a); i.e., rotational motion has the greatest influence on insolation, and the main influence on the rotational motion of the Earth is exerted by the Moon and the Sun, respectively (Smulsky, 2011). Therefore, its evolution depends on the parameters of the Earth's orbit e and $\varphi_{p\gamma}$. Thus, the oscillation of orbital eccentricity e and its perihelion $\varphi_{p\gamma}$ indirectly affects insolation through the tilt angle ε. Their direct influence on insolation is several times less than the angle of inclination ε. According to Milanković's theory, the parameters e and $\varphi_{p\gamma}$ have a fundamental influence on insolation, determining the periods of its fluctuations. Therefore, the insolation values calculated within the framework of the previous theory cannot reflect fluctuations in paleoclimate.

Table 1. Extremes of summer insolation Q_s^{65N}, the moments of their occurrence T, and insolation periods of climate change over the past 200000 years

T, thousand years ago	Q_s^{65N}, GJ/m^2	Insolation periods	Borders periods, thousands of years ago	Climate gradations
4.16	5.97	O_I	0–6.86	Moderately cold
15.88	5.36	1_I	6.86–22.08	Cold
31.28	7.43	2_I	22.08–39.50	Very warm
46.44	4.72	3_I	39.5–53.8	Very cold
60.8	6.93	4_I	53.8–69.1	Warm
72.8	5.79	5_I	76.96–69.10	Moderately cold
83.4	6.52	6_I	88.52–76.96	Moderately warm
95.92	4.92	7_I	102.56–88.52	Very cold
110.8	7.38	8_I	120.08–102.56	Very warm
127.56	5.18	9_I	137.00–120.08	Cold
144.8	6.49	10_I	161.08–137.00	Moderately warm
171.08	5.44	11_I	180.24–161.08	Cold
190.36	6.68	12_I	200.60–180.24	Warm

In this regard, additional factors were introduced into astronomical theory, and the comparison of insolation extremes with periods of warming and cooling was replaced by statistical analysis. Direct and feedback links were considered as additional factors (Bolshakov, 2003). For example, the decrease in Earth's albedo with increasing snow cover during ice ages was seen as a direct link that increased cooling. The decrease in temperature in high latitudes should have been accompanied by an increase in interlatitude exchange, which would have prevented their cooling. This is feedback.

In order to establish the dependence of the isotopic composition of marine and continental sediments on the existing paleoclimate, spectral analysis was and is widely used. It was assumed that the insolation oscillations should contain frequencies associated with the period of eccentricity change e (95400 years) and the angle of inclination ε (41100 years) of the Earth's orbit and the angle of perihelion $\varphi_{p\gamma}$ (21700 years). Here is the value of the oscillation period ε according to the previous theory. The spectra of these frequencies were sought to be detected in the isotopic composition of sediments, for which sedimentation rates were selected. Constructed isotopic composition sets, such as LR4 in (Lisiecki and Raymo, 2005), were called marine isotope stages (MIS), and their change was accepted as a chronology of paleoclimatic changes. In reality, MIS do not reflect paleoclimate changes, and the reason for their variability is different (Smulsky, 2020b).

At this point, it is obvious that these tricks are not necessary. The existing astronomical theory gave incorrect changes in insolation. Actual changes in insolation have different time characteristics. First, the periods of warming and cooling are timed to coincide with the cycles of precession of the Earth's axis. Second, they vary in intensity from very strong to very small and insignificant. Third, periods of significant warming and cooling follow unevenly.

INSOLATION PERIODS AND PALEOCLIMATE CHANGES OVER THE PAST 200000 YEARS

The table shows the characteristics of insolation periods over the last 200000 years (Smulsky, 2016b). Let us consider how they agree with the data on paleoclimate changes in Western Siberia.

Optimum Insolation in the Holocene (Insolation Period O_I)

In the era $T = 4160$ years ago (see Table 1), there is a small maximum of insolation (from 10000 years ago to the present). The optimum is clearly manifested in the interval of 9000–3300 years ago (Vasilchuk, 1982; Ershov, 1989). According to the results of palynological studies, the warming at this time was expressed less strongly than in the previous interglacial period (Ershov, 1989). It is generally accepted that 8000–5000 years ago there was a transgression of the sea, and from 5000 years ago to the present day the sea has been retreating (Lomanchenkov, 1966), in connection with which the formation of new terraces in river valleys occurs (Saxon, 1953; Lomanchenkov, 1966). The upper layer of permafrost rocks in Western Siberia was formed over the last 5000–6000 years (Baulin, 1959; Nekrasov et al., 1990). The formation of hummocky peatlands began approximately 3000 years ago (Shpolyanskaya and Evseev, 1970; Nekrasov et al., 1990).

Last Glacial Maximum (Insolation Period 1_I)

The Sartanian horizon of deposits corresponds to the last glacial period in Western Siberia (Arkhipov et al., 1980; Arkhipov, 2000), the radiometric age of which is within the range of 23000–10000 years BP (Arkhipov, 1997). During this period, the glacial relief of Western Siberia was formed, including marginal moraines along the southern foothills of the Salekhard Ridges and the Khadateysky Ridges of the Tazovsky Peninsula (65.5°–67° N). To the north, at approximately 68° N, are the Yamalo-Gydan moraine belts, stretching from the Yarroto (Yarato) lakes to the east along the Gydan ridge. Further north are the youngest moraines associated with the degradation of the Sartan glacier.

In Scandinavia, the last cooling period is characterized by the late Weichelian horizon (Svendsen et al., 1999). In Arkhangelsk oblast, the maximum of this glaciation dates back to 17000 years ago and deglaciation to 16000 years ago. To the east of Lake Onega, deglaciation is dated to 14400–12900 years ago. On Taimyr, the age of the glacier is determined as 18000–7500 years ago. The area between Norway and the Novaya Zemlya archipelago was covered by a glacier about 10700 years ago.

When the maximum cooling period had passed, the ice flows of the Barents-Kara Ice Sheet along the largest underwater troughs of the Arctic Basin (Franz-Victoria, St. Anna and, Voronin) began to retreat to the Arctic Ocean (Grosswald, 2009). Ice degradation in St. Anna began about 13000 years ago and ended about 10000 years ago.

The Mansiysk Lake, formed during the Sartan period, has approximately the same age: 20000–10000 years (Arkhipov, 1997; Pyatosina, 2005). Moreover, at that time it occupied a smaller area than the more ancient one, the deposits of which are covered by sediments with the remains of mammoths approximately 18000 years old (Pyatosina, 2005).

The age of the Kolpashevskaya terrace on the middle Ob at an altitude of 55 m, formed by the Mansi Sea, is within the range of 12800–10600 years ago (Arkhipov, 1997). It is adjoined by a transit terrace plain (Arslanov et al., 1983), which can be traced through the entire zone of Sartan glaciation to the mouth of the Ob. Its age is 12260 ± 170 years. On the middle Yenisei, a terrace 60–70 m high near Farkovo has an age from 16400 to 11700 years.

As we can see, the dates of the Sartan glaciation and its consequences coincide with the minimum insolation of 15880 years ago.

Warm Insolation Period 2_I

The Barents-Kara Ice Sheet, which existed in Western Siberia during the last ice age, completely melted by 40000 years ago (Svendsen et al., 1999). In many valleys of the Pechora Lowland (for example, in Shapkina, Khvostovaya Sosva, and Soima), wood and peat from under relief-forming moraines are 25000–40000 years old (Grosswald, 2009). Under the moraine that is widespread to the north of the Siberian ridges, there are lake–bog deposits that are 25000 to 50000 years old (Arslanov et al., 1983). Shells on the eastern coast of the Barents and Kara Seas and along the shores of Taimyr and Severnaya Zemlya are 24000–38000 years old (Grosswald, 2009).

The Kazym tract of the Kargin horizon extends along the Obi valley from the village of Kazym-Mys to the town of Kolpashevo and the Vasyugan River basin and to the village of Lipovka on the Tobol River (Arkhipov, 1997). Its age is 33000–31000 years. In the lower reaches of the Yenisei River, from the city of Igarka to the mouth of the Bakhta River, the Konoshchel layers can be traced: an analogue of the Kazym layer, 33000–32000 years old. As a rule, these are lacustrine-alluvial deposits with layers of peat.

The third terraces of the Irtysh and Tobol rivers with absolute marks of 70–75 m near the village of Lipovka are composed of lacustrine–alluvial deposits (Illarionov, 2013). In the section near the village of Lipovka, the age of the wood and plant remains preserved in these deposits ranges from 31780 to 32770 years. The same age is found in the bone remains of steppe bison, woolly rhinoceroses, and ancient horses found in river sediments.

The analogue of the Lipovskaya terrace of the Irtysh and Tobol is the Kiryanskaya terrace, composed of lacustrine–alluvial deposits with peat lenses (a section in the outcrop of the left bank of the Ob River 15 km above the village of Pokur) aged 27500–36300 years (Lauhin et al., 2006). In the Turgai hollow from a well drilled 25 km south of Lake Kushmurun, a piece of wood aged 27800 years was raised to the surface from a depth of 37 m (Grosswald, 1983).

In the Krasny Yar outcrop, 15–20 km south of Novosibirsk, stumps of trees that once grew here are buried under a layer of lake sediments 8–10 m thick. The age of wood remains is 28000–29000 years (Arkhipov et al., 1980). In the Kas-Ket Canal, between the Yenisei and Mansi ancient lakes, under a layer of lake–alluvial deposits, remains of wood and peat aged from 27300 to 29500 years were discovered (Grosswald, 2009).

Thus, the warm insolation period 2_I corresponds to the period of the Karginsky interglacial. The presence of lacustrine–alluvial deposits, high river terraces, and shells of warm-water mollusks on the coast of the northern seas indicates the existence of the West Siberian Sea in the second part of this period, which was connected to the Kara Sea.

The authors of (MacDonald et al., 2012), in the process of studying the extinction of mammoths, analyzed the results of numerous studies carried out in the 1970s–2000s in Siberia and North America, including about 3000 radiocarbon dates, descriptions of lake sediment sections, and the results of spore–pollen analysis. According to their conclusions, the period 40000–25000 years ago was relatively warm, and 25000–12000 years ago it was comparatively cold, which corresponds to the characteristics of the insolation periods 2_I and 1_I we have identified.

Researchers of the mammoth fauna on the October Revolution Island in the Severnaya Zemlya archipelago (Makeev et al., 1979), based on the dating the remains, as well as peat, concluded that there was a warm period 25000–19000 years ago, which was replaced by a cold period 19000–12000 years ago. The cold period deposits are covered by peat aged 9950 ± 100 years. The given dates confirm the intervals of the insolation periods 2_I, 1_I, and O_I, respectively, we have identified.

Very Cold Insolation Period 3_I (Glaciation)

Most researchers believe that in the north of Western Siberia, on the shelf of the Barents and Kara Seas and on the islands, an ice sheet formed repeatedly in the past (Svendsen et al., 1999; Grosswald, 2009). The last maximum stage of development of the Barents-Kara ice sheet was about 50000 years ago (Svendsen et al., 1999).

At that time, its eastern part occupied the northern part of the Kara Sea shelf and almost the entire Taimyr Peninsula and the Putorana Plateau in Eastern Siberia. Its southern boundary extended just below the Arctic Circle and joined the southern boundary of the glacier in Europe (Svendsen et al., 1999; Grosswald, 2009). In the Pechora basin, this glacier melted 40000 years ago.

At a certain stage of the formation of the ice sheet in Western Siberia, the flow of rivers from the Ob and Yenisei basins into the Arctic Ocean ceased, and the depressions filled with water (Grosswald, 2009). The Khanty, Yenisei, and Purovskoye lakes were formed (Volkov et al., 1969; Volkov and Arkhipov, 1978), which subsequently united into the West Siberian lake–sea. The increase in the height of the ice sheet, and then the change from cooling to warming, led to the flow of ice from the ice sheet, which occurred both to the north, into the Arctic Ocean, and to the south. The flow to the north can be traced along underwater troughs—Medvezhinsky, Franz-Victoria, St. Anna, and Voronina, and the flow to the south is marked by the Siberian Ridges in Western Siberia and their continuation in Eastern Siberia. The "border" formed from moraine deposits was called by M.G. Grosswald "the Volkov line." The moraine belt along the Siberian Ridge upland is the southernmost in the region (Arkhipov et al., 1980; Arkhipov, 2000).

As the warming increased, the melting of the ice sheet continued and the freshwater sea continued to expand to such an extent that it began to flow through the Tobol-Turgai trench into the Turan lowland of the Aral Sea region and, possibly, with passages in the south into the Caspian lowland.

Insolation Periods 4_I-12_I

The main extremes of insolation 1_I, 2_I, and 3_I (Table 1) over the last 50000 years are in good agreement with the last two glacial periods in Western Siberia—Sartan and Ermakov, and the Karginsky interglacial between them. The deposits of each subsequent ice age overlap the traces of the previous one, so detecting and dating earlier paleoclimate fluctuations is difficult. Before the Ermakov cold snap, the Kazantsevo interglacial period was noted, which was one of the warmest in the Pleistocene (Arkhipov, 1997). Linden, elm, oak, and hazel grew in the modern southern taiga zone, along with coniferous trees. Chernozem soils were formed in the forest-steppe zone (Volkova, 1991; Arkhipov et al., 1995).

Starting from insolation extreme 3_I, there were no cold snaps (see Table 1). There were two small warmings, 60800 (4_I) and 83160 years ago (6_I), which is confirmed by two layers of peat, aged 65000 and 80000 years, respectively, in the deposits of the Belogorsk Upland along the right bank of the Lower Ob (Arkhipov, 1997). These layers overlie a 100000-year-old moraine corresponding to the peak of cooling at 96000 years ago (period 7_I, see Table 1). Researchers attribute this cooling to the lower layers of the Ermakovsky horizon. In the Middle Ob valley, in the Kiryas geological and geomorphological section, the lacustrine–glacial deposits of the Ermakov horizon are underlain by paleosols aged 120000 years (Arkhipov, 1997), which correspond to the peak of warming 8_I (110800 years ago).

In the deposits of the Middle Neopleistocene of Western Siberia, according to the unified regional stratigraphic scheme of Quaternary deposits, the Tazovsky glacial, Shirtinsky warm, Samara glacial, and Tobolsk warm horizons are distinguished (Volkova, 1999; Gusev et al., 2019). Taking into account the characteristics of these horizons (Gusev et al., 2019), we can see that the Taz glacial horizon coincides with the insolation minimum 9_I we identified, the Shirtinsky warm one coincides with a maximum of 10_I, the Samara glacial one with a minimum of 11_I, and the Tobolsk warm one with a maximum of 12_I.

A comparison of the insolation periods we identified and the results of paleoclimatic studies convincingly show that, in the interval 0–250000 years ago,

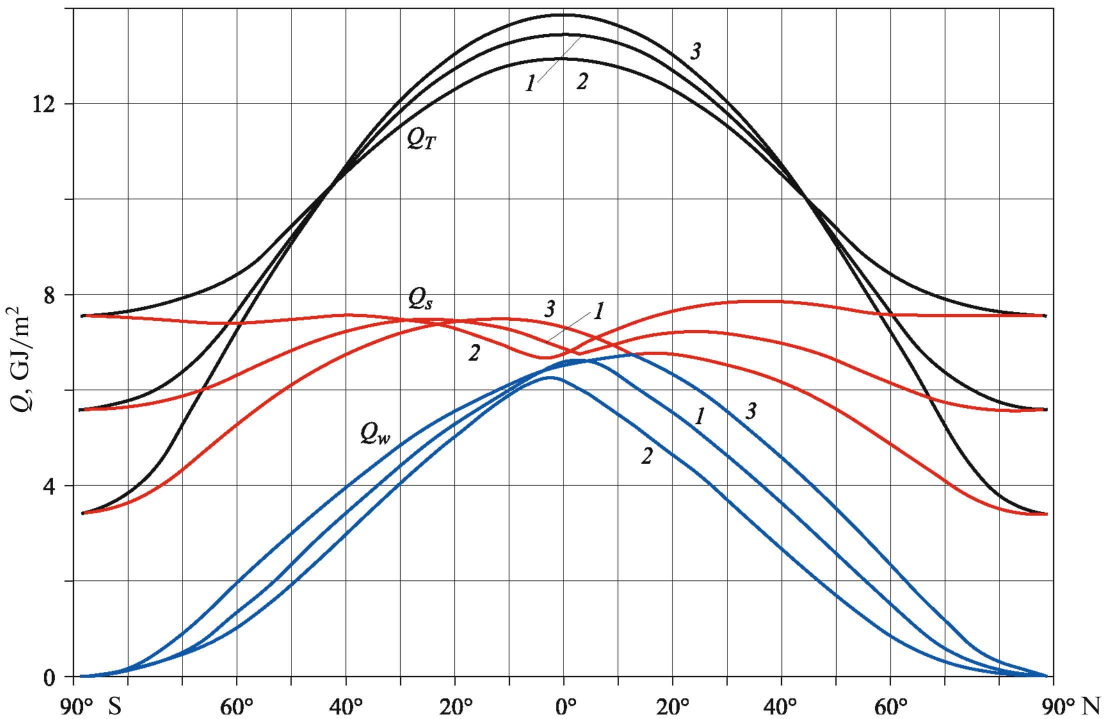

Fig. 2. Latitudinal changes in insolation over the year Q_T, summer Q_s, and winter Q_w insolations over three epochs (*1*–*3*) in the interval from December 30, 2049 to 20 million years ago. (*1*) Modern ($T = 0$; $Q_s^{65N} = 5.9$ GJ/m^2), (*2*) warmest ($T = 9.2475$ million years ago; $Q_s^{65N} = 7.58$ GJ/m^2), and (*3*) coldest ($T = 18.945$ million years ago; $Q_s^{65N} = 4.51$ GJ/m^2).

these periods reflect a change in the paleoclimate. Therefore, they can be recommended for interpreting paleodata and reconstructing the paleoclimate.

CHANGES IN EARTH'S INSOLATION WITH LATITUDE

Figure 2 compares insolation over a year Q_T and summer Q_s and winter Q_w caloric half-years over the last 20 million years in the modern era ($T = 0$) and the warmest ($T = 9.2475$ million years) and the coldest ($T = 18.945$ million years) of the era. These epochs are characterized by the following values of summer insolation at 65° N: 5.9, 7.58, and 4.51 GJ/m^2 respectively. The angles of inclination of the equatorial plane to the plane of the Earth's orbit (ε) in these epochs are 23.44, 32.66, and 14.06°, respectively.

Summer insolation Q_s in the modern era has a minimum value at the poles and reaches a maximum value in the tropics (φ = ε), and near the equator it decreases again (see Fig. 2). From the Cold Era (curve *3*) to warm (curve *2*) summer insolation Q_s at the poles, it increases 2.2 times and, at 65° N, 1.68 times. During the warm period under consideration, summer insolation had an equatorial minimum in the Southern Hemisphere and, during the cold period, in the Northern Hemisphere. At the same time, during the cold period in the Northern Hemisphere, the maximum of insolation Q_s practically degenerates and remains only at its maximum in the Southern Hemisphere. Thus, the cold era $T = 18.945$ million years ago is characterized by very cold summers throughout the Northern Hemisphere. It should be noted that the degeneration of the maximum summer insolation in the Northern Hemisphere is characteristic only of the cold era under consideration.

Winter insolation Q_w at the poles is equal to zero and increases monotonically towards the equatorial region. In the equatorial region, Q_w has a maximum at the same latitude as the minimum of summer insolation Q_s. The most noticeable changes in insolation Q_w occur in midlatitudes. Winter insolation in the cold era 3 is greater than in the warm era 2. That is, winters in cold periods are milder than in warm periods. It should be noted that, for the warm and cold epochs under consideration, 2 and 3, the change in Q_w in the Northern Hemisphere is almost 2 times more than in the Southern Hemisphere.

Annual insolation Q_T in all eras increases monotonically from the poles to the equator, and its course is symmetrical relative to the equator (see Fig. 2). That is, the amount of heat received by the Earth during the year is the same in both hemispheres. From a cold era

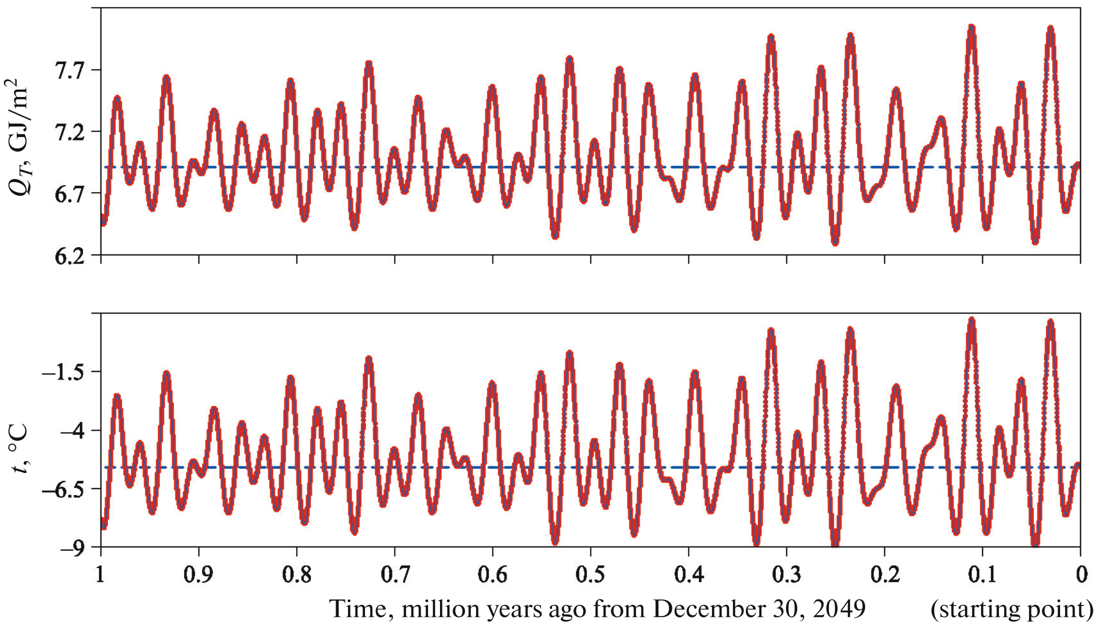

Fig. 3. Changes in the Earth's annual insolation Q_T and annual surface temperature t at 65° N over the last 1 million years. The dotted line is the average value of the parameters in the modern era.

to a warm insolation Q_T at the poles, it increases as many times as insolation Q_s. With decreasing latitude, the difference between annual insolation in different eras decreases, and at a latitude of 45°, annual insolation is the same for all eras.

In the equatorial region, the change in Q_T over the epochs is opposite to its change at high latitudes. During the cold era in question, the Earth received more heat per year than during the warm era. For example, at the equator, the value of Q_T in the cold era is 1.07 times more than in the warm era. Moreover, its change at the equator is 4 times less than in the high-latitude region. Therefore, the main changes in insolation occur at high latitudes.

The considered distribution of three types of insolation by latitude in the most extreme epochs over the past 20 million years practically repeats the existing results for other extreme epochs. However, there are also some peculiarities. For example, in the cold era under consideration, T = 18945 years ago, the maximum Q_s in the Northern Hemisphere degenerates. In addition, in the middle latitudes in winter, insolation changes 2 times more in the Northern Hemisphere than in the Southern Hemisphere.

From the data shown in Fig. 2, it is clear that, over the course of a year, the Earth receives approximately the same amount of heat in both hemispheres. However, it can vary significantly between half-years. Since the amount of heat received over a half-year affects the climate, paleoclimatic changes may also differ across the hemispheres. This is especially noticeable in equatorial and middle latitudes, and in high latitudes the differences disappear.

Changes in the Earth's insolation are achieved by changing the movement of the Sun across the celestial sphere. This is manifested in changes in the time of sunrise and sunset, the length of daylight hours, the duration of polar days and nights, etc. (Smulsky, 2018). For example, during ice ages in the Northern Hemisphere, polar days and nights occur significantly north of the modern Arctic Circle, and, during warm periods, significantly south of it.

CHANGES IN ANNUAL INSOLATION AND TEMPERATURE IN THE NORTHERN HEMISPHERE OVER THE PAST 1 MILLION YEARS

In (Smulsky, 2022a, 2022b), the average latitude near-surface heat capacity of the Earth, determined in two ways, was introduced, with the help of which, based on annual insolation of Q_T, the average annual temperature is calculated. In Fig. 3, the change in annual insolation over 1 million years at 65° N is shown. Annual insolation Q_T changes in phase with summer Q_s^{65N} (see Fig. 1), and its significant oscillations coincide in time with the oscillations of the harmonic Q_{shar}^{65N}. Therefore, the period of precession of the Earth's axis P_{prm} is also the main period of change in annual insolation.

The annual surface temperature at 65° latitude varies in the Northern Hemisphere similarly to the change in annual insolation Q_T (see Fig. 3); accordingly, its oscillations have the same fundamental period. The temperature varies from –9.07 to 0.75°C; i.e., the range of change is 9.8°.

At 80° N, the annual temperature ranges from –33.3 to –2.0°C (Smulsky, 2022a, 2022b); the range of variation is 31.3°. At the North Pole, the annual temperature varies from –50.0 to –2.4°C; the range of variation is 47.6°.

As we move south, the range of fluctuations in annual insolation and temperature decreases, and at a latitude of 45° the values of these parameters remain practically constant. Closer to the equator, their fluctuations increase, but have the opposite direction: in cold periods, it becomes warmer at these latitudes. At the equator, the annual temperature ranges from 28.2°C at the coldest epoch to 24.2°C at the warmest epoch for high latitudes.

MAIN PROPERTIES OF INSOLATION PERIODS OF CLIMATE CHANGE

(1) Insolation periods are timed to coincide with the cycles of precession of the Earth's axis and can repeat every 25750 years.

(2) Very strong cold spells and very strong warm spells follow unevenly. For example, they can repeat themselves in 30000 years or in 300000 years. On average, they repeat every 164000 years.

Cold and warm periods occur 4 times more often. All insolation extremes of climate change occur deterministically, at a strictly defined time.

(3) The nominal duration of insolation periods is 12870 years. The duration of very warm or very cold periods can be 2000–4000 years longer. The duration of nonextreme periods sometimes reaches 25000 years.

(4) Ice ages, i.e., periods of glaciation, affect mainly latitudes above 50°. It becomes warmer in equatorial latitudes.

(5) At high latitudes, annual insolation changes in phase with summer insolation and in antiphase with winter insolation. Therefore, summers during ice ages at all latitudes are colder than today's, and the greater the geographical latitude of the area, the colder the summer.

(6) Winters during ice ages at all latitudes are warmer than modern ones.

(7) During ice ages, the boundary of polar days and nights shifts north of its current position (for example, it may be located north of Bely Island in the Kara Sea, and in warm periods to the south, for example, to the latitude of Tyumen (Smulsky, 2021).

(8) During very cold periods at high latitudes, the amount of heat received per year and during the summer half-year is 50% less than in the modern era. The annual temperature during these periods, for example, at 80° N, decreases by 15.6°, and at the pole by 24.4°.

In the Northern Hemisphere, the amount of heat received during the summer half-year at such an annual temperature up to a latitude of 50° is less than the current amount at the pole. In this case, the snow that fell during the winter does not melt, and the ice sheet can extend to this latitude. The areas of glaciers in Greenland and Antarctica will also increase, the level of the World Ocean will decrease, vegetation will develop, and a soil layer will form in the areas freed from water at all latitudes.

(9) During very warm periods at high latitudes, 50% more heat will be received per year and during the summer half-year compared to the modern era; the annual temperature at 80° latitude in the Northern Hemisphere will increase by 14.4°, and at the pole by 21.5°. The amount of heat during the summer half-year at high latitudes will be 12% greater than in the modern era at the equator. We estimate that the average summer temperature at the North Pole could reach 35°C. At this temperature, the glaciers of Antarctica and Greenland should almost completely melt, and the level of the World Ocean will rise.

(10) In the middle latitudes, the annual insolation of the Earth's surface changes little from period to period. For example, at a latitude of 45° it is practically constant, and the annual temperature fluctuates within a few tenths of a degree near its current value of 9.33°C. Summer and winter insolation change in antiphase. The amplitude of fluctuations in summer insolation is 2 times smaller than the amplitude of its fluctuations at a latitude of 65°. In warm periods, this can lead to an expansion of steppe and desert zones, and in cold periods, to their reduction. Variations in summer insolation affect the area of mountain glaciers. During warm periods, the area of glaciers in the mountains decreases, and it increases during cold periods.

(11) In tropical latitudes, annual insolation changes inversely to its change in high latitudes: during cold periods at the equator and in the tropics, it becomes warmer. This could lead to an increase in the area of deserts and a reduction in the size of mountain glaciers.

Winter insolation mainly fluctuates in phase with annual insolation, and its amplitude is 2 times greater than the annual one. The evolution of winter and summer insolation in the tropics of the Southern Hemisphere can differ significantly from their evolution in the tropics of the Northern Hemisphere.

INSOLATION AND SEDIMENTARY ROCK LAYERS

The properties and characteristics of glacial and interglacial periods of the past, discussed in the previous sections, allow us to reconstruct the paleoclimate. The first attempt at such a reconstruction was carried out by us for Western Siberia based on the value of summer insolation in equivalent latitudes I (Smulsky and Ivanova, 2018). Value I is measured in degrees of latitude, to which the same amount of heat

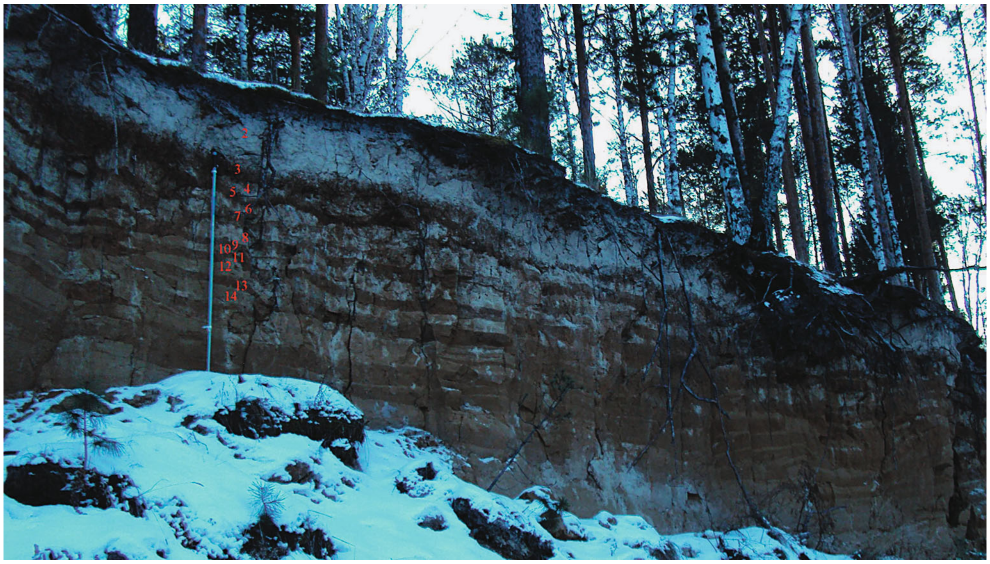

Fig. 4. Exposure of layers of sedimentary deposits in the cliff of the river bank. Tura is 40 km upstream from the city of Tyumen. Photo by the author. The height of the terrace is 20 m above the river level.

is received in the modern era as in the one under consideration.

It was shown that 53000–41000 years ago in the territory north of the Siberian Ridges, insolation *I* was more than 80°. In modern times, there is glaciation at this latitude. Therefore, an ice sheet formed on the territory of the Northern Ridges 53000–41000 years ago. The Ob and Yenisei river outflows into the Arctic Ocean were blocked by an ice sheet, which is why the low-lying part of Western Siberia with elevations of up to 100 m was covered with water. Part of the waters along the Tobol-Turgay trough penetrated into the Turan lowland (Illarionov, 2013) and could pass through the Turkmen Gulf into the Caspian Sea.

After the final disappearance of the ice sheet, the water left the lowlands, vegetation began to develop on the various glacial and fluvioglacial deposits, and a soil layer was formed. As was already noted, over 20 million years there have been 122 periods of significant cooling and warming. The repeated change of these eras is reflected in the change of layers of sedimentary rocks. Often, thick sections of such sedimentary deposits can be observed in natural outcrops along river banks (Fig. 4), seas (Fig. 5), and in the walls of industrial quarries.

Similar outcrops are found in many places in Western Siberia. For example, in 1988, the author saw such a section of sediments in the cliff of the high bank of the Seyakha River near the village of Bovanenkovo (Yamal Peninsula). Alluvial layers here alternate with peaty layers and buried soils.

On the sea shores, exposures of layers of sediments of different ages and genesis are particularly impressive. As an example, Fig. 5 shows layered formations in the steep shores of the Black and Mediterranean seas and the Atlantic Ocean, which, in turn, is associated, among other things, with long-term changes in insolation at high latitudes. For example, during a very warm period, the melting of the Antarctic ice sheet alone could raise sea levels by 75 m compared to today's levels. During a very cold period, the ocean level can drop by the same amount relative to the current level.

Undisturbed layers of Quaternary sediments are found in different places on different continents. Thus, the surface deposits of Central Europe, in which buried soils and loesses are interbedded, contain detailed information about the history of the Pleistocene climate (Imbrie, J. and Imbrie, K.P., 1988).

The layers of these deposits also record the history of fluctuations in the Earth's insolation depending on local conditions. The study of the properties and characteristics of sedimentary layers will allow us to understand in more detail the evolution of the Earth's paleoclimates.

CONCLUSIONS

Over the past 200 years, scientists have come to believe, based on a number of pieces of evidence from the past, that the climate has undergone significant changes throughout the Earth's history. Initially, it was established that in the past the climate was colder than in the modern era, and in high latitudes there was a continuous ice sheet. It then became clear that the cold period was preceded by a warm one, and such climate changes were repeated many times.

Of the many possible causes, the most likely was a change in the Earth's insolation. The Earth's insolation depends on the parameters of its orbit and the tilt of its axis of rotation to the plane of its orbit. As celes-


a
b
c

Fig. 5. Alternation of layers of sediments of different genesis along the sea shores: (a) Black Sea coast of the Caucasus (village of Divnomorskoe), (b) the Mediterranean Sea basin (canyon in the Mides oasis, Tunisia), and (c) Atlantic Ocean (Devon County, England). The photographs are taken from publicly available Internet resources that do not contain any indication of the authorship of these materials or any restrictions on their use.

tial mechanics developed, the evolution of these parameters was determined with increasing accuracy. When the problems of the evolution of the orbit and the axis of rotation of the Earth were finally solved, the periods of change in insolation coincided with the eras of climate change.

This continuous search and the work of many researchers have not been in vain. Many different opinions were expressed, there were many heated discussions, and many different theories were created. However, in the end, the goal was achieved, and the problem was solved. Recognizing the existence of long-term climate changes driven by changing insolation will provide a better understanding of the Earth's history and more reliable planning of human activities in the future.

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CONFLICT OF INTEREST

The author of this work declares that he has no conflicts of interest.

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