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Solar Activity, Cosmic Rays, and Earth Temperature Reconstructions for the Past Two Millennia. Part 2. Analysis of the Relation between the Global Temperature Variations and Natural Processes

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Abstract—Regularities in the long-term global temperature variations for the past two millennia have been analyzed. It was shown that the periods of a prolonged temperature rise and drop were most pronounced before the industrial epoch. Analysis indicates that the extrema in the global temperature variations in the first and second millennia correspond to long-term solar activity increases and decreases. The performed analysis of temperature reconstructions, which were performed using different methods (including the geothermal method), show that the observed climate change during the past two millennia is in good agreement with the variations in the concentration of the ^{14}C and ^{10}Be cosmogenic isotopes modulated by time-varying solar activity.

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1. INTRODUCTION

Climate change is a problem that affects all aspects of life on our planet. It is known that the central paradigm of the Intergovernmental Panel on Climate Change is that present-day climate warming is only caused by the anthropogenic impact. According to the last report of this Panel (*IPCC*, 2013), the surface air temperature over continents and oceans increased by 0.85°C (from 0.65 to 1.06°C) from 1880 to 2012 and by 2–4.8°C in the 21th century. At the same time, it is known that the global climate has substantially and continuously changed during the entire geological history of the Earth. Progress in understanding many climate variability aspects is limited, since instrumental observations are absent for rather long time intervals, especially in the Southern Hemisphere. Instrumental temperature measurements have been performed mostly in the Northern Hemisphere over the last 150 years. The temperature reconstructions for the past two millennia were analyzed in (Dergachev, 2015).

The prediction of future climate changes performed by the followers of the anthropogenic hypothesis is based on modeling the interaction between the atmosphere, ocean, and dry land. Several dozen such models have been developed. The followers of the anthropogenic hypothesis ignore natural factors, since they state that the calculations of the observed global temperature variations are inconsistent if these factors are taken into account. Of course, science has not yet made it possible to understand completely the variations in all of the natural processes that affect the complex climatic system of the Earth. Nevertheless, to estimate past and future climate changes objectively, it is necessary to take into account natural factors affecting climate. In the contrary case, a wrong notion of our knowledge of the climatic system and factors affecting this system and, particularly, future climate change, will finally be formed. We should note that expert estimates of the threat of global warming differ even in the main greenhouse gases: carbon dioxide or water vapor.

We analyzed below the accumulated information about the relation between global temperature variations over the past two millennia and natural factors.

2. SOLAR ACTIVITY AND OTHER HELIOGEOPHYSICAL FACTORS AFFECTING GLOBAL TEMPERATURE

Since solar energy accounts for more than 99% of the total energy input into the Earth environment, it is evident that the Sun is a potential cause of climate changes. Although the possible climate change mechanisms related to the solar variability rest on a solid physical foundation, it is still insufficiently clear whether solar variability controls processes in the climatic system or only stimulates them.

In addition to solar activity (SA), variations in the orbital characteristics of the Earth during its rotation around the Sun, the passage of the solar system through interstellar dust clouds, the drift of continents and orogenic processes, variations in the atmosphere–ocean heat exchange processes and in the ocean water heat content, powerful volcanic eruptions, etc., are related to natural climate change causes on different timescales. The future risks related to a varying climate largely depend on the scales of future climate changes.

The study of the physical processes and phenomena that proceed in the near-Earth space is directly related to the Earth's middle and lower atmosphere. Such a study has been intensely performed from the 20th century, especially from the beginning of the space age. This is critical for solving many problems in meteorology, climatology, geophysics, astrophysics, cosmic ray physics, etc. The near-Earth space, atmosphere, and ionosphere are very important environmental components affecting the climate, weather, radio communication, agricultural productivity, origination of several catastrophic phenomena (flooding, earthquakes, etc.), and public health.

Shumilov (2002) presented the results of studying the influence of different heliogeophysical agents on various layers in the near-Earth space (the magnetosphere, ionosphere, atmosphere, and ozonosphere) and on the Earth climate and biological objects. Electron fluxes were considered as agents (input signals) affecting the ozonosphere and Earth climate. Auroral precipitation of all types affects electric field variations in the vicinity of the Earth. Fluxes of solar and galactic cosmic rays with a high penetrating power (the latter rays penetrate up to the Earth's surface) are also considered corpuscular agents. The Sun, in turn, modulates galactic cosmic ray fluxes by time-varying magnetic fields "frozen" in the solar wind. The interplanetary magnetic field substantially affects magnetospheric electric fields and (via these fields) the energy of particles coming into the ionosphere and lower atmosphere. This work indicated that the influence of natural factors on the near-Earth space may be comparable with the anthropogenic impact and cannot be ignored.

Cosmic rays are the main ionization source at altitudes of ~3 to ~50 km in the atmosphere. This is responsible for the role of the cosmic radiation in the atmospheric processes and, primarily, in the formation of the global electric circuit and, possibly, cloud cover. Charged particle fluxes in the Earth's atmosphere intensify or weaken the cloud formation process. When energetic solar particles and magnetospheric electrons precipitate into the stratosphere, additional ionization results in pronounced variations in the temperature and ozone layer.

The terrestrial manifestations of the long-term solar variability have been intensely studied over the last decades. There is much compelling evidence that short-term (not more than several days) and long-period (from dozens to hundreds of years or more) SA variations actually affect the corresponding changes in the global and regional climate. To elucidate the mechanisms by which SA is related to the Earth climate is the most important problem of solar–terrestrial physics. More and more, researchers arrive at the conclusions that fluxes of cosmic energetic particles, which are effectively modulated by the Sun, play the main role in maintaining the relation between SA and climate (Ogurtsov, 2011). We should note that it is possible to make a reliable and long-term prediction of climate change only if detailed information exists about climate change in the past and if researchers understand the essence of the processes proceeding in the atmosphere under the action of terrestrial, solar, and cosmophysical factors.

Dergachev et al. (2008, 2009) analyzed the climatic characteristics and SA on the timescale covering the past several hundred years in the light of global warming in the 20th century. The data on a change in SA, which was determined from reconstructions of sunspots and the radiocarbon level as a reflection of solar variability, were compared with variations in climatic characteristics. It was shown that cold and warm periods correspond to periods of decreased and increased SA, respectively. Taking into account the fact that the Sun was on the SA growth branch in the 2400 year cycle for almost half of the past millennium (Dergachev, 1996) and the trend caused by the orbital motion of the Sun, we should bear in mind these circumstances when considering future climate changes.

3. ANALYSIS OF REGULARITIES IN PALEOTEMPERATURE VARIATIONS FOR THE PAST TWO MILLENNIA

Moberg et al. (2005) reconstructed the temperature in the Northern Hemisphere for the past 2000 years, combining indirect low-resolution data (lacustrine sediments, plant pollen, stalagmites, mollusk shells, etc.) with ring tree data, in order to understand regularities in natural climate variability and the role of the anthropogenic impact on the climate on scales varying from several decades to several centuries. Low-resolution data, such as lacustrine and oceanic sediments, can give climatic information about large-scale climatic variability on scales of several centuries or longer that can be not covered by tree rings. Using the wavelet transform, the authors divided the weights of indirect data on different timescales and established that the climate is widely variable over several centuries. The analysis of the performed estimations of the variations in the average temperature in the Northern Hemisphere and the modeling results are presented in Fig. 1. Averaging of the low-resolution data revealed trends that are consistent with the geothermal thermometry results (Pollack and Smerdon, 2004), in which the time variations substantially differ from the reconstruction performed by Mann and Jones (2003).

According to the (Moberg et al., 2005) reconstruction, high temperatures similar to those observed in the 20th century up to 1990 took place about 1000–

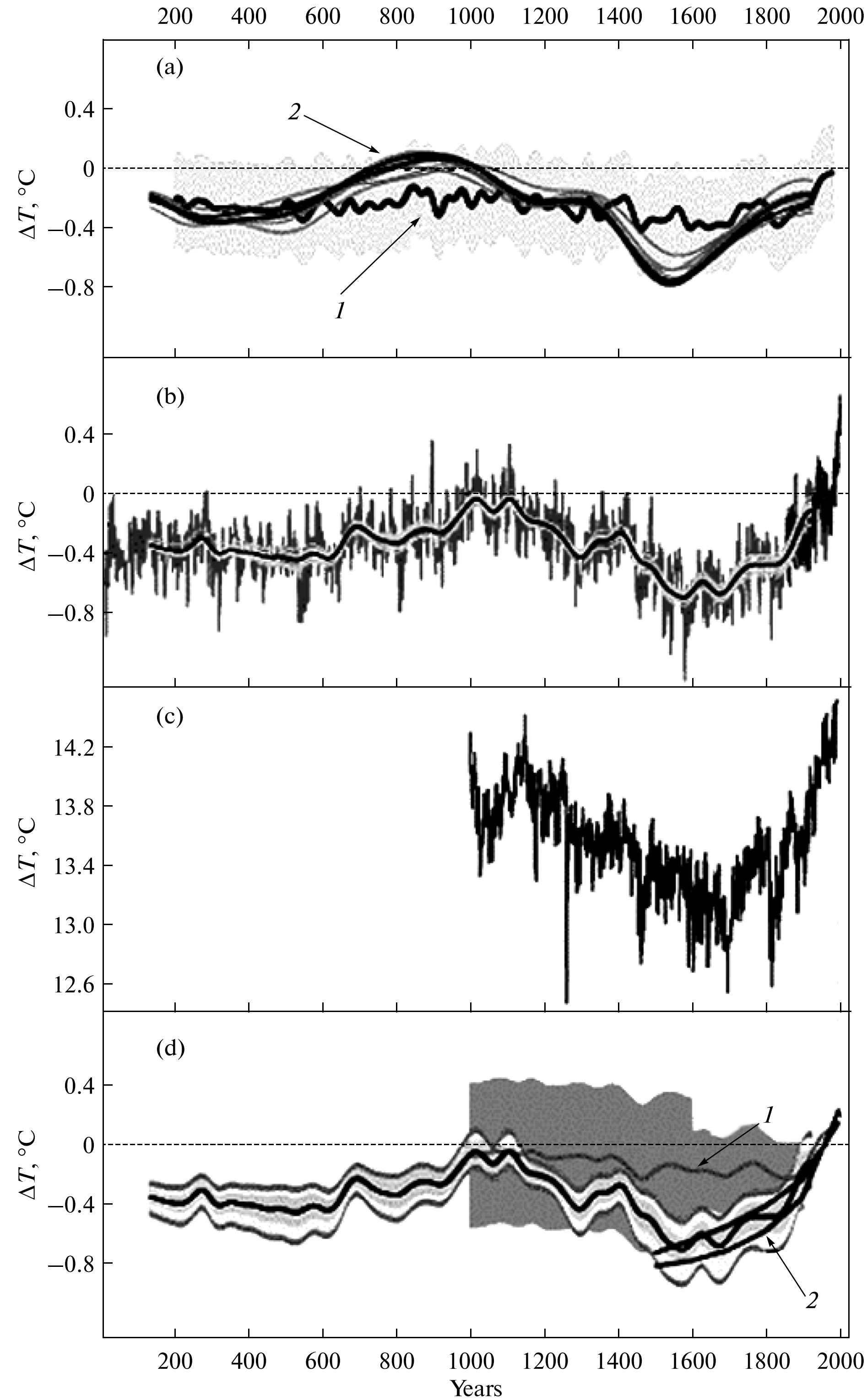

Fig. 1. Variations in the average temperature in the Northern Hemisphere. (a) reconstruction *1* (Mann and Jones, 2003) with regard to two standard deviations (a gray background) and different averaging of low-resolution data (*2*) (the set of smooth lines); (b) calibrated reconstruction (Moberg et al., 2005) with instrumental data; the 80-year component is shown by a solid line; (c) an artificial ECHO-G model (von Storch et al., 2004; Gonzalez-Rouco et al., 2003; Legutke and Voss, 1999); (d) the LF component in the reconstruction presented in Fig. 1b with 95% confidence intervals for the revealed data uncertainties, including data *1* (Mann and Jones, 2003). Surface temperatures estimated from boreholes *2* (Polack and Smerdon, 2004), with their uncertainty intervals, are also shown. The temperature anomalies in Figs. a, b, and d are given relative to the average value for 1961–1990.

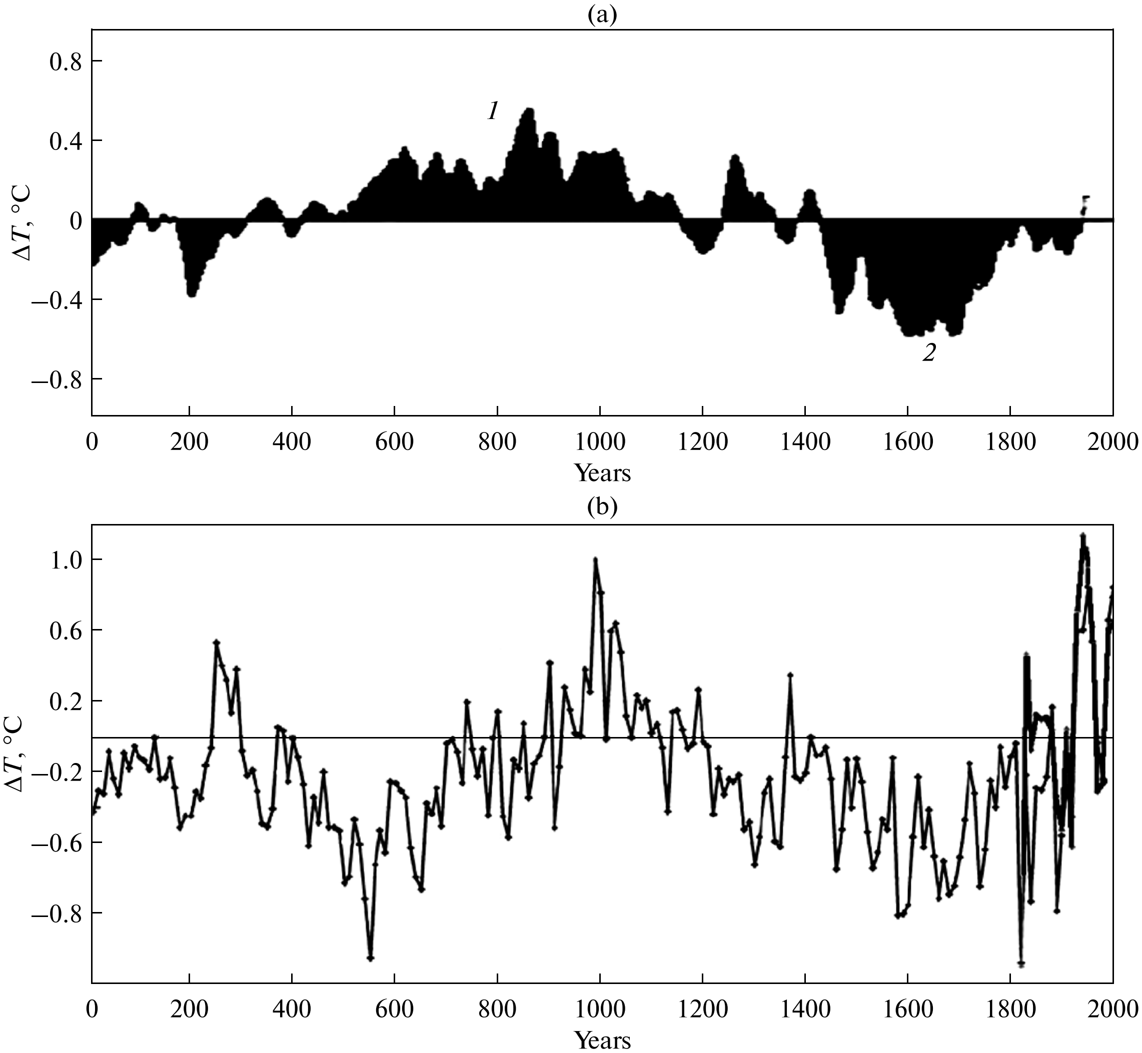

Fig. 2. (a) Reconstruction of paleotemperatures from indirect data without tree ring data (Loehle and McCulloch, 2008); the Medieval Warm Period (*1*); the Little Ice Age (*2*). (b) Reconstruction of the decadal values of the average annual temperatures (average annual anomalies ΔT, °C) for northeastern Europe according to indirect data on climate: dendrochronology, palynology, and historical chronicles (a thin line), as well as the instrumental data (a thick line) (Klimenko et al., 2013).

1100, and the minimal temperature (which was lower than the average temperature for 1961–1990 by approximately 0.7 K) was observed near 1600. This natural temperature variability in the past indicates that the role of natural factors is important.

Loehle and McCulloch (2008) showed that the tree ring growth nonlinearly responds to prolonged warming or cooling periods. In such a case, with observed warming in the 20th century, the temperature reconstruction based on tree ring growth during warm and cold periods can result in erroneous temperature estimations on long timescales. Therefore, the authors reconstructed the global temperature for the period from 16 to 1935 based on 18 reviewed and published indirect climatic data used in the existent reconstructions after eliminating the data related to tree ring growth. The data in each series were smoothed by the 30-year moving average and are shown in Fig. 2a. The average value of the series rather distinctly demonstrates the Medieval Warm Period and the Little Ice Age. In this case the temperature at the Medieval Warm Period maximum was higher than in the 20th century by approximately 0.3°C.

It is known that different indirect data have different resolving powers. Thus, palynological data rarely reach a resolution smaller than 50 years; at the same time, tree ring data make it possible to reconstruct events accurate to a year, to say nothing of historical information and instrumental data.

We compare the global temperature reconstruction (Loehle and McCulloch, 2008) with new data obtained by Klimenko et al. (2013), who used high-resolution dendrochronological data in order to estimate temperature variations in the past. Klimenko et al. (2013) presented the quantitative reconstruction of the average annual temperatures in northeastern Europe for the past two millennia. The performed temperature reconstruction demonstrates that temperature substantially varies over several decades and centuries (Fig. 2b). It was indicated that the maximal average annual temperatures in the preindustrial epoch (in 981–990) were higher by 1°C and the minimal temperatures in 1811–1820 were lower than such temperatures in 1951–1980 by 1.3°C on average.

A comparison of the reconstructed decadal values of the average annual temperature with regional reconstructions and reconstructions for hemispheres makes it possible to detect pronounced climate changes during the past two millennia: the climatic optimum (2nd–3rd centuries), cold epoch (5th–6th centuries), Medieval Climatic Optimum (10th–12th centuries), Little Ice Age (13th–19th centuries), and recent warming (20th century). The authors indicate that these climatic events were observed over the entire Northern Hemisphere and in its individual regions. Sudden warming events were registered in the Arctic Regions in the 1860s–1870s and 1920s–1940s during periods of a stable or even cold climate in central Russia.

The reconstruction performed by Klimenko et al. (2013) differs in a pronouncedly more detailed and high amplitude variability as compared to other reconstructions. The authors explain that the amplitude difference is more considerable, because the temperature variation amplitude at high latitudes is larger than in the Northern Hemisphere and the region of the study, where climate changes are almost synchronous, is comparatively small, which does not result in a pronounced smoothing when parameters are averaged. Similar detailed reconstructions of variations in the surface temperature in the past make it possible to compare instrumental data with multidecade and secular variability, which originates as a result of external impacts and internal climate variability.

We pay attention to certain specific features in the reconstructions for the past 2000 years based on oceanic sediments (Fig. 3). DeMenocal et al. (2000) determined the surface ocean temperatures near the West Africa coast. Figure 3a indicates that the temperatures at the beginning of the first millennium were low and comparable with those during the Little Ice Age. These results were also confirmed by other researchers in the data for the indicated region of Africa. The surface ocean temperature profile obtained in the Sargasso Sea deposits near Bermuda Islands (Keigwin, 1996) (Fig. 3b) indicates that the temperature minimum at the beginning of the first millennium lags behind the data presented in (DeMenocal et al., 2000) by approximately 200 years. The temperature profile from the data on Greenland ice cores (Dahl-Jensen et al., 1998) (Fig. 3c) in this time interval indicates that the temperatures were low,

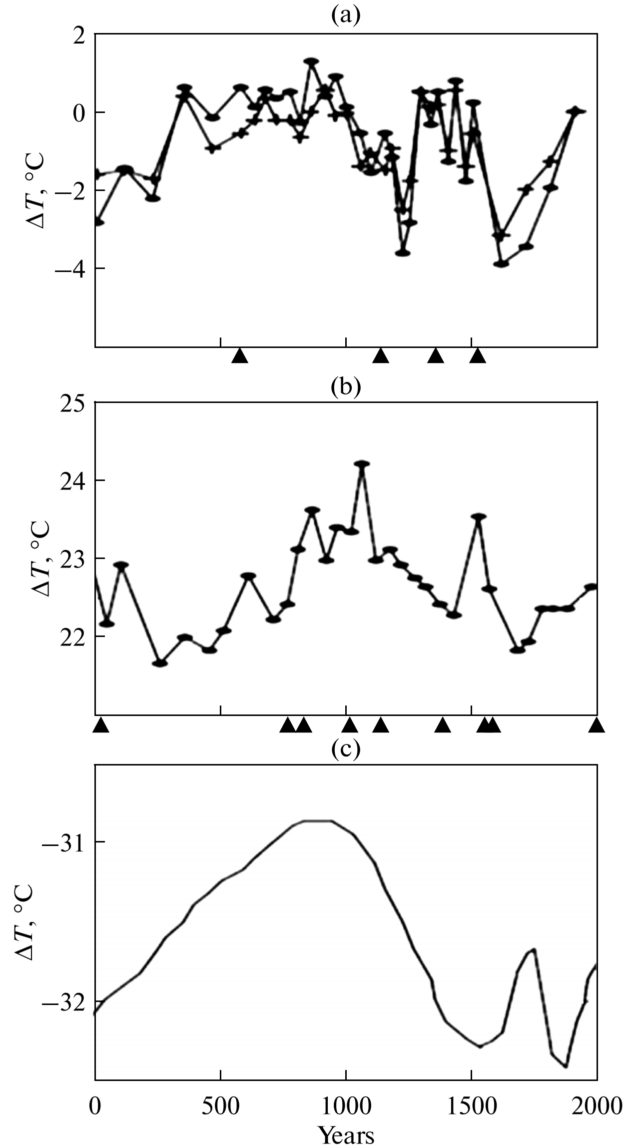

Fig. 3. Comparison of temperature paleoreconstructions performed with data from (a) the eastern subtropical part of the North Atlantic Ocean (DeMenocal et al., 2000), (b) the western part of the North Atlantic Ocean (Keigwin, 1996), and (c) Greenland ice cores (Dahl-Jensen et al., 1998).

although they were higher than such temperatures during the Little Ice Age.

Large-scale climate and global temperature reconstructions based on indirect data are representative recorders of the variable values of the environment when these reconstructions are related to instrumental temperature observations. However, the performed analysis indicates that the various approaches based on short series of direct temperature variation observations do not make it possible to coordinate obtained reconstructions adequately with one another, to obtain an actual pattern of the climate variability, or to determine climate change causes unambiguously.

4. LONG-TERM SA CYCLICITY

The Sun is the main energy source for the Earth's atmosphere. It was established that processes on the Sun are related to climate change through time variations in (a) the total solar radiation responsible for the variable heat input to the lower atmosphere; (b) the UV emission affecting ozone in the stratosphere, which is dynamically related to the troposphere and the lower atmosphere; (c) the cosmic ray flux modulated by SA, which affects the Earth's atmosphere.

The historical chronicles and the study of the variations in the climatic characteristics made it possible to establish two periods of extreme global changes in climate and SA during the past millennium: the Little Ice Age (~1300–1900) and Warm Medieval Period (~900–~1300) (Le Roy Laduire, 1967; Nagovitsyn, 2001). The specific features of time variations in the climatic events during these extrema can be traced in detail on an annual basis, with the use of data on variations in cosmogenic isotopes (^{14}C in annual rings of long-living trees and ^{10}Be in annual ice layers from polar regions and glaciers) that are produced by galactic cosmic rays in the Earth's atmosphere. Modulated by SA, these isotopes come from the atmosphere to the Earth's surface and are fixed in ground samples. It is interesting that the data on the variations in the level of the above cosmogenic isotopes show a fine structure of SA variations in the past. Measurements of the ^{14}C concentration in annual tree rings (e.g., (Stuiver and Quay, 1980)) (Fig. 4a) make it possible to observe that extreme SA variations are distinctly traced in ^{14}C ($\Delta^{14}C$) concentrations: the minimal SA levels correspond to the maximal $\Delta^{14}C$ values and vice versa, which is clearly physically justified. In this case, the cold (Little Ice Age) and warm (Medieval Maximum) periods correspond to decreased and increased SA, respectively. It is evident that $\Delta^{14}C$ variations in the Earth's atmosphere in the past are the source of important information, differentiated in time, about the study of SA and other natural processes on absolutely dated long timescales. Radiocarbon is a global tracer of these processes. The ^{14}C content also reflects the anthropogenic impact on the level of this isotope, which decreased as a result of the combustion of fossil fuels (the Suess effect) and increased after the atomic bomb explosion in the Earth's atmosphere. We note that $\Delta^{14}C$ amplitude variations are the most substantial after approximately 200 years (Dergachev et al., 2005).

Eichler et al. (2009) presented high-resolution data on the oxygen-18 isotope content in the ice core for the past 750 years from a continental Siberian Altai, Belukha glacier (height 4062 m, 49°48′26″ N, 86°34′43″ E). Relative variations in oxygen-18 are indirect data for temperature reconstructions. In Fig. 4b smoothed reconstructed temperatures are shown and are compared with the variation in SA: the sunspot number and solar modulation estimated from the ^{14}C and ^{10}Be cosmogenic isotopes (Muscheler et al., 2007). A shift of 10–30 years exists between the solar influence and temperature, which points to indirect solar–climatic mechanisms related primarily to a change in the atmospheric circulation under the action of oceanic processes.

Spectral analysis of the reconstructed temperatures indicates significant periods of 205, 86, and 10.8 years, which are closely related to the Suess, Gleissberg, and Schwabe solar cycles, respectively. In addition to the indicated cycles, we also managed to detect an approximately 2400-year cycle in long series of the cosmogenic isotope concentration (Dergachev, 1996; Dergachev and Raspopov, 2000; Vasiliev and Dergachev, 2002). According to these studies, the end of the last millennium falls on the wave of decreased SA in this long cycle.

Figure 5 compares the reconstructed data on the solar variability for the past approximately 1200 years (Lean et al., 1995; Lean, 2000; Bard et al., 2000), as well as on the climatic variability based on the lacustrine sediments (Verschuren et al., 2000) and mountain glacier advance and retreat (Holzhauer et al., 2005). A comparison indicates that solar variability on the long timescale shows sudden climate changes, including the Little Ice Age (see Fig. 4a).

The data presented above demonstrate the relation of different reconstructions of past temperature and other climatic characteristics to SA and the time-varying intensity of galactic cosmic rays.

A comparison of the cosmic ray intensity variations, as reconstructed from the measured content of radiocarbon in tree rings (Reimer et al., 2004) and beryllium-10 in Greenland (Usoskin et al., 2002) and Antarctic (Raisbeck et al., 1990) ice layers (Fig. 6a), shows that these data are in good agreement with one another. The tendency toward a temperature variation in the Northern Hemisphere (Fig. 6b), except for the data presented in (Mann et al., 1999), follows long-term variations in the cosmogenic isotope concentration. A similar pattern is traced when we compare the cosmic ray intensity (Fig. 7a) and the temperature, as reconstructed based on the speleothem data from Spannagel Cave in Austria (Mangini et al., 2005) (Fig. 7b). In this case a low galactic cosmic ray flux is related to a high temperature and, consequently, climate warming. A colder climate corresponds to a high flux of galactic cosmic rays. The difference between maximal temperatures in the Medieval Warm Period and minimal temperatures in the Little Ice Age in Central Europe reached approximately 1.5°C (Fig. 7b). The high correlation between the intensity of cosmic rays modulated by SA ($\Delta^{14}C$) and temperature ($\delta^{18}O$) is support for this as the main cause of climate changes.

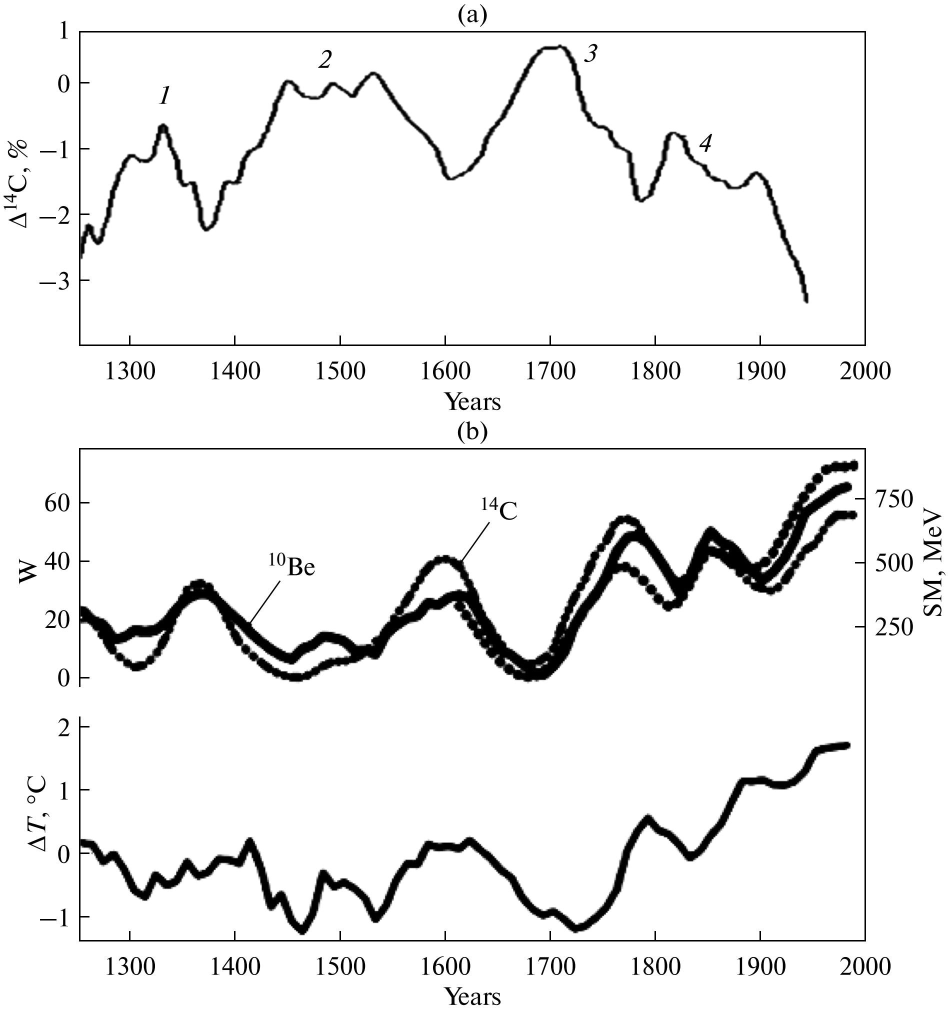

Fig. 4. (a) Extreme variations in SA and radiocarbon concentration ($\Delta^{14}C$) in samples of dendrochronologically dated tree rings from the past millennium (Stuiver and Quay, 1980). SA minimums: Wolf (*1*), Spörer (*2*), Maunder (*3*), and Dalton (*4*). (b) Comparison of the temperature, reconstructed based on O-18 data from continental Siberia (the Altai region, Belukha glacier) with a change in the sunspot number (1610–2000, a dotted curve) and solar modulation (SM, MeV), following from the data on ^{14}C (a dot-and-dash curve) and ^{10}Be (a solid curve) (Muscheler et al., 2007).

The current data indicate that there are both short-term cycles that last several dozen years, as well as longer cycles with a duration reaching several hundreds or thousands of years. This is in good agreement with the corresponding cyclic variations in SA and the galactic cosmic ray flux, which manifest themselves in climatic characteristics. Quasi-cyclic variations in SA make it possible to project short-term global temperature trends. Taking into account long-term ~210- and ~90-year solar cycles, we traced the tendencies in global temperature changes caused by processes related to SA; this indicated (Dergachev et al., 2008) that unusual global temperature variations will hardly be observed in the coming years, which will remain close to the region of values registered near 2000.

5. PROSPECT OF A GLOBAL TEMPERATURE CHANGE

As a result of seasonal ice layering, it is possible to determine reliably the age of ice cores. Researchers determine the atmospheric concentrations of greenhouse gases during deposition by analyzing bubbles and gases dissolved in the ice, and the average annual temperature is calculated based on the oxygen-18 or deuterium concentration deviations (similar data of such analyses in the past atmosphere were presented, e.g., in (Luthi et al., 2008)). With these data, researchers distinguished eight climatic (glacial) cycles lasting approximately 100 kyr each, which are generally similar to one another: a rapid temperature rise to a maximum with a subsequent drop (interglacial periods)

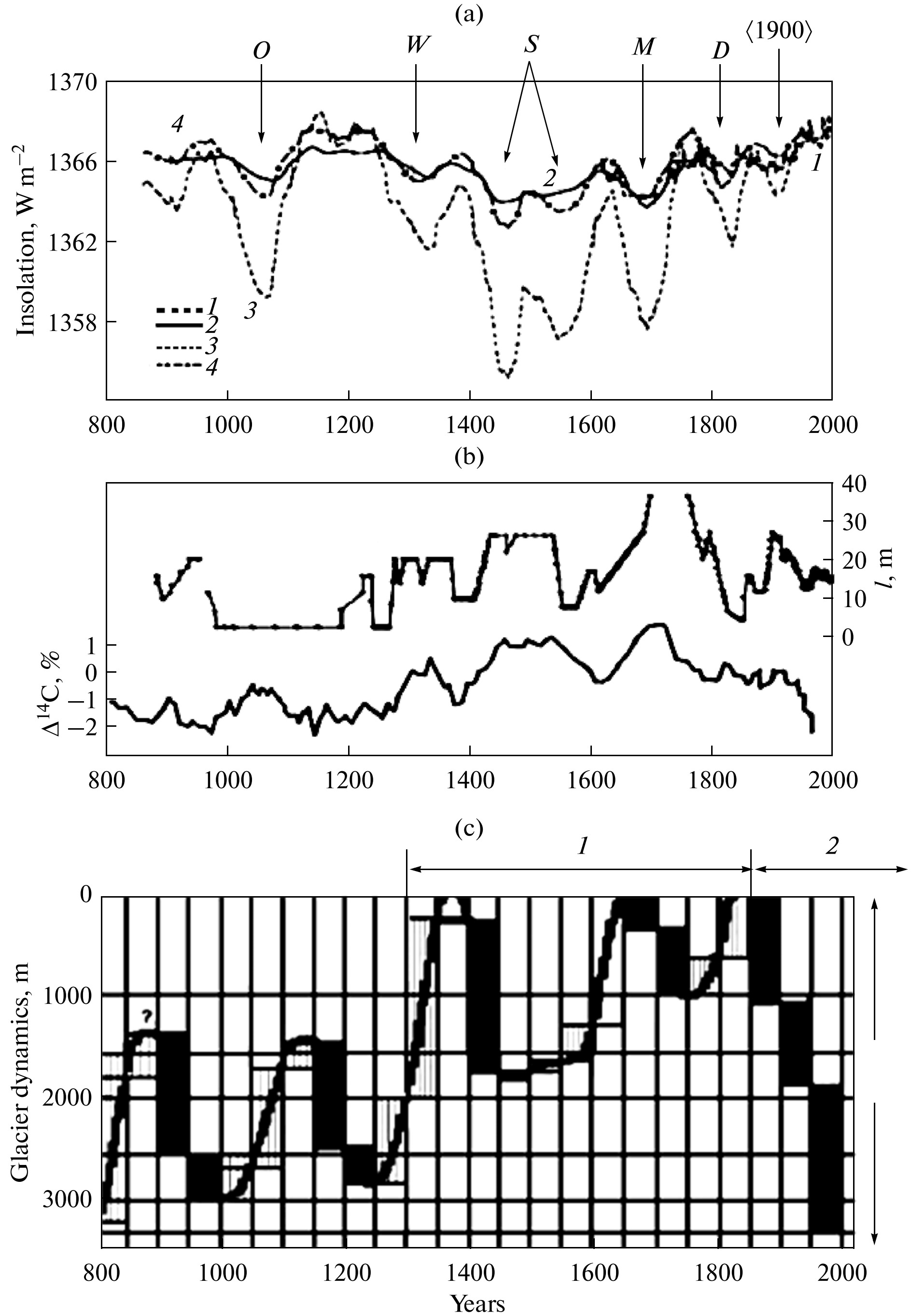

Fig. 5. Comparison of data on the solar and climatic variability for 1200 years. (a) Solar radiation: reconstruction (Lean et al., 1995) from series of data on the sunspot number (*1*), reconstruction (Lean, 2000) from data on the cosmogenic isotope concentration (*2*), reconstruction (Bard et al., 2000) on assumption that the solar radiation during the Maunder Minimum was lower than the present-day value by 0.65 W m^{-2} (*3*), reconstruction (Bard et al., 2000) at −0.25 W m^{-2} for the Maunder Minimum, extremely low SA levels: Oort (O), Wolf (W), Spörer (S), Maunder (M), and ⟨1900⟩. (b) Radiocarbon (Δ^{14}C) level as a reflection of solar variability and fluctuations in the level (Δl) of Lake Naivisha in Africa (Verschuren et al., 2000). (c) Dynamics of the mountain glacier advance and retreat (Holzhauzer et al., 2005); arrows show the glacier advance and retreat. Little Ice Age (~1300–1850) (*1*) and global warming (from ~1950) (*2*) are marked by horizontal lines.

and prolonged intervals with low temperatures and carbon dioxide concentrations.

Stable warm states (interglacial periods) last about 10–12 kyr, and cold (glacial) states are characterized by a rather distinct periodicity of approximately 100 kyr. Spectral analysis of the oxygen-18 or deuterium concentration series of oceanic sediments can be related to a change in the Earth orbital characteristics

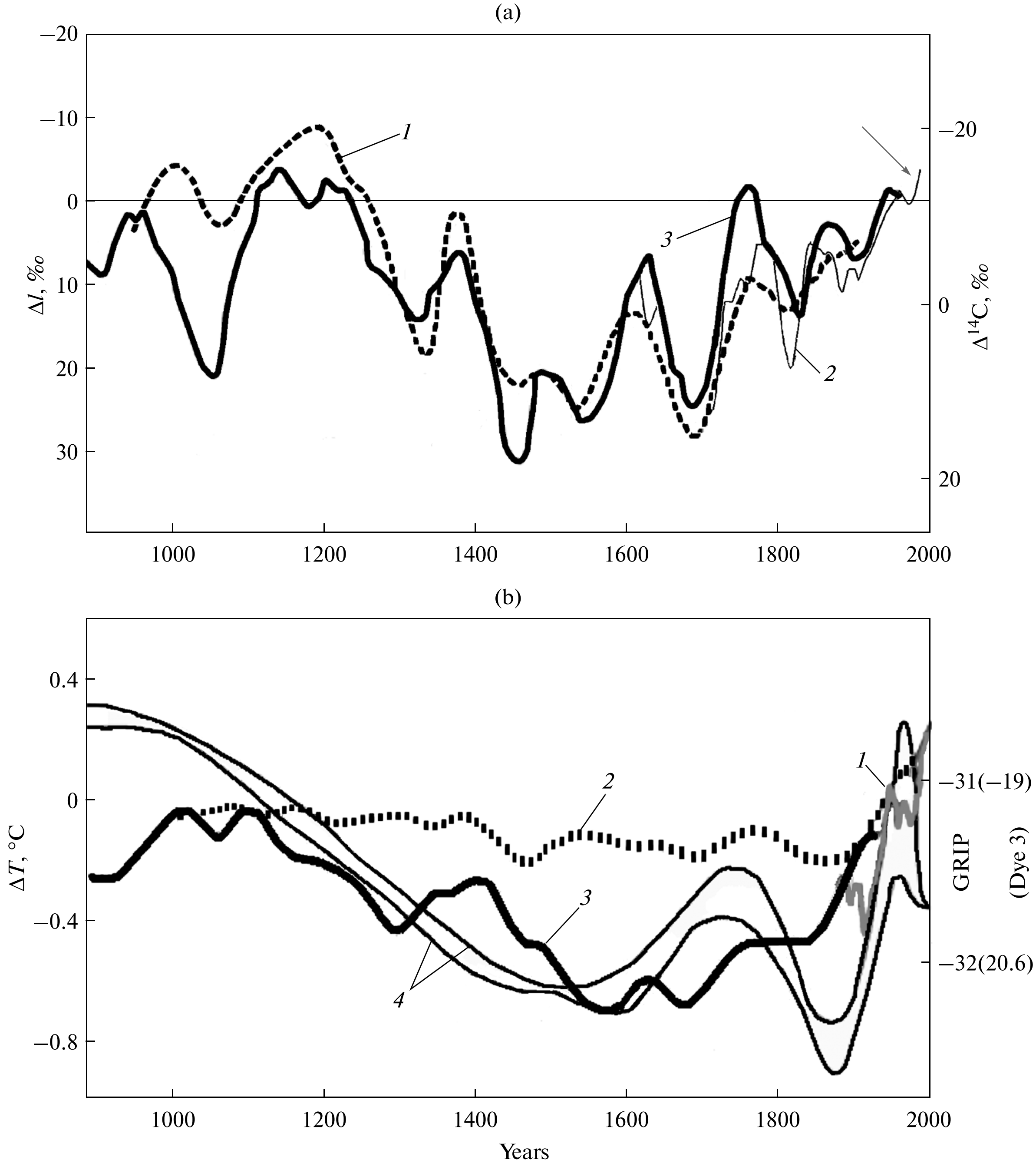

Fig. 6. Comparison of changes in (a) the galactic ray intensity relative to 1965 (ΔI), determined from the variations in the concentrations of ^{14}C in tree rings ($\Delta^{14}C$) (Reimer et al., 2004) (*1*), ^{10}Be in Greenland ice (Usoskin et al., 2002) (*2*), and ^{10}Be in Antarctic ice (Raisbeck et al., 1990) (*3*) (the scales are inverted along vertical) over the past millennium with (b) reconstructed temperatures in the Northern Hemisphere: the smoothed instrumental data series (*1*), the indirect data series (Mann et al., 1999) (*2*), and the series of indirect data (Moberg et al., 2005) (*3*), from the borehole temperature survey in Greenland (Dahl-Jensen et al., 1998).

during its rotation around the Sun. During this period, the temperature and greenhouse content varied in parallel to each other: the amount of carbon dioxide in the atmosphere decreased in cold epochs and, on the contrary, increased during warm periods. The World Ocean level has similar parallel variations in the air temperature and carbon dioxide. Shorter warm interglacial periods, when the ice substantially melted, took place between glacial epochs. We should note that the CO_2 concentration in the past atmosphere started increasing only several hundred years after the warming onset, according to the Antarctic data. From this it

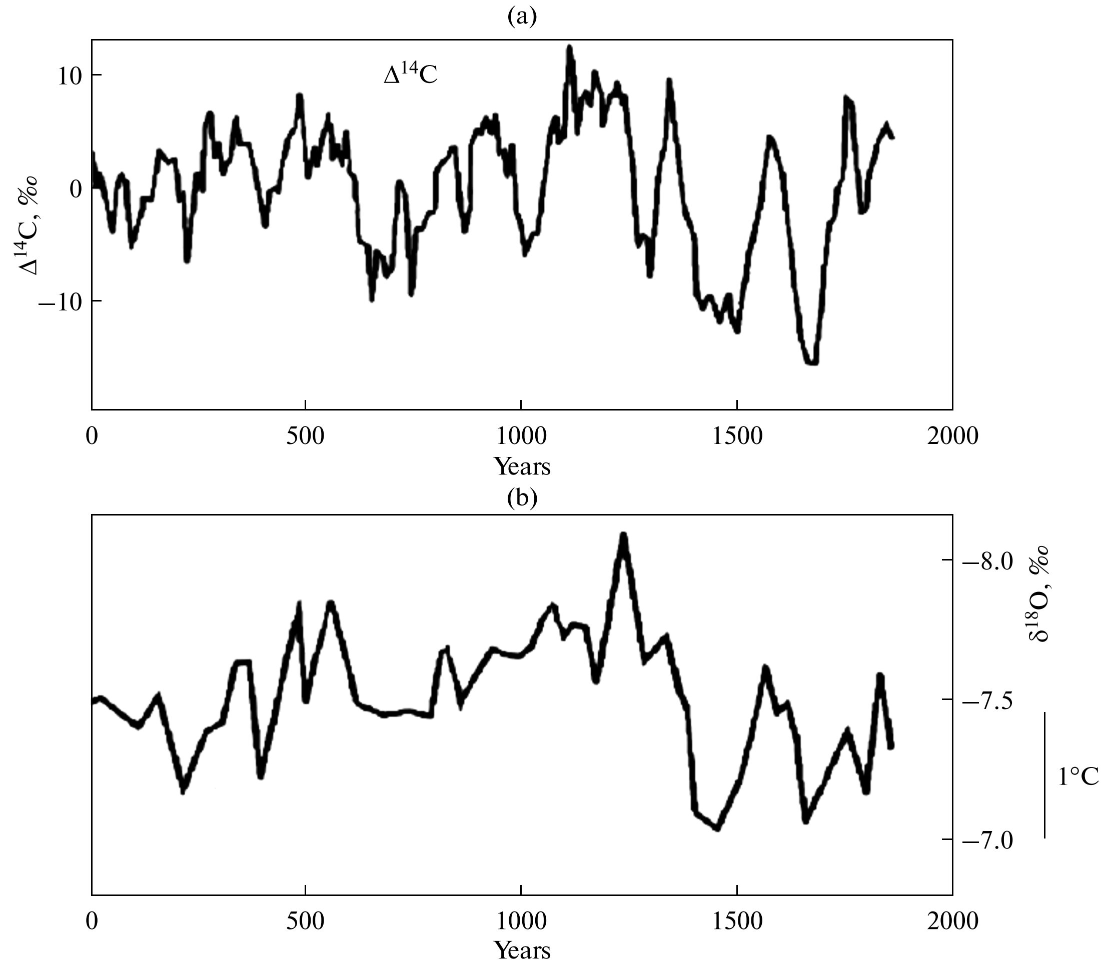

Fig. 7. Comparison of time variations in (a) the galactic cosmic ray intensity ($\Delta^{14}C$) (Stuiver and Quay, 1980; Reimer et al., 2004) (the scales are inverted in vertical) and (b) the reconstructed temperature from Austrian caves (Mangini et al., 2005).

follows that changes in the greenhouse gas concentrations at the glacial cycle critical instants took place after temperature variations rather than before them. Such a situation is the opposite of the situation today, when it is assumed that an increase in the greenhouse concentration in the atmosphere, caused by anthropogenic activity, initiates a global temperature rise.

The latest advance of glaciers in the Northern Hemisphere reached its peak approximately 18–20 ka ago. Approximately 14 ka ago, the temperatures started rising, and the ice sheets in North America and Greenland started melting approximately 8–9 ka ago. Between 7 and 5 ka ago, the climate was comparatively warm and the temperature was higher than the present-day temperature by approximately 1°C. For more than 11 kyr, humanity has lived in the interglacial (Holocene), which should be followed by the next glacial period. It is also important to note that the Holocene climatic optimum level is 1.5°C, as low as the maximal temperature in the previous interglacial (128–116 ka ago), when a pronounced anthropogenic impact was absent on the Earth.

To decrease the uncertainty of short-term climate predictions, it is necessary to consider interglacial periods similar to the present-day period in high-resolution paleoclimatic data. This will allow us to better estimate future climate change. We should note that it is difficult to find a complete analog to the present-day interglacial climate in the available climatic data. Although variations in the solar insolation can be an initial trigger of glacial cycles, other factors that are inherent to the Earth's system could not help affecting the development of glacial periods.

If we select identical variations in the orbital parameters of our planet in order to compare the interglacial periods during the last millennium with one another, only two interglacials that correspond to the periods about 400 and 800 ka ago can be potential analogs for our Holocene and its future history. During these periods, the Earth fell into the periods with a low orbital eccentricity that are similar to the period when the Holocene started.

The reconstructions of the climate and gas content of the atmosphere indicate that the interglacial period

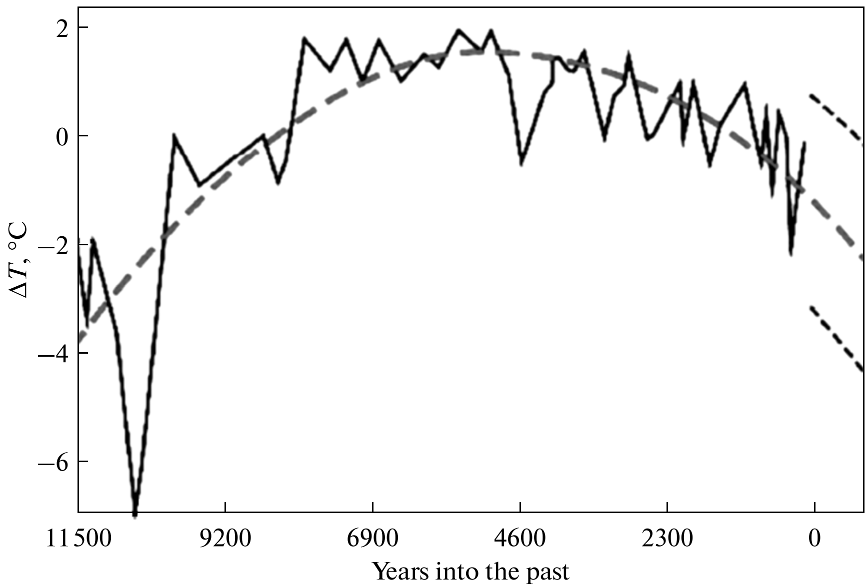

Fig. 8. The tendency toward a change in the average annual temperature on the East European Plain in the Holocene.

that took place near 400 ka ago (the marine isotopic stage, MIS-11) was rather prolonged and lasted about 28 kyr (Tzedakis et al., 2012). The studies indicate that the three interglacials (MIS-5, MIS-7, and MIS-9) before the Holocene (MIS-1) were much warmer, and the present-day global temperature is still lower than the temperature at that time by 1.5–2°C. This means that the temperature variations on the Earth are within natural variations typical of the past millennium, despite the possible anthropogenic impact. Based on the climatic data of Antarctic ice cores, Kotlyakov (2012) analyzed the tendency toward a change in the annual temperature in the current interglacial from the beginning of this period (Fig. 8). The present-day epoch is on the descending segment of the temperature curve, and humanity will live under rather warm conditions, without considering warming caused by anthropogenic greenhouse gas emissions, for a long time, if we consider that the temperature variation scenario for our interglacial period, which started approximately 11.5 ka ago, should follow global temperature variations during MIS-11. However, to what extent we can be sure that the beginning of the next global cooling period will be delayed?

It was shown above that the interglacial that took place 800 ka ago, i.e., MIS-19, may also be an analog of the present-day interglacial period. Although the variations in the Earth orbital parameters for MIS-11 and MIS-19 are similar, the duration of MIS-19 (only about 10 kyr according to the data presented in (Tzedakis et al., 2012) is much shorter than that of MIS-11. Unfortunately, the causes of such differences in the duration between MIS-11 and MIS-19 have not been elucidated. At the same time, researchers mainly emphasize MIS-11 when considering the prospect of further development of the present-day interglacial period.

We should also pay attention to the fact that pronouncedly larger amplitudes of interglacial periods in the 0–430 ka interval than those during the period from 430 to 800 ka ago were registered in the data from Antarctic ice cores for the past 800 kyr. This may be caused by different responses of the climatic system to the external and internal influences during the entire period. If we relate future climate change only to a prolonged period with a low eccentricity and small solar oscillation amplitude, this will most probably result in a rapid termination of the Holocene rather than in an increase in its duration by several dozens of thousand years.

We have several unsolved problems related to astronomical theory and the climate change data obtained from natural archives.

6. CONCLUSIONS

Analysis of temperature reconstructions performed using different methods, including the geothermal method, indicates that the climate change observed for the past two millennia is in good agreement with the change in SA and concentrations of ^{14}C and ^{10}Be cosmogenic radionuclides modulated by time-varying SA.

On the whole, the analysis of the change in the cosmogenic radionuclide level in the Earth archives unambiguously demonstrates that ^{14}C and ^{10}Be can successfully be used to study specific features in the solar variability and cosmic ray intensity on a large timescale. Both ^{14}C and ^{10}Be, which are cosmic ray intensity indicators, undoubtedly make it possible to reconstruct the history of several solar–terrestrial coupling characteristics.

On the global scale, cosmic rays play a key role in many atmospheric processes. They participate in the formation of cloudiness and thunderstorm clouds. The influence of ionization on cloudiness is the most probable effect of galactic cosmic rays.

The pronounced climate change over the last several hundred years puts forward the problem of the possible interaction between the climate and geomagnetic field on timescales from several decades to hundreds of years and more.

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