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The effects of galactic cosmic rays, modulated by solar terrestrial magnetic fields, on the climate

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Abstract. The results of analyzing the paleodata on solar activity variations (variations of cosmogenic ^{14}C and ^{10}Be isotopes in the terrestrial records, such as glaciers, tree rings, sea-floor marine and lacustrine sediments, loess, etc.), the paleomagnetic and archeomagnetic data, as well as the paleoclimatic data, prove that the flows of galactic cosmic rays, modulated by heliomagnetic and geomagnetic fields, affect the climate of the Earth. In this study we analyzed different periods of time, namely, the last millennium, the Holocene epoch (up to 10–12 thousand years ago), and the time interval of 10–50 thousand years ago. Our analysis suggested that the variations of the cosmic ray fluxes seemed to be the most effective factor responsible for long-term climate variations.

1. Introduction

For more than a hundred years many geoscientists discuss the effect of solar activity variations on the Earth's atmosphere and climate changes. This problem became more acute during the last years in connection with the global warming during the last century. The physical causes of this warming are a subject of hot discussions. The popular view that the global warming is caused by purely anthropogenic factors is argued by the growing number of opponents whose arguments suggest the possibility of a high natural climatic change. The natural changing of the climate may be associated both with the outside effect on the climate parameters (for example, with the solar activity (SA) and with the solar radiation), and with some internal processes operating in the atmosphere-ocean-continent (A-O-C) system, and also with the interaction between the outside factors and the internal processes operating in a strictly nonlinear A-O-C system with its own frequencies and noise. The latter may intensify the outside signal several times, this naturally leading to the higher efficiency of the outside factor effects. [*Drijhout at al.,* 1999; *Lawrence and Ruzmaikin,* 1998; *Waple et al.,* 2002; *White et al.,* 1997].

The authors of some papers [*Mann and Jones,* 2003; *Mann et al.,* 2003] state that the global warming in the last century was unprecedented during the last two millennia. This does not agree with the estimates reported by other authors [*Esper et al.,* 2002; *Soon et al.,* 2003; and others]. The authors of the latter publications claim that the climate of the 20th century was not uniquely warm during the last millennium. Although *Soon et al.* [2003] agree that in some local areas the anthropogenic effect on the climate may be quite substantial at the present time. Some authors [*Dergachev and Raspopov,* 2000a, 2000b; *Lockwood et al.,* 1999] emphasize that the global warming of the last century was favored by the long-term growth of the solar activity. As follows from the paper by *Dergachev and Raspopov* [2000b], the whole of the last century was at the ascending wave of the quasi two hundred-year cycle of the solar activity. As follows from *Lockwood and Stamper* [1999], a change in the intensity of the solar activity in the last century might have caused a 52-percent growth of the global temperatures during the time period of 1910 to 1960 and a 31-percent growth of temperature from the end of 1970 to the present time. It should also be noted that about 120–130 thousand years ago, during the interglacial period ("Eemian" period in the

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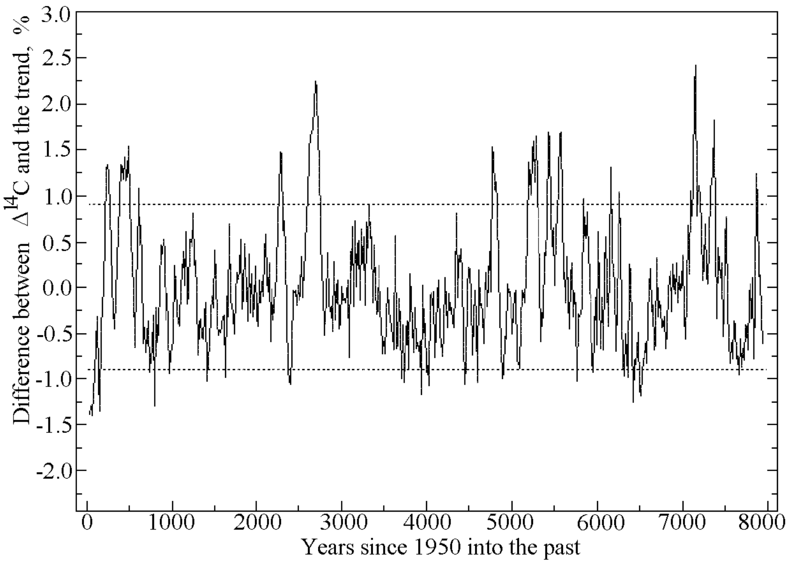

Figure 1. Variations of Δ^{14}C in tree rings [*Stuiver and Becker,* 1993] during the last 8000 years after removing a long-term trend. The error of Δ^{14}C measurements was about $\pm 0.2\%$.

western terminology and "Mikulinean" period in the Russian terminology) the global temperature was almost the same as the modern one, although the anthropogenic effect was obviously absent. Therefore the discussion of the effects of natural factors and, primarily, of the solar activity and the associated variation of the solar radiation and the fluxes of galactic cosmic rays (GCR), as well as of the effect of the geomagnetic dipole variations on the climatic processes, is important for understanding the physical causes of the modern climatic changes. The modern instrumental data available for the solar activity and the instrumental series of temperature data are highly restricted in time. For this reason in our analysis of the association of long-term solar activity variations, GCR intensity, and geomagnetic dipole changes with climatic changes we must rely on the use of paleodata that have preserved in the Earth's "archives" (glaciers, tree growth rings, bottom marine and lacustrine sediments, loess, and the like). The aim of this study was to estimate the contribution of the natural factors associated with the solar and geomagnetic variability and with the galactic cosmic ray flux to the global climatic changes. This analysis was made for different time intervals, such as, the last millennium, the Holocene epoch (up to 10–12 thousand years ago) and the time interval of 10–50 thousand years ago.

2. Paleodata for Variations in the Solar and Galactic Activity and for Changes in the Geomagnetic Field and Climate, Used in This Study

Regrettably, no direct and reliable data for the solar activity are available for the period earlier than the 17th century. However, one of the manifestations of the solar activity is the modulation of galactic cosmic ray (GCR) fluxes. The GCR fluxes, in their turn, produce radioactive isotopes ^{14}C and ^{10}Be, as they interact with the constituents of the Earth atmosphere, the concentrations of which are modulated by the solar activity [*Bard et al.,* 1997; *Damon and Jiricowic,* 1992; to name but a few]. These cosmogenic isotopes participate in various exchange processes that operate in the environment before they get into the dated terrestrial archives (records): ^{14}C is recorded in tree rings and deep-sea sediments and ^{10}Be, in glaciers, bottom sediments, and loess. With the increase of solar activity the magnetic fields of the solar wind scatter highly and deviate the fluxes of galactic cosmic rays that flow into the Earth atmosphere, which decreases the production rate of ^{14}C and ^{10}Be. It appeared that the ^{14}C production rate during the epoch of the Maunder minimum of the solar activity (1645–1715 year interval) was 20–30% higher than during the time that followed. Moreover, the other epochs of raised ^{14}C concentrations (Δ^{14}C) were found during the last millennium. The comparison of the data obtained with some fragmentary data for the solar variability allowed us not only to trace their connection, but also to outline the epochs of high and low solar activity in the more distant past. We identified the Spörer (1470–1550), Wolf (1280–1350), and Oort (in the vicinity of 1060) minima, the nature of which, associated with the solar activity variations, was confirmed by the results of measuring ^{10}Be isotope in the ice of the polar ice caps [*Bard et al.,* 1997]. It was thus proved that the variations of cosmogenic ^{14}C and ^{10}Be isotopes provide direct information about the long-term solar variability [*Dergachev,* 1996]. The ^{14}C radiocarbon half-life is 5730 years. Therefore the information obtained on the basis of analyzing the ^{14}C concentration may be considered of as a reliable one in the time scale of 10 and more thousand years. ^{10}Be has a half-life period of about 1.5 million years and, consequently, the time scale based on the ^{10}Be data is significantly larger than that for ^{14}C. At the present time

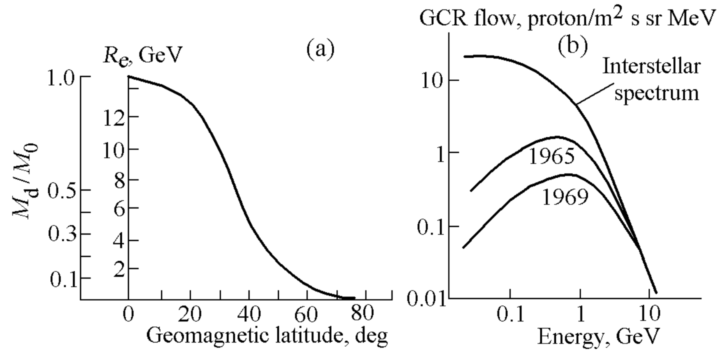

Figure 2. (a) Relationship between the cut-off rigidity of cosmic rays and the geomagnetic latitude and a change in the dipole moment (M_d/M_0); (b) GCR energy spectra in the Earth vicinity during the minimum (1965) and maximum (1969) of solar activity and the interstellar spectrum.

there are data on the Δ^{14}C variations in tree ring growth for the last 600 years with annual resolution [*Stuiver and Braziunas,* 1993]. Data on the ^{14}C concentration with resolutions of the orders of 10 and 20 years were obtained [*Stuiver et al.,* 1998]. In our study we used these data series as information of solar activity variations and of the intensity of cosmic rays in association with climate changes using a time scale of up to 1000 years and Holocene time. In this analysis we used the time scale of 10 to 50 thousand years and the data available for ^{10}Be concentration variations in the Greenland ice [*Grootes and Stuiver,* 1997]. The time resolution of these data is as high as decades of years. As an example, Figure 1 shows Δ^{14}C variations for the last 8000 years, obtained from tree-ring chronology [*Stuiver and Becker,* 1993].

The fluxes of galactic cosmic rays (GCR) are modulated and scattered not only by geomagnetic fields. It is well known that the geomagnetic field shields the Earth from cosmic rays. The cutoff rigidity R_e for the vertical cosmic ray flux in a dipole magnetic field can be expressed as

$$R_e = M_d \cos 4\alpha / 4r_0 \ ,$$

where M_d is a dipole magnetic moment, r_0 is the radius of the Earth, and α is geomagnetic latitude. The curve plotted in Figure 2a shows variations in the cutoff rigidity as a function of the latitude for the modern geomagnetic dipole moment M_0. The abscissa of this plot also shows a scale which allows one to make allowance for the effect of the changing dipole moment (M_d/M_0). Note that the screening of cosmic rays by the geomagnetic field is the highest in the equator region. Figure 2b shows variations in the energy spectrum of GCR proton flux at the maximum and the minimum of the 11-year solar activity cycle in comparison with an interstellar spectrum [*Weber and Lockwood,* 1998]. The analysis of the data plotted in Figure 2a suggests that where the dipole moment reduces to the value of 0.2 M_0, the rigidity R_e in the equatorial region must decline from 15 to 3 GeV (Figure 2a), as a result of which the amount of galactic cosmic rays reaching the Earth atmosphere must grow several times larger (Figure 2b). Therefore, variations in the concentrations of cosmogenic isotopes provide information of changes in the geomagnetic dipole for the last 12000 years [*Teanby and Gubbins,* 2000], obtained by way of generalizing the archeo- and paleomagnetic data. When we examined the time interval of 10–50 thousand years, we used the data reported by *Lehman et al.* [1996] for changes in the geomagnetic moment.

The common practice is to use the concentrations of stable oxygen isotope ^{18}O (δ^{18}O) in the cores of ice and marine deposits. The concentration of this isotope is essentially a parameter that provides information for the temperature of the environment where the precipitation was formed (clouds, surface water layers, etc.). In this study we used the data available for δ^{18}O variations in the cores of the Greenland ice from the GISP-2 Hole [*Grootes and Stuiver,* 1997].

When discussing the paleodata for the solar activity, it need be kept in mind that the Sun is the main source of energy that arrives at the Earth. However, solar activity may control climate changes in two ways. On the one hand, associated with the solar activity are changes in the solar radiation, including the ultraviolet rays, whose variations may be as high as 10% during the eleven-year cycle of the solar activity. However, no experimental data have been obtained to prove any long-term (more than decades of years) solar radiation variability. On the other hand, the fluxes of galactic cosmic rays, modulated by the solar activity, can affect some atmospheric processes, including the state of the cloud cover, and, hence, may control the climatic processes. For this reason, when we use the paleodata for long-term variations in the solar activity, we actually discuss the effects of variations in the galactic cosmic ray fluxes on the climate.

3. Correlation Analysis of the Data Available for Changes in the Solar Activity (Intensity of Galactic Cosmic Rays) and in the Climate During the Last Millennium

The cosmogenic ^{14}C and ^{10}Be isotopes are significant not only as the important indicators of the solar activity and galactic cosmic ray fluxes and establishing a correlation between the data available for the evidence of the natural

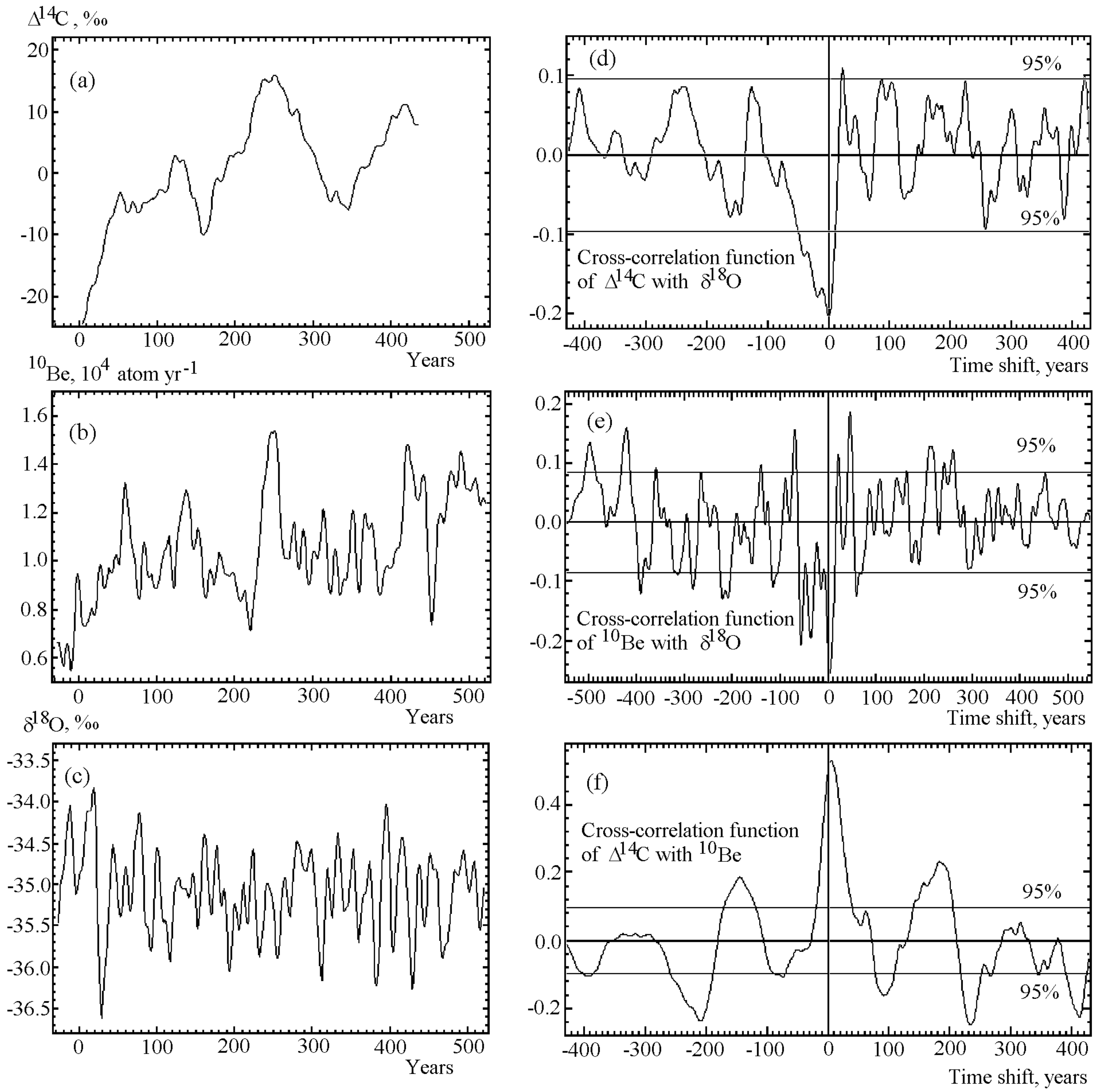

Figure 3. Changes in the concentrations of: (a) ^{14}C [*Stuiver et al.,* 1998], (b) ^{10}Be [*Beer et al,* 1994], and (c) ^{18}O [*Grootes and Stuiver,* 1997] during the last 500 years and the calculated cross-correlation functions of their pairs: ^{14}C and ^{18}O (d), ^{10}Be and ^{18}O (e), and ^{14}C and ^{10}Be (f).

processes obtained from oceanic and terrestrial records or from ice cores, but also provide critically important data for precipitation rates and the dynamics of the climatic system. Note, that in contrast to ^{14}C found in tree rings (the ^{14}C, after oxidation to $^{14}CO_2$ gas mixes between the atmosphere and ocean in the complex exchange of the carbon reservoirs), ^{10}Be has a simpler exchange reservoir system in ice layers (after its formation ^{10}Be grows attached to aerosol and settles in the ice layers or in the oceanic sediments). In turn, the comparison of the behaviors of these two radioisotopes in their exchange reservoirs provides data on the changes that take place in the characteristics of the carbon exchange system. As a result of the damping effect of the carbon exchange system, the cycle amplitudes in the ^{14}C concentration, lasting hundreds of years, are suppressed 10–20 times, with the phase shift being several tens of years, whereas the amplitudes of the ten-year cycles are suppressed 50–100 times with a phase shift of a few years [*Dergachev and Stupneva,* 1975].

Let us consider the effect of galactic cosmic rays on the climate for the period of time covering the last millennium and characterized by the availability of data with a high degree of accuracy and resolution. Using the annual measurements of $\Delta^{14}C$ in tree rings [Stuiver et al., 1998], the ^{10}Be

content in the Dye-3 Greenland ice core [*Beer et al.,* 1994], and the ^{18}O concentration (δ^{18}O) available for the GISP-2 Greenland ice core [*Grootes and Stuiver,* 1997], we carried out a cross-correlation analysis of these data (Figure 3) to prove the effect of galactic cosmic rays on the climate. As mentioned above, the stable isotopes found in the cores of ice and marine sediments can be used as thermometers and reflect abrupt climatic events. In particular, the ratios of stable δ^{18}O isotopes in the ice cores from Greenland and Antarctica provide information on the temperature of the cloud from which the snow had fallen.

In order to exclude the meteorologic effects that may be present in the annual data, the above-mentioned data series were smoothed with the help of a linear filter [*Alavi and Jenkins,* 1965] with the gradual growth of its smoothing parameter: $T_{\text{cut-off}}$ = 3, 5, 10, and 20 years, which corresponds to the filter cut-off point at the signal half-power. The next step was to plot some selected estimates of the cross-correlation function for each pair of the initial series of data and their smoothed components [*Jenkins and Watts,* 1972]. The resulting values were used to estimate the data reliability (see Table 1) at the significance level of 95%, which proved that the respective pairs of the initial data and their smoothed components were not "white" noise or, to be more exact, not correlated sequences of purely random numbers. Table 1 demonstrates that in the case of the concentration of the ^{14}C and ^{18}O isotopes the significant correlation exists only for the smoothed components, beginning with the smoothing parameter of 10 and more years, whereas in the case of the ^{10}Be and ^{18}O isotope pair concentration it exists both for the initial series themselves and for their smoothed components. Moreover, this correlation intensifies with the growing value of the linear filter smoothing parameter. Consequently, since the concentration of the ^{18}O is the indicator of the atmosphere temperature, the meteorologic effect masking the relationships between the data series concerned can be smoothed using a linear filter with the optimal value of the smoothing parameter equal to 10 years.

Figure 3 shows the smoothed components of the initial data with the optimal smoothing parameter value of 10 years (a, b, and c) and some selected estimates of their cross-correlation values (d, e, and f), which showed the 95-percent significance of the potential existence of a correlation relationship between the concentration of the isotopes of the respective pairs. It follows from Figures 3d and 3e that the changes in the ^{14}C and ^{18}O concentrations, as well as in the ^{10}Be and ^{18}O concentrations, are in opposite phases, that is, the maximum concentrations of the former isotope correspond to the minimum concentrations of the latter, which is clearly shown in Figures 3a, 3b, and 3c. These figures also show the shifts between the compared pairs of the data (for instance, a 3- or a 4-year shift for ^{14}C and ^{10}Be, with the latter being ahead of the former), this being associated with the formation conditions of the respective isotopes and with their respective reservoirs. The high correlation between the ^{14}C and ^{10}Be series (45% compared to the threshold value of 5%, see the table) suggests the common modulation mechanism for the formation rate of these isotopes.

The analysis of the data presented in the tables and of the correlated functions of the investigated data pairs presented in Figure 3 suggests the conclusion of a close relationship between the changes in the intensity of galactic cosmic rays and in the climate during a time period of hundreds of years and allows one to trace some common regularities in their variation, namely, the increase of the galactic cosmic ray intensity correlated with the temperature decline.

Table 1. Reliability values at the significance level of 95% for the initial data sequences and their smoothed components denoting that the pairs concerned are not uncorrelated sequences of purely random numbers

Pairs of series	Percent significance values				
	Initial data	Smoothed $T_{\text{cut-off}}$ components in years			
		3 years	5 years	10 years	20 years
Δ^{14}C and δ^{18}O	0%	4%	5%	7%	18%
^{10}Be and δ^{18}O	1%	5%	12%	21%	35%
Δ^{14}C and ^{10}Be	25%	33%	40%	45%	46%

4. Spectral and Correlation Analysis of the Data for Changes in the Cosmic Ray Intensity, Geomagnetic Field, and Climate During the Holocene

The climate during the last 10 thousand years was more stable and warm compared with the previous period prior to and after the retreat of the last glaciation, which began approximately 21 thousand years ago. It should also be noted that the magnetic dipole moment of the Earth was the highest during the last 10 thousand years, compared to the previous period, which might have resulted in the much lower level of the galactic cosmic rays arriving to the Earth atmosphere during this long period of time.

The parameter that has been measured most thoroughly and continuously is the cosmogenic ^{14}C concentration throughout the time interval of the last more than 10 thousand years (Figure 4). The most notable component in the long series of Δ^{14}C measurements with a magnitude of up to 10% is a long-term trend which seems to have been caused by a change in the Earth's dipole moment [*Dergachev,* 1974] which has been confirmed qualitatively, and also quantitatively, for some periods of time by archeomagnetic and paleomagnetic data. This can also be proved by the data presented in Figure 4 for the comparison of changes in the dipole moment using the data available for the thermal magnetization of samples from America, Asia, and Europe [*Teanby and Gubbins,* 2000]. The arrows in the figure mark the peaks of the intrusion of galactic cosmic rays into the Earth's atmosphere. These peaks coincide with the coldest conditions during the last >10 thousand years [*Dergachev and Chistyakov,* 1995]. Of particular interest are the two peaks marking the changes in the Earth dipole moment

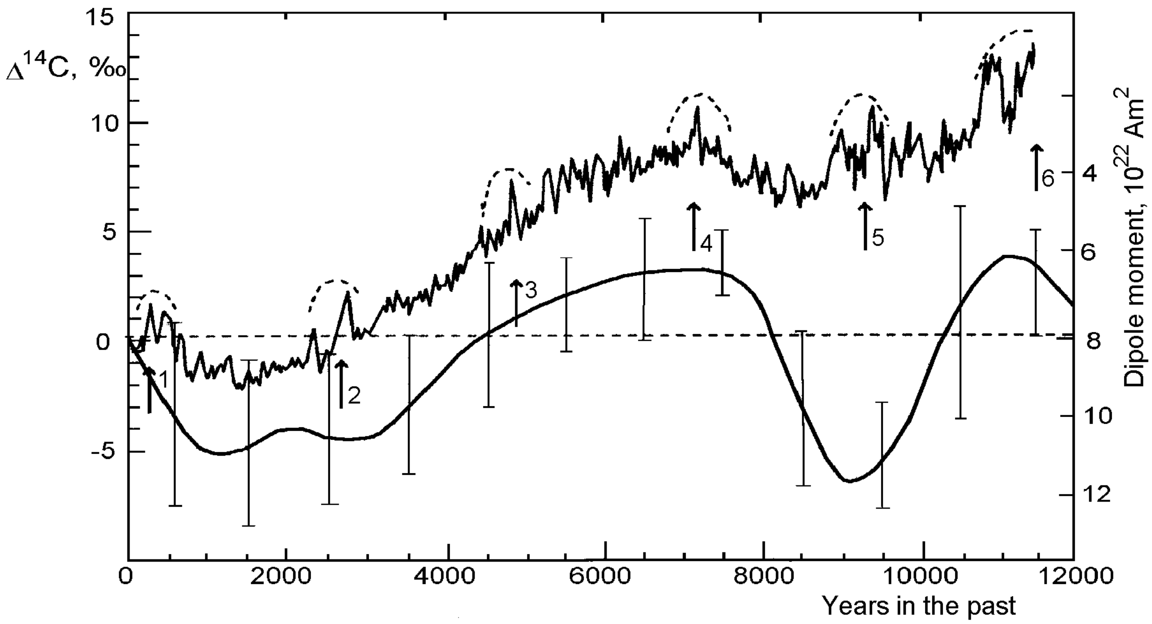

Figure 4. Variation of ^{14}C concentration in time (upper curve) [*Stuiver et al.,* 1998] and of the dipole moment of the Earth after smoothing (lower curve) [*Teanby and Gubbins,* 2000]. The scale of the magnetic field is inverted. The modern value of the dipole moment is 8×10^{22} Am^2.

that took place about 2 and 9 thousand years ago (the last peak was not found in the previous archeomagnetic data series). It is remarkable that the new archeomagnetic data explained the low ^{14}C level in the time interval of 7 to 11 thousand years ago by a change in the dipole moment. These data proved that changes in the geomagnetic dipole modulated the ^{14}C level and, hence, the intensity of galactic cosmic rays.

Apart from this long-term trend, the entire measurement interval showed Δ^{14}C fluctuations with magnitudes varying from fractions of percent to about 1.5%. After removing the long-term trend, the Δ^{14}C time series was investigated in the time interval of the last 8000 years (Figure 1) [*Vasiliev and Dergachev,* 2002; *Vasiliev et al.,* 1999]. It was found that the abnormally high Δ^{14}C values had repeated, after a break of 2300–2400 years, in the vicinities of roughly 500, 2700, 5400, and 7200 years ago. The power spectrum of this series (Figure 5) includes the most intensive line indicating the ~2400-year period. This spectrum can be used as a source of information about the factors that had caused changes in the natural processes under study. The long-term cyclicity was proved using regional climatic data, namely, the spectra of changes in the width of the annual rings of long-lived trees and in the Δ^{14}C values measured in them [*Sonett and Suess,* 1984]. Moreover, a statistically significant correlation was found between the 2400-year cycle and the annual ring widths of the trees growing at high altitudes in the White Mountains of California. Under these conditions temperature can be the most important limiting factor of the radial growth of annual tree rings. The 2400-year period was traced in the dendrochronological data for European oak [*Schmidt and Gruhle,* 1988]. *Damon and Sonett* [1992] traced three cold periods separated by a roughly 2400-year period using dendroclimatic data. *Dergachev and Chistyakov* [1995] analyzed numerous data containing information of the long-term variations in the climatic characteristics and found that during a 2400-year variation cycle the colder climate had been associated with high Δ^{14}C amplitudes and the warm climate, with the lower ones.

The levels of galactic cosmic rays (GCR) in the Earth's atmosphere are inversely related to the intensities of helio and geomagnetic fields. The calculations reported by *Dergachev* [1978] and *Castagnoli and Lal* [1980] show that the ^{14}C production rate becomes more sensitive to changes in the solar modulation during the minimum values of the dipole moment. At higher latitudes, where the values of the dipole moment of the Earth are 10–20% of the modern field value, the GCR flux may be more than twice higher than the modern GCR flux, whereas with the doubled value of the dipole moment the GCR flux is not higher than the 50-percent value of the modern flux. It is important to emphasize that in the case of very low values of the dipole moment, differences in the GCR levels between the maxima and minima, associated with the 210-year solar cycle, grow at least by an order of magnitude. Consequently, both of these factors affect, to a higher or lesser degree, ionization in the atmosphere and, hence, produce climatic changes.

In order to analyze a relationship between the geomagnetic field variations and the concentrations of cosmogenic isotopes and stable oxygen using a 10,000-year scale, we carried out a cross-correlation analysis of the long-term trend of radiocarbon data and of the smoothed curve of the Earth dipole moment variation. The smoothing scale was taken to be ~1000 years in order to exclude the contribution of

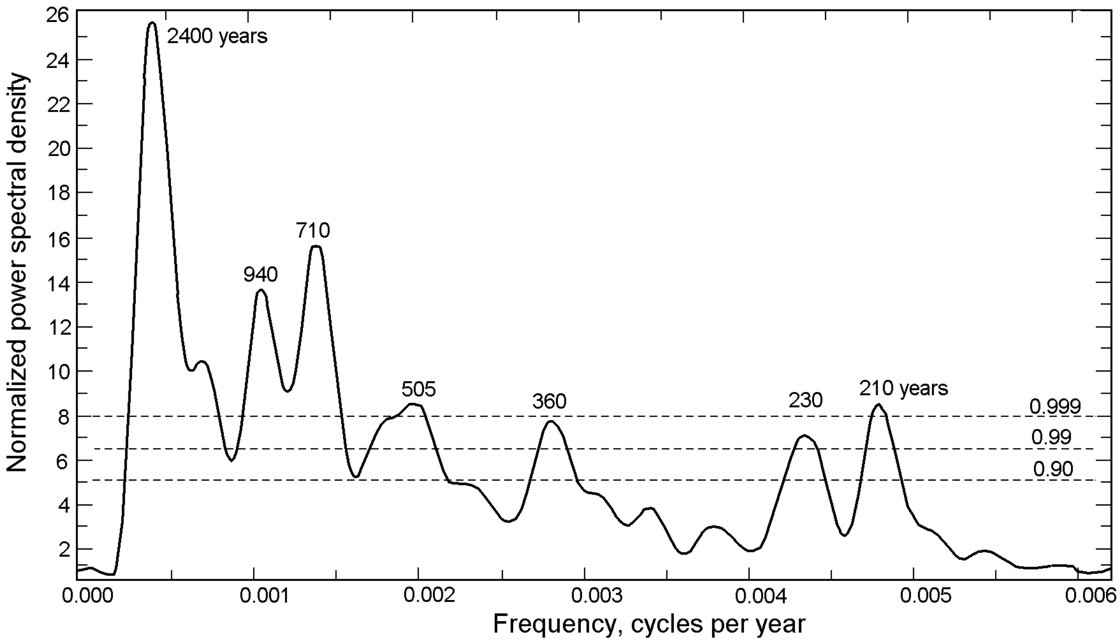

Figure 5. The normalized spectral power of changes in the ^{14}C concentration over 8000 years after the removal of the long-term trend [*Vasiliev and Dergachev,* 2002]. The dotted lines denote the confidence levels.

the nondipole variations of the field. As long as this pair of data series is concerned, 75% of the cross correlation values exceeded the 95-percent level of significance, which proves the high correlation between these data, the correlation coefficient between these data series being −0.6. The high-frequency portion of the radiocarbon data series, after the long-term trend had been subtracted, did not show any significant possibility for the existence of correlation with the smoothed curve of the Earth dipole moment variation. An approximately similar pattern was observed for the cross-correlation analysis of the long-term trend of the radiocarbon series and the smoothed $\delta^{18}O$ series: 82% of the values of the cross-correlation function exceeded the 95% level of significance with the correlation coefficient being 0.6. Similarly not high was the significance of the potential correlation for the high-frequency data. At the same time the cross correlation analysis of the radiocarbon data series, from which the trend corresponding to the curve of the Earth's dipole moment variation was extracted, the high-frequency component of the radiocarbon series and of the smoothed series of $\delta^{18}O$ variations showed the significant possibility for the existence of correlation (69% of the correlation function values exceeded the 95-percent level of significance), the correlation coefficient being equal to 0.6. Hence, these data prove that $\delta^{18}O$ variations reflect the main features of the cosmic ray effect.

The results of the spectral analysis of the high-frequency measurements of the ^{14}C (without the removal of the long-term trend), ^{10}Be, and ^{18}O concentrations over the time interval of 3300 to 15600 years ago are presented in Figure 6. Note that the rate of ^{10}Be formation at high latitudes is less sensitive to the magnetic field. All of the spectrograms discussed showed the same characteristic harmonics: ~3200, ~2500, and ~1500 years, yet with different intensity ratios among them for each particular spectrum, that is, with different contributions to the total signal energy, the amplitude of the ~2500-year harmonic being higher than that of the ~1500 year one. Note that after the removal of the trend the time interval of the last 8000 years clearly shows a fundamental line at the frequency corresponding to 2400 years (Figure 5). It should be mentioned that the spectral analysis of the $\delta^{18}O$ data series shows a stable spectral power at the frequencies close to or identical with the frequencies observed in the ^{14}C and ^{10}Be concentrations, that is, in galactic cosmic rays. Since the initial data series include a high trend, the confidence of the harmonics detected using a criterion of random data sequences is not high: at the level of 2σ for the large periods of 2000 to 4000 years, and at the level of σ for the periods of 1400 to 2000 years, and at still lower levels for smaller periods of time. However, the accuracy of spectrogram resolution (20 years) and the stable positions of peaks at the same experimental periods with the reliability of their detection exceeding 3σ or 4σ, depending on the parameters of the high-frequency filtering of the initial data [*Dergachev and Dmitriev,* 1998] prove the real existence of the detected periodicities.

To sum up, the cyclic changes of climate in the time scale of tens of years to millennia show that the fairly stable climate during the last 10 thousand years experienced the effect of galactic cosmic rays (GCR), modulated by the solar ac-

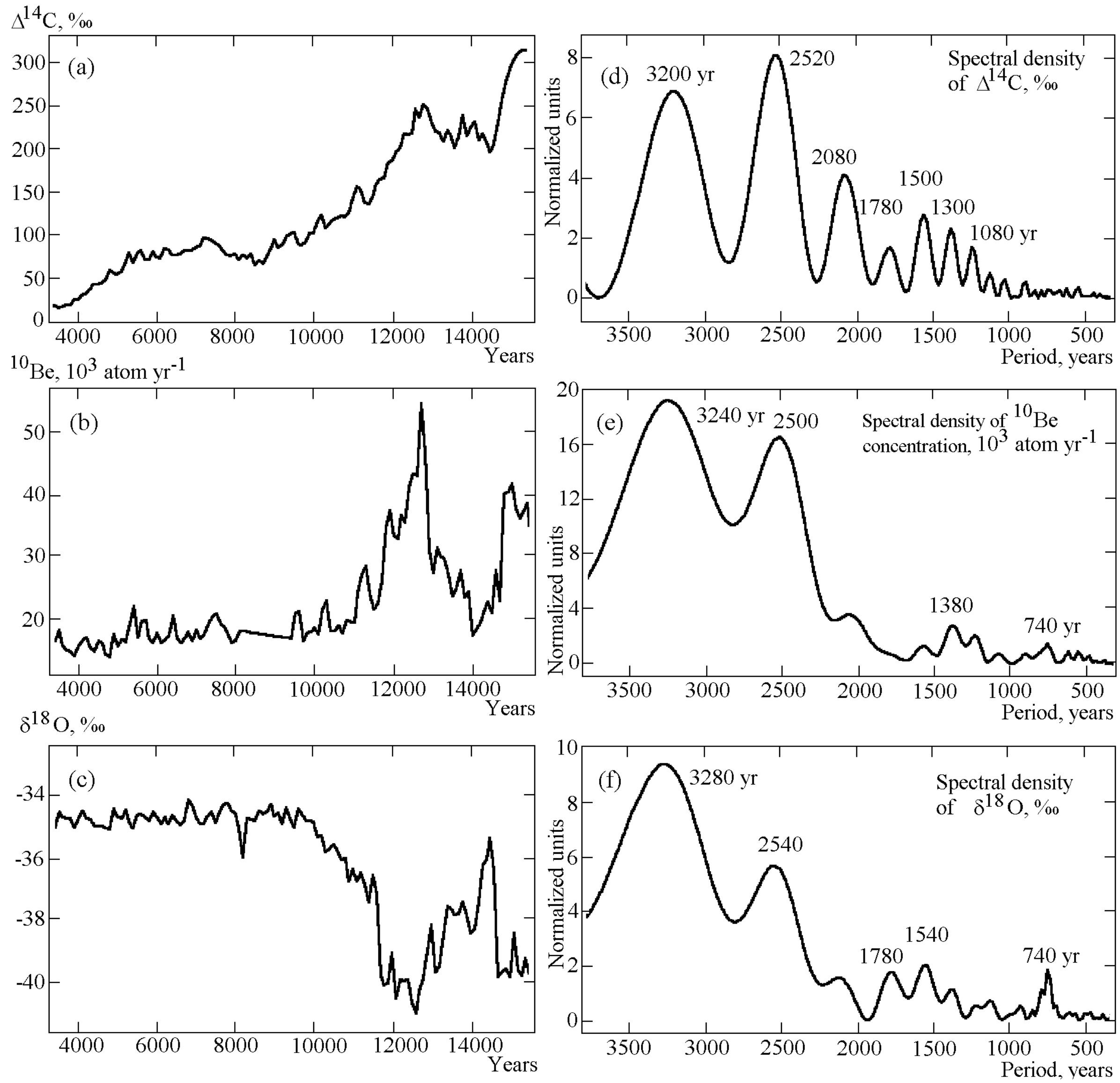

Figure 6. Concentration variations of (a) ^{14}C [*Stuiver et al.,* 1998], (b) ^{10}Be [*Finkel and Nishiizumi,* 1997] and (c) ^{18}O [*Grootes and Stuiver,* 1997] over the time interval of 3300 to 15600 years ago and the selective estimates of the normalized spectral density of the ^{14}C (d), ^{10}Be (e), and ^{18}O (f) concentrations. The numbers denote the time periods used.

tivity the effect of which is reduced significantly by the high magnetic field of the Earth. The period of $\sim$2500 years expressed in the $\Delta^{14}C$ and ^{10}Be data seems to be of the solar origin. A 2400-year periodicity has been established in the Sun motion around the center of the solar system masses [*Charvátová,* 2000]. Periodicities and variations in the maxima and minima magnitudes often show 1400 to 1600-year cycles in the paleoclimatic data. Historic observations show good correlation between the climate at the time scales of approximately this length and the observed solar phenomena, such as the number of sunspots, as well as auroras.

It should also be noted that during the time interval discussed the modulating effect of the geomagnetic field controlled the lower GCR effect on the Earth's atmosphere, this obviously controlling the warmer climate of the Holocene. The high geomagnetic field also lowered the efficiency of the modulating effect of the solar fields on GCR, as a result of which only the long-term cycles can be traced in the concentrations of cosmogenic isotopes, in particular, the $\sim$2500-year cycle which is followed by the $\sim$2500-year quasiperiodic cooling. On the whole, our analysis suggests that cosmic rays prove their association with a climatic change during the Holocene, when the dipole moment of the Earth remained to be sufficiently high.

5. Analysis of the Data Available for Changes in the Solar Activity, Geomagnetic Field, Cosmic Rays, and Climate During the Interglacial Epoch (∼10–50 Thousand Years Ago)

A distinctive feature of the time interval of 50 to 10 thousand years ago was a high climate variability. About 20 000 years ago the last glaciation period experienced its maximum. Moreover, characteristic of this period were ±3°–5°C quasiperiodic variations in the global temperature (during a few decades of years). This time period experienced three geomagnetic digressions: Gotenburg, Mono, and Lashamp [*Petrova et al.,* 1992], during which the northern geomagnetic pole moved into the Southern Hemisphere and back. It is known that geomagnetic excursions usually take place during the low values of the geomagnetic dipole [*Cox,* 1969]. Therefore the chosen time interval is favorable for analyzing cosmic ray variations (^{10}Be concentration variations in the Earth records), caused by the solar activity and geomagnetic dipole variations, and climatic changes.

The climatic events of the period concerned can be estimated quantitatively and dated exactly, this removing the problem of interpreting these data which are associated with the uncertainty of the age variation with depth. All climate indications derived from the data of ice cores and marine and continental deposits point to the rapid high-amplitude mode variations between the wholly glacial and relatively mild interglacial conditions. These rapid events can be grouped into characteristic cycles of various durations, such as the Bond cycles (10–15 thousand years), Heinrich cold events (about 6–7 thousand years), and warm cyclic events (∼2500 years), known as the Dansgaard-Oeschger events [*Bradley,* 1999]. Without discussing these cycles, it should be noted that the ∼2500-year cycle (or the 1400–1600-year cycles) all began with the abrupt 5°C warming for a few decades or a shorter period of time and were modulated during the whole of this time period [*Bradley,* 1999].

In order to trace the effect of cosmic ray intensity variations on the climate during its unstable epoch, we can compare the ^{10}Be and ^{18}O concentration changes in the GISP-2 ice core (Greenland) and the Earth dipole moment variation during the last 38 thousand years after calibrating the volcanic data [*Lehman et al.,* 1996]. The data available for the Earth's dipole moment, ^{10}Be, and δ^{18}O were averaged over 200 years. (Figures 7a, b, and c) and brought to accord with the same period of time lasting from 3400 to 39900 years ago. The pairs of these data series were subject to a mutual correlation analysis (Figures 7d, e, and f). Figures 8d and e, show that the change in the Earth's magnetic field coincides with a change in the δ^{18}O concentration (Figure 7d) and is out of phase with the ^{10}Be concentration change (Figure 7d), the temporal changes of the magnetic field anticipating, in both cases, the respective changes in both isotope concentrations by the same time interval of 3200 years. Moreover, both curves show two extremums for the zero and 3200-year values of the shift scale. Consequently, the 3200-year period of time which had been identified from the spectral densities of these isotopes and from the ^{14}C concentration (Figure 6) must have been caused by the effect of the geomagnetic field.

Worthy of noting are the correlation coefficient values and the high degree of certainty of the potential existence of the mutual relationships for the respective pairs of the data: −0.65 (70%) for the Earth's magnetic moment and the ^{10}Be concentration, +0.71 (72%) for the magnetic moment of the Earth and the ^{18}O concentration, and −0.89 (53%) for the ^{10}Be and ^{18}O concentrations. The remarkably coincident variations of these data suggest the effect of galactic cosmic rays on the ^{18}O concentration. The pattern of the significant cyclic millennial-year variation of both cosmogenic isotopes and δ^{18}O depicts first of all the effect of solar modulation on the galactic cosmic rays, because the dipole moment of the Earth is very low in this time interval. In the case of the unstable climate it becomes colder under the conditions of the low magnetic field and high GCR activity.

The most detailed data for obvious and high climatic oscillations are available for the last glacial-interglacial transition period (15000–11500 years ago). Let us see the pattern of climate and GCR variations in this time interval. Figure 8 shows temperature variations (δ^{18}O) in the Greenland region and GCR variations (^{14}C and ^{10}Be) over the time interval of the glacial to interglacial transition. The changes in the ^{14}C and ^{10}Be concentrations demonstrate clearly the long-term changes that lasted thousands of years with the thousand-year changes overlapping them. Therefore, the presence of similar frequencies in the spectra of the data discussed and, moreover, the similarity of the details prove their interconnection. The data presented in the last two figures show that the δ^{18}O concentrations are coherent with both the ^{10}Be concentrations and also with the Δ^{14}C data. It is remarkable that these data series are coherent not only in the phase but also in the amplitude, this providing a reliable proof for a definite relationship in the cosmic rays-Sun-climate chain.

Note that the reconstructed pattern of climatic changes and cosmic ray intensity in the southern hemisphere prove the synchronous behavior of these natural processes in both hemispheres. The high-resolution paleomagnetic data obtained at the continental margin of the Antarctic Peninsula (68°S, 78°W) for the last more than 100 thousand years [*Sagnotti et al.,* 2001], the cosmic ray intensity (^{10}Be concentration), and the temperature (δ^{18}O concentration) in the Antarctic ice cores are presented in Figure 9. The similitude of the curves proves the obvious relationship between the temperature variations and variations in the intensity of the galactic cosmic rays modulated by the magnetic field of the Earth.

6. Discussion of the Results

The analysis of a relationship between the climatic changes and the variations of galactic cosmic rays, modulated by the solar activity and by changes in the geomagnetic field, carried out in this study for three intervals of time (the last millennium, the Holocene Epoch, and the period of 50–10 thousand years ago), allow us to make the following conclusions: (a) galactic cosmic rays (GCR) seem to be the main factor that affect the climate; (b) the solar modulation

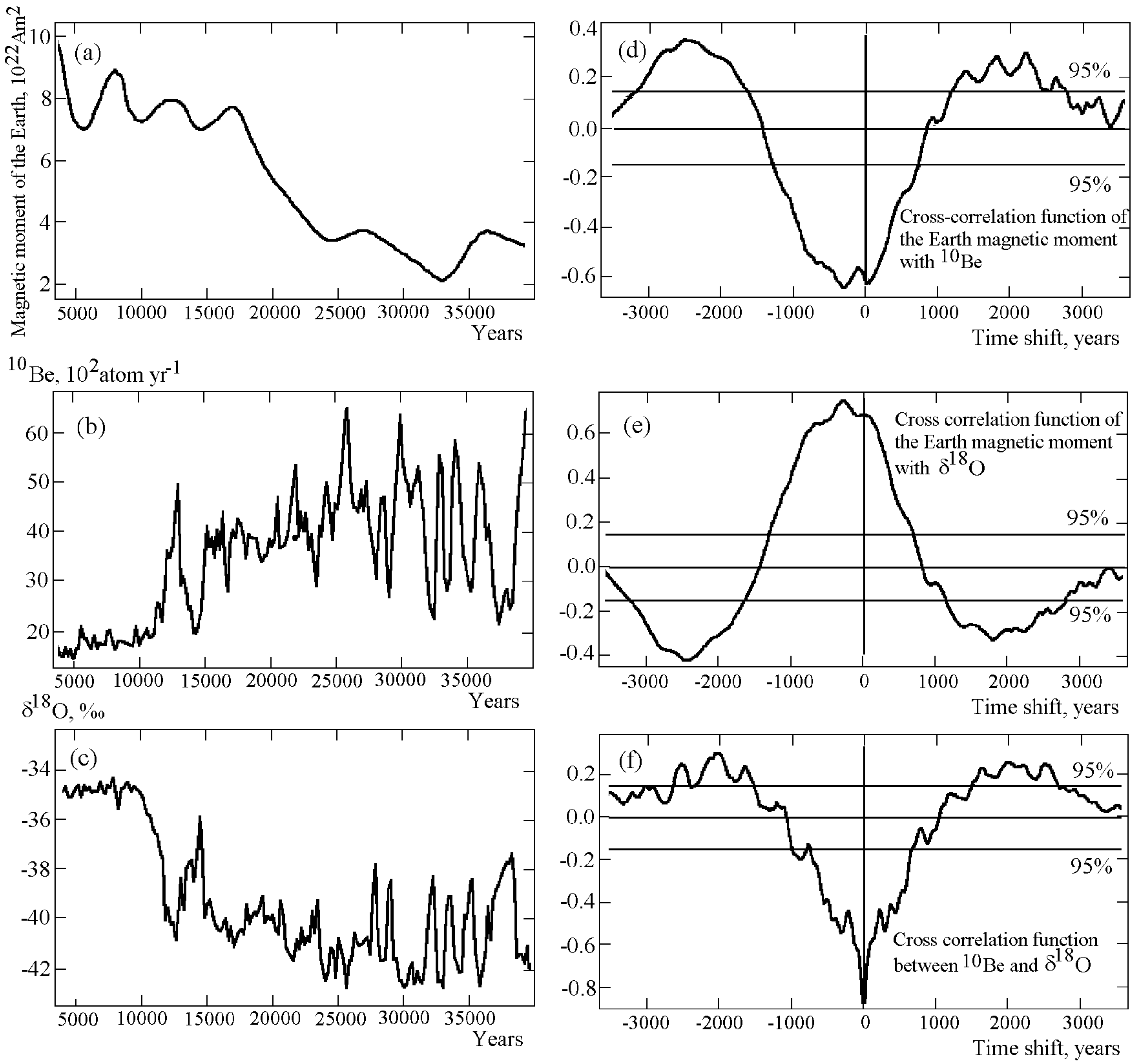

Figure 7. (a) Variation of the Earth dipole moment [*Lehman et al.,* 1996], (b) ^{10}Be concentration [*Finkel and Nishiizumi,* 1997] and (c) ^{18}O concentration [*Grootes and Stuiver,* 1997] over the time interval of 3400 to 39900 years ago and the selected estimates of the cross correlation functions for the Earth magnetic moment and ^{10}Be concentration (d), for the Earth magnetic moment and ^{18}O concentration [*Grootes and Stuiver,* 1997] over the time interval of 3400 to 39900 years ago, and the selective estimates of the cross-correlation functions for the following pairs: the Earth magnetic moment and the ^{10}Be concentration (d), between the Earth magnetic moment and the ^{18}O concentration (e), and between ^{10}Be and ^{18}O concentration (f).

of the galactic cosmic rays controls this effect, and (c) the significant decline of the geomagnetic dipole, compared to the present one, resulted in the higher flow of galactic cosmic rays into the atmosphere and in the cooling of the climate. It appears that the ratio: $Q_{\mathrm{m}}/Q_0 = \mathrm{const} \times (M/M_0)^{-0.5}$ between the change of the Earth's magnetic moment M and the production rate of cosmogenic Q isotopes in the Earth atmosphere, derived from the experimental data obtained for a short period of cosmic ray observation in the epoch of a comparatively high magnetic moment [*Elsasser et al.,* 1956], cannot be used for very low M values (here M_0 and Q_0 are the values of the magnetic moment and the production rate of ^{14}C in the present-day epoch).

In order to prove the critical importance of accounting for the GCR effect on the climate, we have to trace a correlation between the GCR intensity variations and the climate characteristics over a longer time scale. In the last years significant attention has been given to collecting detailed data not only for ice cores, but also for marine sediments, which allow one to extend the time scale for hundreds and millions years ago. *Frank et al.* [1997] analyzed 19 cores from the Atlantic and Pacific ocean floor deposits and obtained

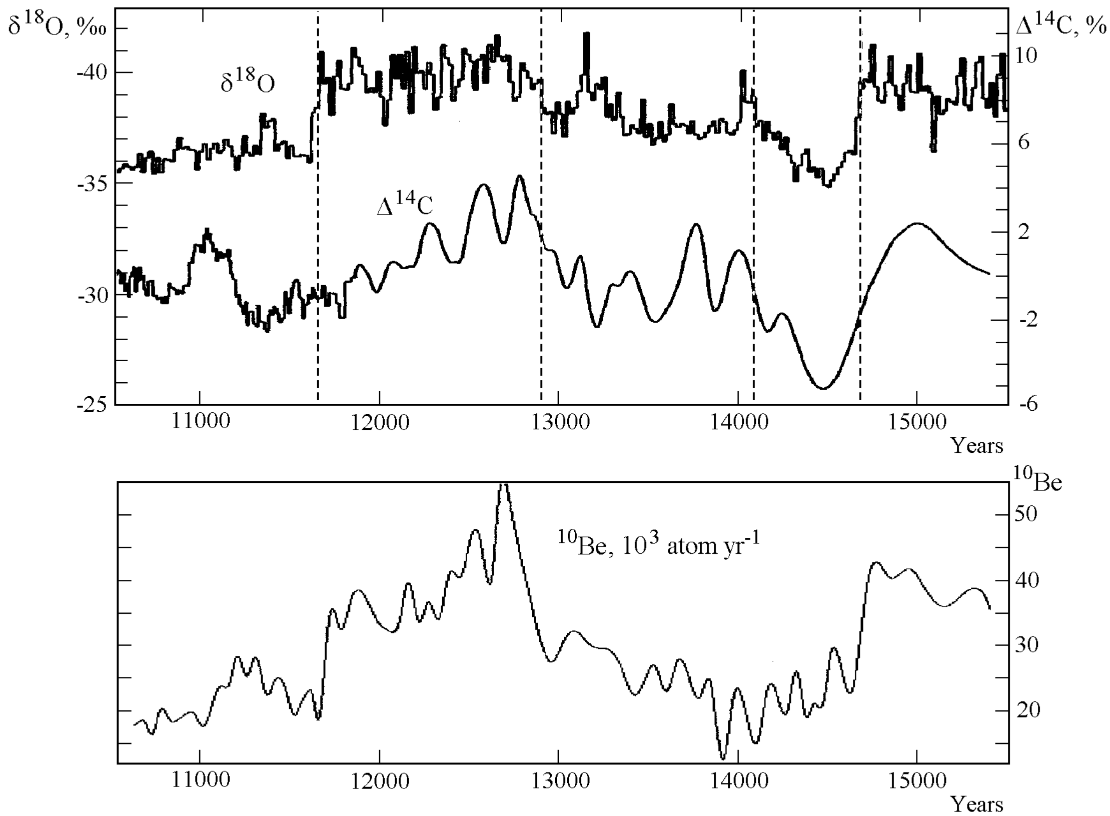

Figure 8. Variations in the concentrations of ^{18}O [*Grootes and Stuiver,* 1997], ^{14}C [*Stuiver et al.,* 1998], and ^{10}Be [*Finkel and Nishiizumi,* 1997] during the glacial-interglacial transition from 11500 to 15000 years ago.

changes in the ^{10}Be formation rate for the last 200 thousand years. Combining the data of magnetic measurements in oceanic drill-holes from the 17 localities, *Guyodo and Valet* [1996] obtained the relative changes of paleointensity of the geomagnetic field for the last 200,000 years.

Being unable to make a detailed analysis of their data here, we can note that the effect of changes in the intensity of galactic cosmic rays and in the geomagnetic field on the climate was much more complex. One of the problems is the variation of the ^{10}Be concentrations in the deep-sea sediments, associated with the uncertainty of Be accumulation rate and tranfer in oceanic deposits during the glacial cycle. High ^{10}Be concentrations might have accumulated in oceanic deposits during the time of warm interglacial periods as result of glacier melting. This might have caused more sediment accumulation and, hence, the higher ^{10}Be concentration in the cores corresponding to the given period of time, whereas ice cores contain ^{10}Be which precipitated from the atmosphere. For lack of reliable data for GCR variations during large time intervals, we analyzed a relationship between the variations in the Earth's dipole magnetic moment obtained from 33 series of the data available for deep-sea sediments [*Guyodo and Valet,* 1999] and ^{18}O concentrations in oceanic deposits [*Shackleton et al.,* 1990] for the last 800 thousand years. The peaks of the field intensity corresponded to the temperature lows. The correlation coefficient was -0.6. Note that the long series of these data did not show any stable periodicity, whereas the δ^{18}O variation series showed peaks at 23, 41, and 100 thousand years, which are usually associated with terrestrial orbital parameters [*Milankovich,* 1939].

In the overwhelming majority of studies the large-scale climatic changes with periods of tens and hundreds of thousand years are described in terms of the Milankovich theory. At the same time the analysis of the numerous climatic data available shows that many aspects of explaining the climate in terms of the astronomic theory remain unsolved. The longest climatic cycles seem to result from GCR modulation by the Earth magnetic field and from the effect of some orbital parameters on the galactic cosmic rays. This follows from the fact of finding a relationship between the Earth position and the glacial-interglacial chronology. The mechanism responsible for this relationship may be caused by the solar-latitudinal GCR variations as a result of the latitudinal variations of the solar magnetic fields or as a result of changes in the Earth orbit inclination, the plane of this orbit precessing with a period of 70 thousand years, which must induce changes in the gravitational effect of the Sun and planets on the geomagnetic field which, in its turn, modulates the GCR penetration into the Earth atmosphere. Generally, in

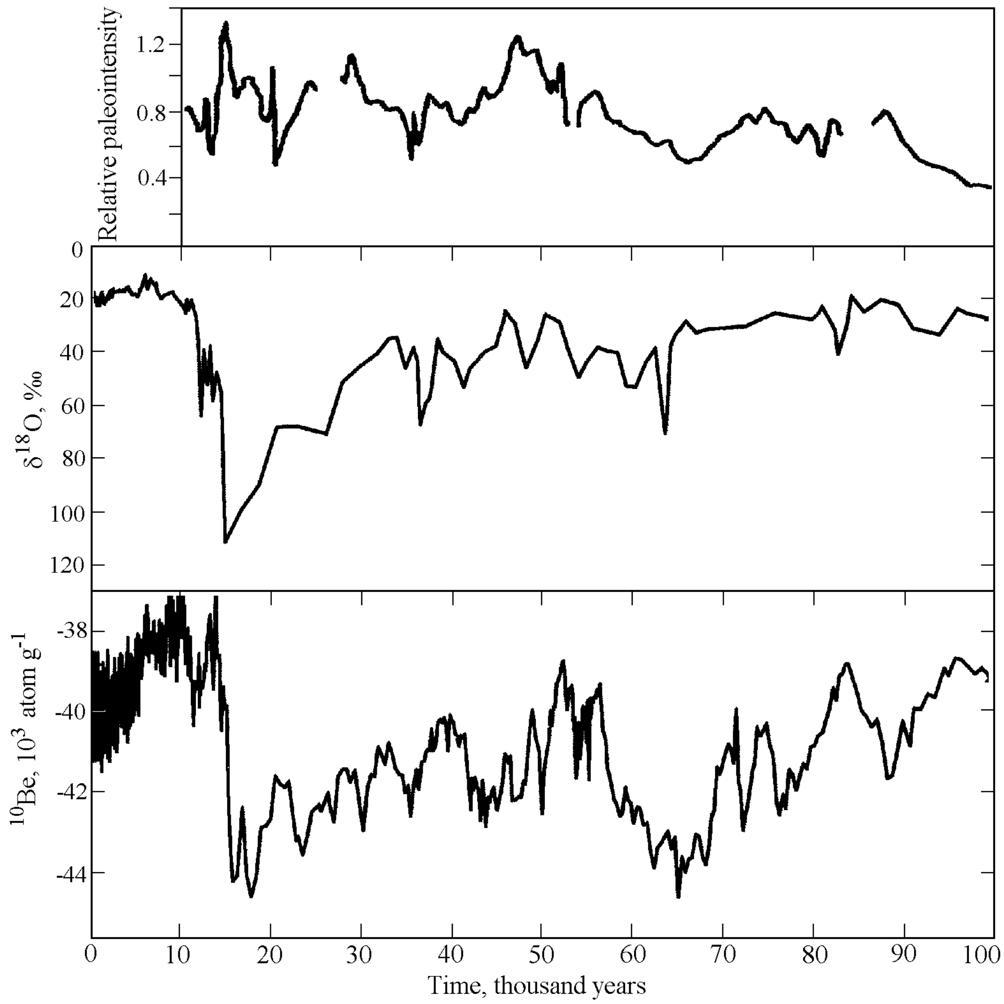

Figure 9. Comparison of the Earth magnetic field intensity (a) derived from the cores of the Antarctic rocks [*Sagnotti et al.,* 2001] with changes in the concentrations of ^{10}Be (b) and ^{18}O (c) in the ice cores collected at the Taylor Dome Site, Antarctic Continent [*Steig et al.,* 2000].

terms of large time scales the efficiency of the heliosphere for the GCR penetration into the Earth's atmosphere can vary greatly. This problem calls for a particular discussion.

Let us consider the potential mechanisms of the effects of the solar variability and cosmic rays on the atmospheric processes. It is known that the most reliable data for climatic changes in many regions of the world embrace the time period slightly longer than a century. Using short time scales and based on the direct measurements, the physical processes operating on the sun and affecting the Earth's atmosphere, thus leading to changes of the climate, are changes in the solar radiance [*Lean and Foukal,* 1988], changes in the solar activity which produce large changes in ultraviolet radiation [*Lean et al.,* 1998], this causing changes in the stratospheric ozone content [*Van Geel et al.,* 1999], and the effect of GCR on clouds and atmospheric circulation, this leading to changes in the ion production rate in the troposphere [*Pudovkin and Raspopov,* 1992; *Pudovkin and Veretenenko,* 1995; *Svensmark,* 1998; *Svensmark and Friis-Christensen,* 1997]. Each of these potential solar mechanisms has its own advantages and disadvantages, the latter being justly criticized. Nevertheless, each of them rests on the solid physical basis, and at the present time there are reasons to establish a causal relationship between these mechanisms and climatic changes, which will eventually allow us to determine which one (or ones) of them can be potentially important for the problem concerned.

In terms of the potential climatic effect the most vigorous is the total solar irradiation. The discovery of variations in the total solar irradiation (approximately 0.1% for the 11-year cycle), coherent with changes in the spot formation activity of the Sun [*Fröhlich and Lean,* 1998], suggests the possibility of the direct mechanism of the Sun effect on the climate. Unfortunately, the recorded small variation in the solar energy flow and the limited interval of measurements, where no potential long-term trend in the variation of the Sun energy flow can be recorded, leaves a high freedom of activity for both the proponents and opponents of this mechanism.

The physical mechanism, which does not require large variations in the total solar irradiation, can be associated with the high variations of the complete solar radiation can be associated with high variations in the solar ultraviolet radiation during the 11-year solar cycle (up to 10%). This mechanism is responsible for the formation and destruction of ozone in the stratosphere, which must cause changes in the chemical composition of stratospheric gases and, hence, in the troposphere. However, the problem of stratospheric effects on the troposphere and climate remains to be controversial and partially contradictory. This mechanism of the indirect effect of the solar activity on the lower atmosphere is associated with a necessity to account for complex dynamic processes in the atmosphere. Neither is there any convincing evidence that it may be one of the main mechanisms responsible for climatic changes.

In contrast to the above mechanisms, the physical mechanism associated with the GCR flow attaining the Earth's lower atmosphere can cause changes in the climate by way of affecting the processes of cloud condensation and atmospheric circulation. It is important to note that this mechanism removes the problem of incompatibility between the energy flows from the solar electromagnetic radiation ($\sim 10^{10}$ erg m^{-2}s^{-1}) and from cosmic rays ($\sim 10^2$ erg m^{-2}s^{-1}).

It has been established that the GCR flux arriving into the Earth atmosphere is modulated by the processes operating in the heliosphere, associated with the variations of the magnetic field, convected from the Sun by solar wind, and varies in connection with the 11-year cycle of the solar activity. The GCR flows have an inverse correlation with the cycle of the solar spots: they have maximum values at the cycle minimum, and minimum values at the cycle maximum. In contrast to the solar cosmic rays, the substantial galactic cosmic ray fluxes of high energy are able to reach the upper layer of the troposphere. Penetrating into the stratosphere and troposphere, the flow of the particles may produce cloud condensation nuclei and, hence, create ionization which is the main cause of the atmospheric conductivity. The GCR fluxes are responsible for the ionization of the Earth atmosphere below 35 km. Geomagnetic activity also affects the GCR intensity and, hence, the cloud condensation nuclei, causing changes in the cloudiness. The growth of GCR fluxes in the Earth's atmosphere must lead to the growth of low clouds, especially in the tropic regions, to the growth of the albedo of these clouds, and to the decline of the lower atmosphere temperature. The effect of the charged particles of cosmic origin on the cloudiness and precipitation has been proved by many geoscientists [*Pudovkin and Raspopov,* 1992; *Pudovkin and Veretenenko,* 1995; *Roble,* 1985; *Stozhkov et al.,* 1996]. *Svensmark and Friis-Christensen* [1997] showed, as a result of their observations, that ionization may control the global cloud cover. A change in the low clouds during one cycle is about 3–4% [*Pallé Bago and Butler,* 2002], whereas a change in the GCR level from the maximum to the minimum of the cycle was roughly 10–12%, a change in the ionization at the level of the troposphere turned out to be about 20% of this period.

Clouds play an important role in the Earth radiation budget, capturing the outgoing radiation and reflecting the radiation falling to the atmosphere. It is highly necessary to carry out experimental observations for establishing a correlation relationship between the GCR flux and cloudiness, which would provide a missing connection of the solar-climatic relationships. Recent satellite observations proved the existence of correlation between the GCR flux and the temperature of the upper boundary of the low clouds with a 99.8% significance level [*Svensmark,* 1998]. *Svensmark* [1998] proved that a temperature change produced by the GCR effect on the clouds from 1975 to 1989 was 3–5 times greater than the temperature change caused by changes in the total solar irradiation. The temperature of the low clouds was found to be >273 K, that is, they were warm and consisted of liquid water drops. The subsequent studies, for instance, [*Pallé Bago and Butler,* 2000], demonstrated that the mechanism for explaining a relationship between clouds and cosmic rays can be found via the role of atmospheric ionization in aerosol formation. In the case of typical atmospheric oversaturation ($\sim$1%) a liquid cloud drop is formed only in the presence of aerosol which acts as a condensation center.

Assuming the linear function of cloudiness response to the GCR effect, *Svensmark* [1998] reconstructed changes in the low cloud cover using the data recorded by a Huancayo monitor from 1953 to 1999 (Figure 10). Using the measurements of the solar magnetic flow which modulates the galactic cosmic rays, correlated with the satellite observations performed during 1964–1995, he also estimated the radiation effect of the clouds during the studied time interval (Figure 10) and proposed a roughly 1.4 W m^{-2} warming at the expense of variations in the low clouds during the last century (1901–1995) along with a twofold change in the solar magnetic flow. It should be noted that the warming during the same period time caused by the growing carbon dioxide content has been estimated to be about 1.5 W m^{-2} and the warming caused by a change in the solar radiation was about 0.4 W m^{-2} [*Lockwood and Stamper,* 1999]. Thus, the experimental data available for the radiation effect of cloudiness justify the further study of the GCR effect on the clouds. It should be noted that the combined GCR effects in the Earth atmosphere can help to solve the energy aspect of the climatic effect on the basis of this mechanism.

Although there is some correspondence between the low cloud cover, observed from the satellites, and the GCR intensity at the high level of significance, the length of the data base is too short to eliminate a number of uncertainties in the attempt to ascertain the long-term behavior of the cloud cover. The proving of a relationship between GCR and the cloud cover will provide a new mechanism for climate changes. Moreover, in contrast to the other mechanisms considered above the study of the GCR effect on the weather and climate has a few advantages, namely:

(1) the galactic cosmic rays (GCR) are recorded in the form of ^{14}C, ^{10}Be, ^{26}Al, and other isotopes of cosmic origin in annual tree rings (^{14}C), in ice layers (^{10}Be), and in ma-

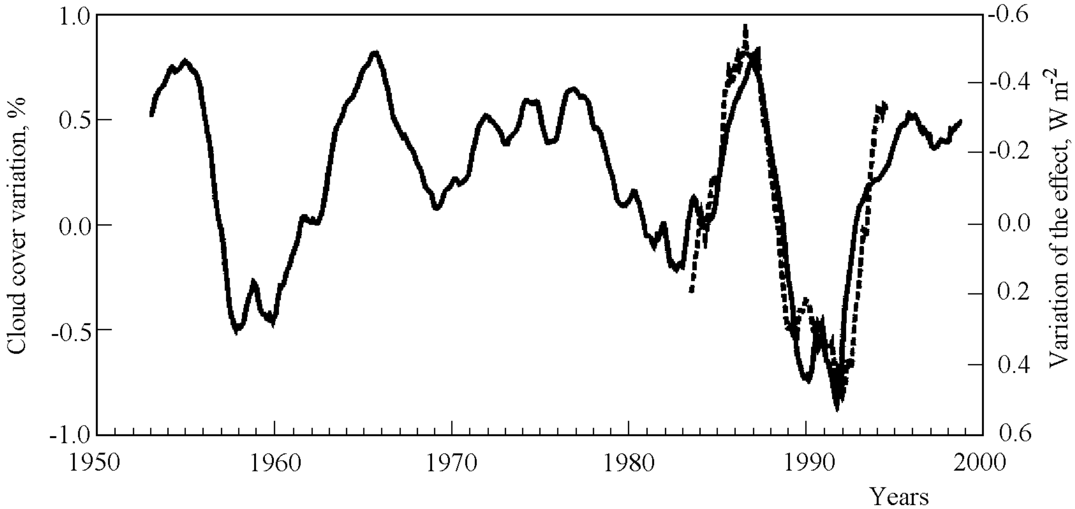

Figure 10. Comparison of the varying ^{10}Be concentrations (solid curve) measured in the ice core from Site Dye-3 (Greenland) [*Beer et al.,* 1994], which can be used as indicator of solar activity in the past, with temperature variations in the Northern Hemisphere (dotted line) [*Groveman and Landsberg,* 1979; *Jones,* 1994].

rine deposits (^{10}Be and ^{26}Al), this allowing us to trace their detailed chronologic histories over thousands and even tens and hundreds of thousand years;

(2) the snow produced from the clouds under the GCR effect falls to ice cupolas and glaciers and accumulates in the ice layers, the stable isotope ratios in the ice cores providing information on the temperature of the cloud from which snow precipitated;

(3) the study of variations in the concentrations of cosmogenic isotopes over a large time scale, caused by temporal variations of the solar and terrestrial magnetic fields, as well as of variations in the concentration of stable ^{18}O isotope in the ice layers, allows one to estimate the role of this mechanism in climate changes.

7. Conclusion

Analysis of the data available for cosmogenic nuclides, namely, for ^{14}C in tree rings, for the period of more than 10,000 years and for ^{10}Be in the ice cores for the period of almost 40,000 years provides a convincing proof for the long-term modulation of the intensity of cosmic rays in the vicinity of the Earth by the solar and geomagnetic fields. The history of the climate variations over the studied time interval can be easily traced in the data of stable isotopes from the cores of ice and oceanic sediments.

The results of this study prove the existence of a direct relationship between the long-term variations in the intensity of cosmic rays and the surface temperature of the Earth. Most clearly traced is the relationship between the long-term variations in the intensity of galactic cosmic rays, modulated by the solar and geomagnetic activity, and climate during a period of ∼10 to ∼40 thousand years from the data available for changes in the concentrations of stable oxygen isotopes and ^{10}Be in the cores of Greenland ice.

Since the ratios of stable oxygen isotopes provide information on the temperature of the cloud from which snow precipitated, and the cosmic rays were the nuclei of this cloud condensation, leading to precipitation from it, the discovered relationship proves that cosmic rays were the main factor affecting the weather and climate during tens of thousand years. Therefore, there is no need to require any significant long-term changes in the solar radiation.

Nevertheless, although there is a strictly substantiated correlation between the galactic cosmic rays, modulated by the solar and geomagnetic fields, and climate over different time scales, further research need be carried out to prove a physical relationship among the galactic cosmic rays, the solar and terrestrial fields, and the orbital movements of the Earth.

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