Connection between the Earth's Climate Change and Variations in the Geomagnetic Field and Cosmic Ray Fluxes During the Past Ten Thousands of Years

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Abstract

A possible influence of changes in cosmic ray fluxes and solar variability on climate has been the subject of intense investigations in recent years. Recent studies have shown that the interrelation between the geomagnetic field parameters and climate can also be traced on different time scales. A connection was presented in this analysis between the Earth climate change and variations in the geomagnetic field and cosmic ray fluxes based on the data obtained from different natural archives for the Holocene. So paleodata analysis of variations in cosmic ray fluxes, geomagnetic field, and climate has revealed that correlation between these data has existed on the time scales of several thousand and ten thousand years. Examination of data on changes in the Earth's magnetic moment over the past ~10,000 years and proxy data on precipitation at low latitudes has shown that time changes in the geomagnetic dipole moment can play an important role in controlling rainfall at low latitudes in some regions of the Earth. Through these processes, the geomagnetic field of the Earth's atmosphere could affect climate change in the Earth's past. Of course, not all aspects of this complex problem are understood now.

Keywords

Natural Archives; Cosmogenic Isotopes ^{14}C and ^{10}Be; Climate Change; Oxygen-18 Concentration; Geomagnetic Intensity Variations; Geomagnetic Pole; Periodogram and Spectral Analysis

Introduction

An abrupt global temperature rise at the Earth's surface from the end of the 19th century has stimulated an increased interest of understanding the mechanisms of climate change. There are difficulties in explaining the observed climate change by both the anthropogenic factor and natural factors (solar variability, orbital effects of solar radiation variation, influence of solar ray fluxes modulated by solar activity on atmospheric processes, UV solar radiation variability, etc.) that affect climate. Nevertheless, at present neither of the factors can be ignored without a careful consideration of its possible effect on climate.

In spite of the fact that many mechanisms that interpret the climate change during the last millennia have been suggested, the reasons for the global temperature rise observed at present still remain unclear. At the same time, recent detailed reconstructions of climate change for the periods from tens to hundreds and thousands of years clearly indicated that climate change is attributable mainly to natural factors.

Analysis of the instrumental observations of variations in solar activity, cosmic ray intensity, and climate characteristics and also the data obtained from records in natural archives (annual growth tree rings, ice layers, stalactites, and so on) for time scales of tens to thousands of years provides a conclusive evidence of the climate sensitivity to solar activity. This is confirmed by analysis of the interrelation between reconstructions of solar activity in the past and the proxy data on climatic variability (Lohman *et al.*, 2004). Extraterrestrial observations of changes in the integral flux of solar radiation have a short history (from 1975) and indicate that solar radiation experiences rather small changes (about 0.1%) (Wilson and Hudson, 1991; Fröhlich, 2006; Kopp and Lean, 2010). For this reason, advocates of the anthropogenic climate change are sceptical about this mechanism of solar forcing.

In recent years, the theory of indirect solar forcing of climate has been developed. According to this theory, climate is affected by fluxes of galactic cosmic rays that continuously impinge on the Earth's atmosphere (Scherer *et. al.*, 2006) and which are the main source of ionization in the Earth's lower atmosphere (Kirkby, 2007).

The galactic cosmic ray (GCR) fluxes penetrating into the Earth's atmosphere are modulated and are not only scattered by heliomagnetic fields but are also subjected to the influence of the geomagnetic field. Due to influence of the Earth's dipole moment, the geomagnetic field shields in different manners the GCR fluxes that impinge at low and high latitudes. The shielding is maximal at low latitudes and minimal at high latitudes. As noted in (Usoskin *et al.*, 2008), precipitation at low latitudes is the climatic parameter which is closely associated with atmospheric processes and sensitive to variations in the GCR fluxes modulated by variations in the geomagnetic dipole moment. It is, therefore, important to consider regional effects of cosmic rays, since variations in the geomagnetic field strength and direction affect the rate of production of cosmogenic nuclides. However, variations in the Earth's magnetic field are rarely included into the consideration of the connection between magnetic field variations and climate. Along with this, some researchers revealed a correlation between variations in the geomagnetic field value and structure and climate change. The authors of (Worm, 1997) analyzed palaeomagnetic and palaeoclimatic data and showed that geomagnetic field excursions were accompanied by coolings. On the other hand, Pospelova (Pospelova *et al.*, 1998; Pospelova, 2000) has shown that geomagnetic field excursions can be accompanied by not only coolings but also warmings. It is an experimentally established fact that excursions occurred under different climatic conditions, but, irrespective of the excursion ages and types, their commencements and completions coincided with coolings. If it is taken into account that variations in geomagnetic field parameters during excursions and reversals have an oscillatory character (Petrova *et al.*, 1992), multiple climate changes during the time period of an excursion can be an indication that there is a physical mechanism through which geomagnetic field changes affect the climate. It was demonstrated in (Galet *et al.*, 2005; Galet *et al.*, 2006) that variations in the geomagnetic dipole value influenced the ancient civilizations, which was due to abrupt climate changes. Courtillot *et al.* (2007) has drawn attention to the fact that the correlations between geomagnetic field variations and climate are probably underestimated. As all these authors suppose, the climate change can occur due to interaction between cosmic ray fluxes and the lower cloud cover during time intervals of extreme oscillations in the position of the magnetic dipole axis.

To elucidate the cause-and-effect relationship between the climate change on different time scales and the factors responsible for this change, including the geomagnetic factor, it is necessary to carry out multidisciplinary investigations of the sources that contain information on climate.

In this paper, we analyzed and compared high-resolution data on changes in the geomagnetic field, galactic cosmic ray intensity, and climate on a time scale of the last ten thousands of years. Major attention is given to the last 10,000 years. Along with temperature, the main emphasis is on one climatic parameter, i.e., precipitations at low latitudes.

Patterns of Time Variations in the Geomagnetic Field and Galactic Cosmic Ray Intensity

Similar to the solar modulation of GCR, the intensity of GCR fluxes is modified by the Earth's magnetic field. Therefore, it is interesting to examine the correlation and relations between variations in the Earth's magnetic field characteristics and climate change on different time scales. This will allow one to separate the effects of the solar and geomagnetic factors on climate. In addition to direct measurements of magnetic field characteristics at magnetic observatories in recent centuries, data on geomagnetic field variations can be obtained by archaeomagnetic and palaeomagnetic methods. One of the major problems in the use of proxy data in studies of climate change is a decrease in the accuracy of dating of palaeomagnetic data as one goes deeper and deeper into the past.

According to the modern ideas, the geomagnetic field is generated by the Earth's rotation due to the interaction between convective motions in the liquid conducting core and electrical currents. These factors give rise to the dynamo effect which sustains the system known as the Earth's magnetic field. The magnetic field exhibits complex spatial-temporal variations. The state of the magnetic field and time variations in the field intensity provide important information on the processes in the coupled Sun–Earth system.

The Earth's magnetic field varies over an extraordinary large range of timescales. Changes on timescales from decades to millennia are called secular variations. They are closely related to the processes that generate the field in the Earth's electrically conducting liquid outer core. Geomagnetic field variations on timescales from seconds to years are mostly caused by external currents in the ionosphere and magnetosphere activated by the solar wind. The intensity of such variations depends on the latitude, season, time of the day, and solar wind parameters.

The most important information on the geomagnetic field intensity variations were derived from instrumental and archaeomagnetic data for the past 10–12 kyr. A record of changes in the Earth's magnetic field elements is provided by the remanent magnetization of rocks. The palaeomagnetic method can be used to extract the ancient remanent magnetization of rocks and to reconstruct the field direction and its variations over time. Palaeomagnetic data are used to reconstruct the history of the Earth's magnetic field over the past few million years. Recent investigations of the geomagnetic field intensity on longer timescales have revealed a decrease in the dipole intensity by an order of magnitude. At the same time, the nondipole intensities (quadrupole and octupole components, etc.) varied insignificantly. This suggested that numerous total reversals of the Earth's magnetic field, such that the positions of the magnetic north and south (dipole) interchanged, occurred. It should be noted that during a reversal, the magnetic field does not vanish: it develops several poles at different locations and has a complex nondipole nature.

It is commonly believed that the mechanism of the influence of large-scale changes in the Earth's geomagnetic field value on climate (Dergachev *et al.*, 2006) is associated with the impact of changes in the Earth's dipole moment on the GCR flux intensity. The data on concentrations of cosmogenic nuclides (variations in ^{14}C and ^{10}Be which are produced in the atmosphere under the influence of GCR) in well-dated natural archives (tree rings, ice layers, stalactite and stalagmite layers) for the last 10,000 years have a time resolution from 1 to 10-20 years. Because of uncertainty in dating the samples in (Dergachev *et al.*, 2006), the data on the Earth's dipole moment variations during the 10,000-year interval were grouped into time windows of 500 years for the first 4-5 thousand years before present and 1,000 years for subsequent time intervals. However, in spite of this difference in the time resolution, the comparison of data on changes in the ^{14}C (Stuiver *et al.*, 1998) (FIG. 1a) and ^{10}Be (Voonmus *et al.*, 2006) (FIG. 1b) concentrations with changes in the dipole moment (Teanby and Gubbins, 2000; Yang *et al.*, 2000; Korte and Constable, 2010) (the scales are inverted in FIGs. 1c, 1d, and 1e) revealed the same long-term trends.

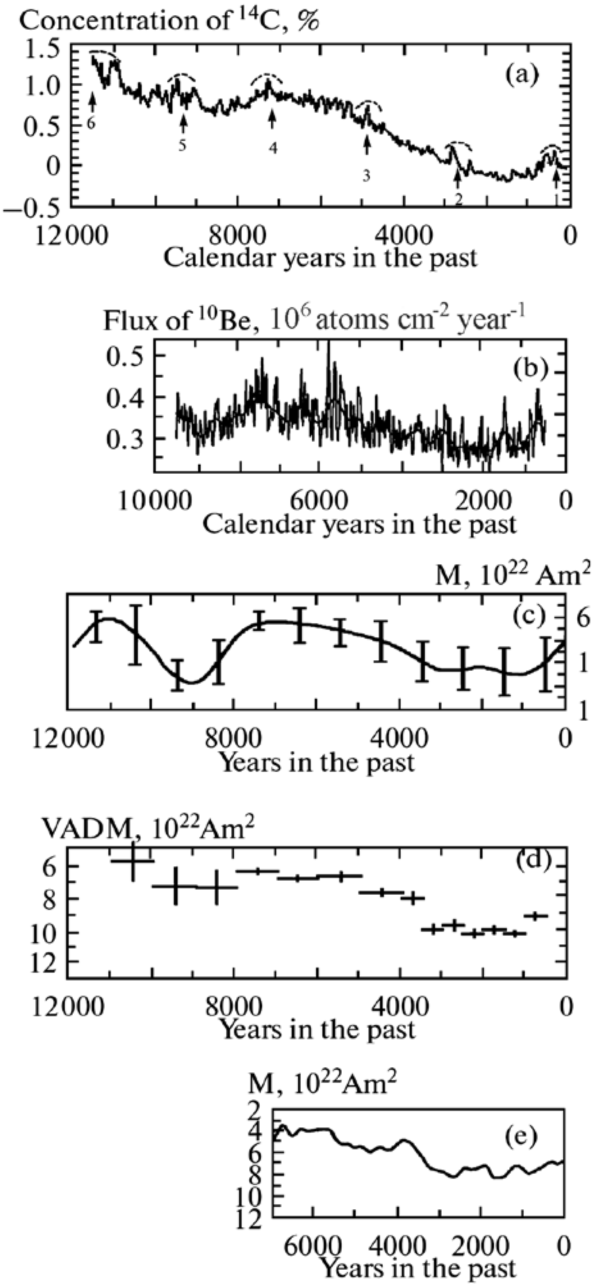

FIG. 1 COMPARISON OF TIME VARIATIONS IN CONCENTRATIONS OF RADIOCARBON IN TREE RINGS OF 10–20 YEARS (STUIVER *ET. AL.*, 1998) (ARROWS - THE GREATEST CONCENTRATION INCREASES) (a); IN THE ^{10}BE FLUX OBTAINED FROM ICE CAP LAYERS IN GREENLAND (VOONMOOS *ET AL.*, 2006) (b); IN SMOOTHED DATA ON CHANGES IN THE EARTH'S MAGNETIC MOMENT CHANGES (TEANBY AND GUBBINS, 2000) (VERTICAL LINES INDICATE THE DATA UNCERTAINTY) (c); IN THE DATA ON THE VIRTUAL AXIAL DIPOLE MOMENT (VADM) CHANGE (YANG *ET AL.*, 2000) (d); AND IN ESTIMATES FOR THE GEOMAGNETIC DIPOLE MOMENT BASED ON SPHERICAL HARMONIC ANALYSIS FOR THE LAST 7000 YEARS (KORTE AND CONSTABLE, 2005) (e).

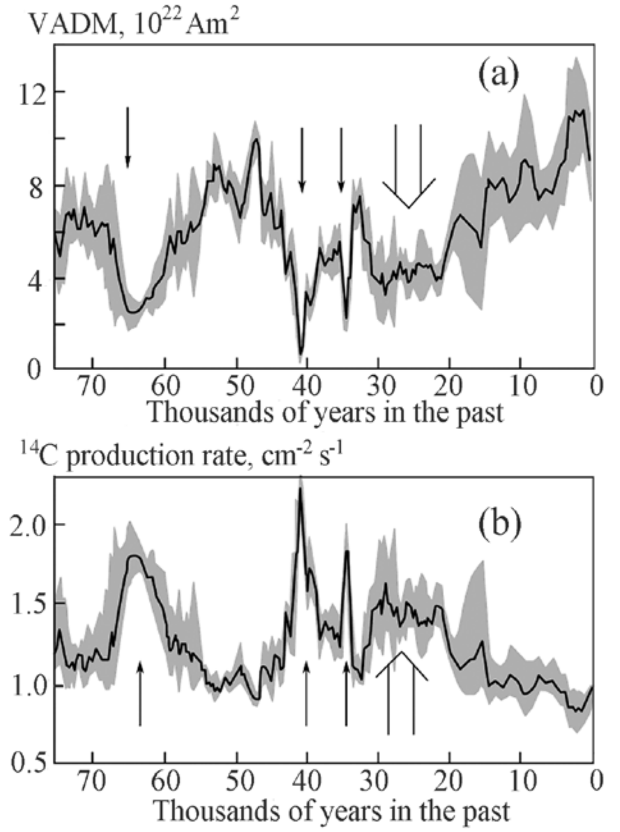

FIG. 2 COMPARISON BETWEEN VARIATIONS IN THE VADM INTENSITY (a) AND ^{14}C PRODUCTION RATE FOR THE LAST 75 KYR (b). ARROWS SHOW EXTREME CHANGES IN THE VADM INTENSITY AND RADIOCARBON PRODUCTION RATES COINCIDING WITH GEOMAGNETIC FIELD EXCURSIONS.

Among the most important characteristics of the Earth's magnetic field on the time scale of the last tens of thousands of years are the moments of abrupt variations in the dipole field during a short time, i.e., a geomagnetic excursion which gives rise to considerable variations in the GCR flux in the vicinity of the Earth. As an example, let us consider FIG. 2 that compares the high-resolution palaeointensity reconstructed from sedimentary records worldwide (Laj *et al.*, 2002) and variations in the ^{14}C production rate (Masarik and Beer, 1999) recorded in natural archives, such as varved lake sediments, tree rings, and corals, over the past 75 kyr. Note that the geomagnetic field variations derived from these records are consistent with variations in the geomagnetic field components. It is also interesting to note that the pronounced valleys in the palaeointensity at 41 and ~35 kyr and minima at 60– 65 and 20–30 kyr more or less correspond to Gothenburg (15–20 kyr), Mono Lake (25–30 kyr), Laschamp (35–45 kyr), and Kargopolovo (60–70 kyr) geomagnetic excursions (e.g., (Petrova *et al.*, 1992). It can also be seen from FIG. 2 that time intervals of the lowest geomagnetic field coincide with an abrupt increase in the ^{14}C production rate and, hence, with an enhancement in the cosmic ray flux that can stimulate climate change. This confirms the conclusions of Pospelova (Pospelova *et al.*, 1998; Pospelova, 2000) on climate changes during geomagnetic field excursions.

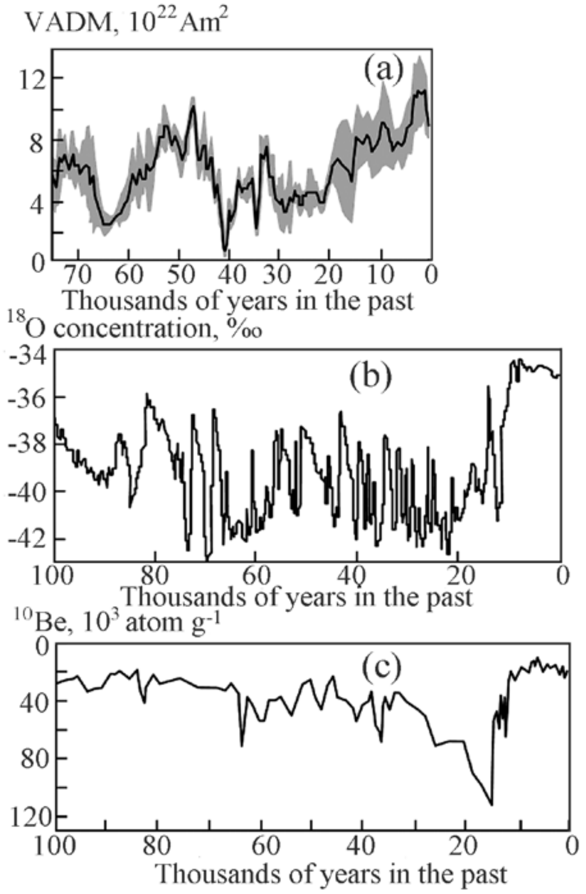

FIG. 3 COMPARISON OF VARIATIONS IN THE EARTH'S VIRTUAL AXIAL DIPOLE MOMENT (LAJ *ET AL.*, 2000) (a) AND CONCENTRATIONS OF δ^{18}O (TEMPERATURE) (GROOTES AND STUVER, 1997) (b) AND ^{10}BE (STEIG *ET AL.*, 2000) (c) FOR THE LAST SEVERAL TENS OF THOUSANDS OF YEARS.

Analysis of detailed palaeomagnetic data (a change in the virtual dipole moment of the Earth, FIG. 3 (Laj *et al.*, 2000)) and palaeoclimatic temperature (a change in the relative concentration of stable oxygen isotopes ^{18}O and ^{16}O (FIG. 3b) (Grootes and Stuiver, 1997) and also the data on changes in the ^{10}Be concentration (FIG. 3c) (Steig *et al.*, 2000) for the last 100 kyr evidently indicates that the climate during the last 10 kyr (the Holocene Epoch) substantially differs from the climate of the previous 90 kyr. Relatively high and low ^{18}O concentrations in FIG. 3 reflect sharp warming (interstadials) and cooling (stadials) events, respectively.

Owing to systematic archaeomagnetic studies of archaeological materials carried out during the last decades, detailed curves of variations in the magnetic field direction and strength in different regions can be obtained. They can be used to reconstruct the main features of regional variations in the geomagnetic field for periods of tens to hundreds of years over the last two-three millennia.

Analysis of the data sets for France performed in (Gallet *et al.,* 2005) showed the repeated systematic coincidence in sharp variations in the direction and maxima of field strength around 800 BC; 200, 800, and 1400 AD; and possible coincidences from 500 to 600 and around 1600 AD. These sharp variations are referred to as "archaeomagnetic jerks".

The jerks are related to different geophysical phenomena of global nature, such as geomagnetic field variations, the Earth's rotational speed, and global surface temperature variations. It was interesting that the evidence for the first four archaeomagnetic jerks was obtained in archaeomagnetic studies in Korea (Yu *et al.*, 2010). In (Gallet *et al.,* 2005), multiple temporal coincidences between archaeomagnetic jerks and climatic coolings lasting for several decades in the North Atlantic and in Eastern Europe (retreats and advances of the Alpine glaciers) were also revealed. This can be attributed to the influence of changes in the geomagnetic field morphology on the GCR flux interacting with the atmosphere. The sources of these jerks are still unclear.

The simultaneous occurrence of the jerks raises an important question of whether they are global or regional. It has recently been found (Dumberry and Finla, 2007) that archaeomagnetic jerks are apparently associated with the dynamics of processes at the Earth's core surface from middle to high latitudes in the northern hemisphere. Studies of archaeomagnetic jerks on the scale of the last three millennia have led to the conclusion that they correspond to the episodes of maximum geomagnetic field hemispheric asymmetry (Gallet *et al.*, 2009), which is important for understanding of some properties of long-term magnetic field variations. By studying the behavior of the magnetic field on the historical scale, the authors of (Usoskin *et al.*, 2008) interpreted the evolution of the eccentric dipole that can affect the path of cosmic rays entering the atmosphere. The archaeomagnetic jerks in this case can be the manifestations of unusual effects of cosmic rays on the atmosphere. This influence can be comparable with or even dominate over the solar signal at middle latitudes, which is in favor of the assumption that the climates of some regions of the Earth can be especially sensitive to magnetic field variations.

Though separate climatic data series for the last 10,000 years have a sufficiently high spacial and time resolution, the complexity of the climate system does not allow one to develop the model that can adequately explain many features of climate variability. Each new step in understanding of features of the climate system is a result of comparison of the proxy high-resolution climatic series and climate-affecting factors.

Systematic measurements of both the Earth's magnetic field and global temperatures are on the same short time scale of ~150 years. These measurements indicate that the field strength decreases over time, and the magnetic poles change their positions from one year to another. The Earth's magnetic field affects the rate of energy transfer from the solar wind to the Earth's atmosphere, and pole wandering changes the geographical distribution of fluxes of galactic and solar cosmic rays. Analysis of variations in the temperature and position of the Earth's magnetic poles from 1900 up to the present carried out in (Kerton, 2009) revealed strong correlations between them, which suggested that they are related. The physical mechanism responsible for such a relationship, is, however, unclear.

The Geomagnetic Field, Galactic Cosmic Rays, and Precipitation at Low Latitudes

Because of the important role of the Earth's magnetic field in the GCR fluxes reaching different latitudes, it is necessary to investigate in detail variations in the geomagnetic dipole moment and correlation between variations in climate parameters and intensity of the GCR flux for the last millennia. To study a potential link between the geomagnetic dipole moment and climate, let us consider new high-resolution data on the field strength obtained solely from burned archaeological materials and lava flows (i.e., materials not subjected to climatic changes (Knudsen *et al.*, 2008) and (i) $\delta^{18}O$ measurements in the caves in the vicinity of the ocean that characterize precipitation at low latitudes (stalagmite Q5 from the Qunf cave in southern Oman (17°10′N, 54°18′E (Fleitman *et al.*, 2003) and (ii) stalagmite DA from the Dongge cave in southern China (25°17′N, 108°5′E (Wang *et al.*, 2005) (FIG. 4).

Both data sets are compared with the cosmogenic ^{14}C concentration that characterizes galactic cosmic rays which in turn characterize solar activity. It should be noted that, as shown in (Usoskin *et al.*, 2008), the connection between GCR and cloud cover is the most pronounced at low latitudes, and, as a result, the water vapor concentrations in the Earth's atmosphere must be higher at low latitudes. In order to establish a relationship between the geomagnetic field and precipitation, it is also important to bear in mind that the GCR fluxes at low latitudes are screened to the highest degree by the geomagnetic field. Unfortunately, there is no sufficient information on the geomagnetic dipole moment in the distant past, which is mainly due to many lacunas in the data on the field strength for different latitudes.

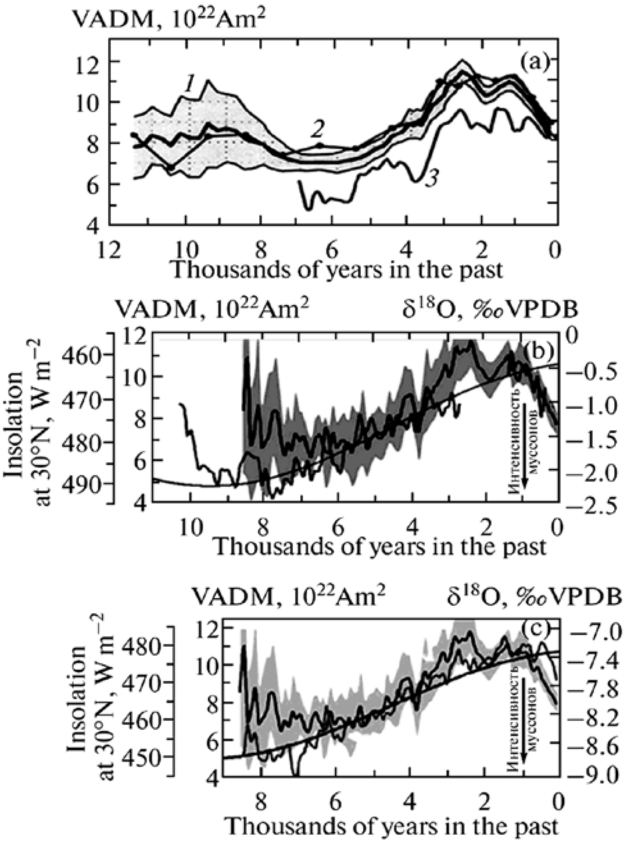

FIG. 4 RECONSTRUCTION OF THE DIPOLE MOMENT (a) WITH 2σ - ERROR ESTIMATES (SHADED AREA) FROM (KNUDSEN *ET AL.*, 2008) (*1*), (YANG *ET AL.*, 2000) (*2*), AND (KORTE AND CONSTABLE, 2005) (*3*). THE VADM (THE CENTRAL SOLID LINE (KNUDSEN *ET AL.*, 2008) WAS DETERMINED BY AVERAGING THE FIELD STRENGTH BY USING WINDOWS OF 500 YEARS FOR THE LAST 4000 YEARS AND 1000 YEARS BEFORE 4000 YEARS. COMPARISON BETWEEN CHANGES IN THE DIPOLE MOMENT (KNUDSEN *ET AL.*, 2008) (UPPER CURVE, WITH ALLOWANCE FOR UNCERTAINTY) AND MEASURED δ^{18}O (BOTTOM CURVE) IN STALAGMITES FROM THE QUNF CAVE, SOUTHERN OMAN (FLETMANN *ET AL.*, 2003) (b) COMPARISON OF CHANGES IN THE DIPOLE MOMENT (KNUDSEN *ET AL.*, 2008) (UPPER CURVE, WITH ALLOWANCE FOR UNCERTAINTY) WITH MEASURED δ^{18}O IN STALAGMITES FROM THE DONGGE CAVE, SOUTHERN CHINA (WANG *ET AL.*, 2005) (c). THE SMOOTH CURVES IN FIGS. 2B AND 2C SHOW VARIATIONS IN INSOLATION (BERGER, 1978) FOR SUMMER MONTHS (JUNE, JULY, AND AUGUST) AT 30°N.

FIG. 4 compares reconstructions of the geomagnetic dipole moment (Knudsen *et al.*, 2008) and data derived from measurements of the ^{18}O concentration in a stalagmite from the Qunf cave in southern Oman (Fleitman *et al.*, 2003) (a) and a stalagmite from the Dongge cave in southern China (Wang *et al.*, 2005) (b) which characterize the precipitation intensity. To carry out the comparison, the data on the ^{18}O concentration and dipole moment variations were grouped and averaged using the same procedure. By using the sliding windows of 500 years for variations in the geomagnetic dipole moment for the interval of the last 4,000 years and of 1000 years for the data before this interval, the authors of (Knudsen and Riisager, 2009) revealed high correlation coefficients between the δ^{18}O data for stalactites in the caves of southern Oman and southern China in the interval of the last 5,000 years (0.81 and 0.87, respectively). The correlation between the precipitation variations and the dipole moment with a resolution of the order of a century was also turned out to be high, i.e., 0.81 and 0.86, respectively (FIGs. 4b and 4c).

The smoothed curves in FIG. 2a and FIG. 2b show variations in insolation in summer months: June, July, August at 30^{O} N, and the hatched area shows the 2 sigma uncertainty in the dipole moment.

Long-term variations in precipitation intensity can be due to changes in solar insolation (Henderson *et al.*, 2008). To find out whether there is a link between solar radiation and monsoon rainfall or not, it was subtracted from the data in FIGs. 2b and 2c using the summertime insolation at 30°N (Berger, 1978). The correlation coefficient for the data from the cave in southern China for the 5,000-year interval was high, i.e., 0.71 (a centennial window was used). For the cave in southern Oman, the correlation was high for the first 1,500 years and then there was a lacuna in the data. It is likely that an increase in the geomagnetic dipole moment leads to a reduction in the monsoon precipitation (arrows in FIGs. 2b, 2c). Note that the correlation coefficient between ^{18}O and dipole moment is higher than that between ^{18}O and insolation. In addition, it can be seen that around 8,000-9,000 years ago the behaviors of the δ^{18}O and VADM curves sharply differed from that of the insolation curve, but the behaviors of the δ^{18}O and VADM curves correlated with each other.

It follows from FIG. 2 that, as the magnetic field decreases, the GCR fluxes and the monsoon rainfall intensity increase. This can be a consequence of the differences in solar and geomagnetic modulation of galactic cosmic rays. The long-term reduction in precipitation at low latitudes observed in these data is in good agreement with the results obtained in recent studies (Cai *et al.*, 2010; Griffiths *et al.*, 2010).

Connection Between Changes in Cosmic Rays, Geomagnetic Field, and Climate in the Past

The paleoclimatic studies indicated that the time interval of climatic warming (the Holocene Epoch) which is characterized by the most favorable natural conditions for the human being continue for about 10 kyr. It is interesting to analyze in more detail the data on variations in cosmogenic isotope concentrations, geomagnetic field strength, and climate typical of the Holocene.

Earlier studies (Dergachev *et al.*, 2006; Dergachev *et al.*, 2007) suggested that variations in cosmic ray fluxes correlated with climate change over intervals 0–10 and 10–100 kyr in the past. Therefore, the examination of changes in the cosmic ray intensity and paleointensity in natural archives may be of critical importance for understanding the role of geomagnetic variations in climate change.

A detailed reconstruction of variations in the geomagnetic dipole moment which controls the cosmic ray intensity was carried out in (Knudsen *et al.*, 2008) for the last ~10 kyr. It was based on the data derived exclusively from burned archaeological materials and lava flows unaffected by climatic biases (FIG. 4a).

The concentration of stable oxygen isotope ^{18}O (δ^{18}O) in ice cores and marine sediments is typically used as a paleoclimatic parameter. The observed ^{18}O concentration in sediments is a function of air temperature and, hence, information on the temperature of the environment where the sediments were accumulated can be obtained from the concentration of this isotope. The δ^{18}O measurements in Greenland ice cores give information on the temperature of the cloud from which snow precipitated onto the Greenland territory.

The interaction of cosmic rays with nuclides of the Earth's atmosphere gives rise to production of cosmogenic isotopes ^{10}Be and ^{14}C. Their radioisotope production rate depends on the cosmic ray flux at the atmosphere boundary and varies under the action of solar activity and the Earth's magnetic field. The ^{10}Be atoms are captured by aerosols in the atmosphere and are deposited on the Earth's surface in 1–2 years. Seasonal climate processes result in formation of annual glacier layers which can be regarded as dated natural archives because of the layered structure. The production of ^{14}C is followed by acidification to ^{14}CO$_2$ which enters the carbonic cycle and becomes involved in the exchange between the atmosphere, biosphere, and hydrosphere.

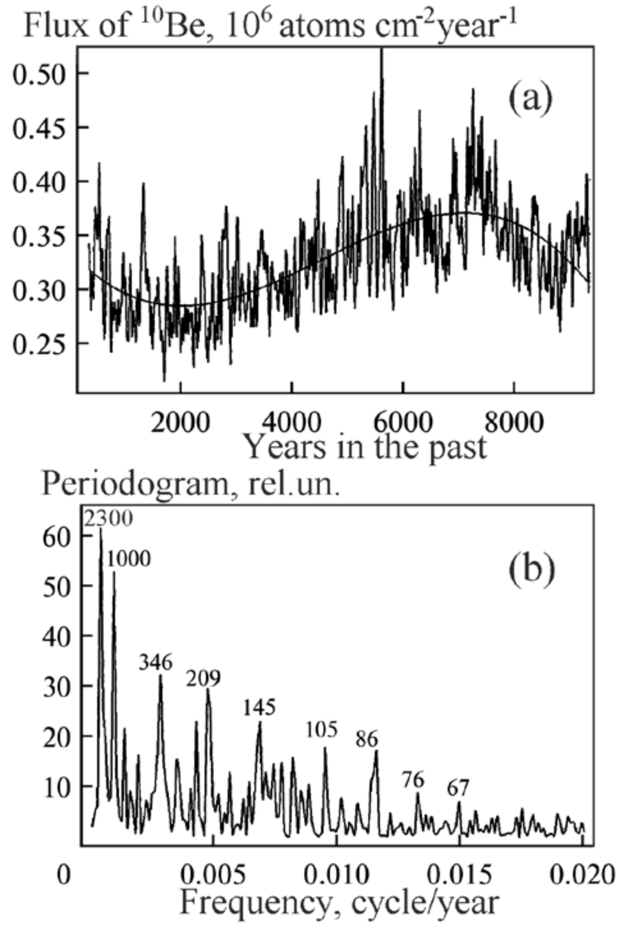

FIG. 5 DEPOSITION RATE (FLUX) OF ^{10}BE OVER 9300 YEARS, 10^6 ATOMS CM^{-2} YEAR^{-1} (VONMOOS *ET AL.*, 2006). THE SOLID CURVE SHOWS THE TREND (a). PERIODOGRAM FOR THE ^{10}BE FLUX (FIG. 5a). THE POWER IS PLOTTED ALONG THE VERTICAL AXIS IN RELATIVE UNITS. THE PERIODS (IN YEARS) ARE SHOWN FOR THE MOST SIGNIFICANT SPECTRAL LINES (b).

We analyzed detailed data on the ^{10}Be concentrations obtained from Greenland ice core samples (GRIP project) (Vonmoos *et al.*, 2006) for the last 9,000 years. FIG. 5a shows the ^{10}Be flux in 10^6 atoms cm^{-2} year^{-1}. The solid curve shows the long-term component of the flux (trend); which is apparently caused by variations in the Earth's magnetic field (Yang *et al.*, 2000; Korte and Constable, 2005). The trend was removed when the data were prepared for analysis. FIG. 5b shows the periodogram obtained on the basis of the method for analyzing data developed in (Lomb, 1976; Scargle, 1982) and later modified in (Press and Rybicky, 1989). FIG. 5a shows (by numbers) the periods of the most pronounced lines. The intense lines in the periodogram can be of a solar, geomagnetic, or climatic origin. The line with a nearly 2300-year-long period is the most intense one in FIG. 5b. This line is also present in the data on radiocarbon (Vasiliev and Dergachev, 2002). However, its origin has not been adequately explained. Note that the 2300-year periodicity in the time interval of Holocene is observed in climate changes as well. For example, Noren *et al.* (2002), when analyzing terrigenous sedimentation in-wash layers which reflect rainfall events of exceptional intensity/duration in 13 lake drainage basins in the northeastern United States, found that the frequency of storm-related floods varied in regular 2,300-2,500-year cycles during the past 13,000 years.

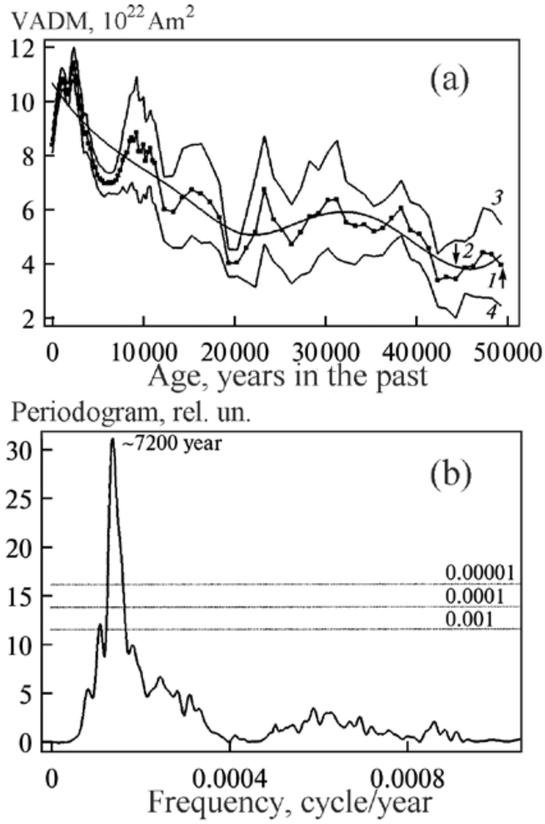

FIG. 6 (a) VADM FOR 50,000 YEARS (KNUDSEN *ET AL.*, 2008). THE SAMPLE AGE IS PLOTTED ALONG THE HORIZONTAL AXIS. THE BLACK CIRCLES SHOW THE VADM OBTAINED FROM EXPERIMENTAL DATA (CURVE 1). CURVE 2 SHOWS THE SMOOTHED VALUES, AND CURVES 3 AND 4 SHOW THE VADM ERRORS. (b) PERIODOGRAM FOR VADM (FIG. 6 a). THE FREQUENCY IS PLOTTED ALONG THE HORIZONTAL AXIS IN CYCLE/YEAR, AND THE POWER IS ALONG THE VERTICAL AXIS IN RELATIVE UNITS. THE HORIZONTAL LINES SHOW SIGNIFICANCE LEVELS.

The main features of long-term changes in the geomagnetic field can be derived from the data given in (Knudsen *et al.*, 2008). FIG. 6a shows variations in the Earth's virtual axial dipole moment (VADM) over the last 50,000 years. The dots show the VADM values obtained from experimental data; curve 2 shows the smoothed values. Curves 3 and 4 show the VADM errors estimated by Knudsen *et al.* (2008). The smoothed VADM values (curve 2) monotonously increase from the past to the present in this time interval, varying from ~4×10^{22} to ~11×10^{22} Am^2. FIG 6b shows the VADM periodogram calculated for the last 50,000 years. The curve with a period of about 7,200 years is seen to dominate in the periodogram.

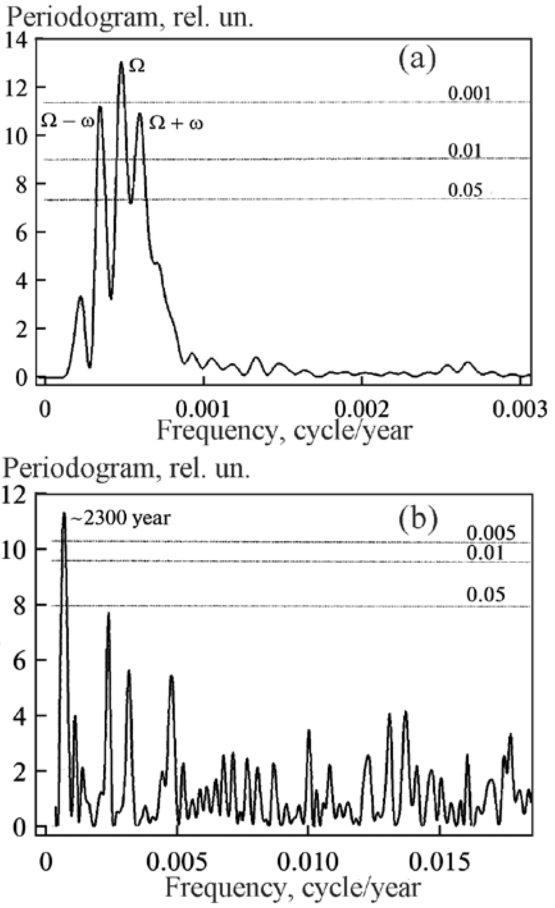

FIG. 7 (a) PERIODOGRAM OF VADM FOR THE MOST THOROUGHLY STUDIED INTERVAL OF 12,000 YEARS. THE FREQUENCY IS PLOTTED ALONG THE HORIZONTAL AXIS IN CYCLE/YEAR, AND THE POWER IS DEPICTED ALONG THE VERTICAL AXIS IN RELATIVE UNITS. THE HORIZONTAL LINES SHOW SIGNIFICANCE. (b) ANALYSIS OF DATA ON THE GEOMAGNETIC POLE POSITION FOR 8,000 YEARS (KOVACHEVA, 1997). A PERIODOGRAM OF LONGITUDINAL VARIATIONS IS PRESENTED.

Fig. 7a shows a periodogram of VADM for a time interval of 0–12 thousand years in the past. The periodogram has a triplet of lines designated by Ω, $\Omega - \omega$, and $\Omega + \omega$. The main line (frequency Ω) is an analog of the most intense line in FIG. 7b with a period of about 2,300 years. The periodicity in the VADM data points to the probability of geomagnetic field variations with periods of about 2,300 years.

Different models are used to describe the Earth's magnetic field, e.g., (Merrill *et al.*, 1996). The declination and inclination in the dipole model allow one to find the positions of the virtual geomagnetic pole (VGP). Detailed data on the geomagnetic field for 8,000 years were given in (Kovacheva, 1997); they contain information on the virtual geomagnetic pole and virtual dipole moment (VDM). The periodogram we obtained from these data shows that a nearly 2,300-year-long cycle is present in the data on the VGP, but absent in the data on the geomagnetic field strength (FIG. 6b).

FIG. 7b shows that the geomagnetic pole longitude varied cyclically during the last 8,000 years with a fundamental period of about 2,200–2,300 years. The line splitting and triplet formation can be explained by a low-frequency modulation with a period of about 7,200 years (FIG. 6b) of the geomagnetic dipole moment.

Cycles with the periods coinciding in the limits of an error and equal to about 2,300 years have been revealed in the data on the ^{10}Be deposition rate and VGP. Bakhmutov (2006) reconstructed the VGP positions for the last 13,000 years by using the palaeomagnetic data for lacustrine sediments in the northwest of Russia (mainly from Karelia and the Kola Peninsula) and archaeomagnetic data from Ukraine. The comparison of these palaeomagnetic data with those for north–northeastern Europe (Bakhmutov, 2006) has shown that the alternation of cold and warm periods can be due to the VGP wandering. Hence, the magnetic field can affect the climate through variations in the geomagnetic pole position, which can cause a change in the density of condensation centers formed due to the atmosphere ionization by cosmic rays (Usoskin *et al.,* 2008; Kovaltsov and Usoskin, 2007).

Analysis of direct and proxy data on variations in galactic cosmic rays (^{14}C in tree rings and ^{10}Be in ice cores), solar activity, geomagnetic dipole moment, and climate change δ^{18}O in ice cores) in the Holocene Epoch was carried out by Dergachev *et al.,* (2006). The cross-correlation analysis between these data has led to the conclusion that a change in δ^{18}O in ice cores reflects the main features of the effect of cosmic rays, the geomagnetic dipole moment, and long-term variations in solar activity on climate for the Holocene. Spectral analysis of the δ^{18}O series has shown a stable spectral power at frequencies close to those observed in the variations in the ^{14}C and ^{10}Be concentrations, i.e., in the galactic cosmic ray intensity changes.

Conclusions

The problem of climate change over the past hundred years raises the question of the possibility of interaction between the climate and the geomagnetic field on time scales of decades to hundreds of years or longer. Correlation analysis of palaeodata on variations in cosmic ray fluxes, geomagnetic field, and climate has shown that these data have been interrelated on the time scales of several thousand and ten thousand years. Analysis of data on changes in the Earth's magnetic moment over the past ~10,000 years and the proxy data on precipitation at low latitudes has shown that the time changes in the geomagnetic dipole moment can play an important role in controlling rainfall at low latitudes in some regions of the Earth. Through these processes, the geomagnetic field in the Earth's atmosphere could thus affect climate change in the Earth's past. Of course, not all aspects of this complex problem are understood now and further investigations are needed.

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