ISSN 0016-7932, Geomagnetism and Aeronomy, 2012, Vol. 52, No. 8, pp. 959–976. © Pleiades Publishing, Ltd., 2012.

Impact of the Geomagnetic Field and Solar Radiation on Climate Change

V. A. Dergachev[a], **S. S. Vasiliev**[a], **O. M. Raspopov**[b], **and H. Jungner**[c]
[a] *Ioffe Physical–Technical Institute, Russian Academy of Sciences, St. Petersburg*
e-mail: v.dergachev@mail.ioffe.ru
[b] *Pushkov Institute of Terrestrial Magnetism, Ionosphere, and Radiowave Propagation, Russian Academy of Sciences, St. Petersburg*
[c] *University of Helsinki, Finland*

Received March 3, 2012

Abstract—Recent studies have shown that, in addition to the role of solar variability, past climate changes may have been connected with variations in the Earth's magnetic field elements at various timescales. An analysis of variations in geomagnetic field elements, such as field intensity, reversals, and excursions, allowed us to establish a link between climate changes at various timescales over the last millennia. Of particular interest are sharp changes in the geomagnetic field intensity and short reversals of the magnetic poles (excursions). The beginning and termination of the examined geomagnetic excursions can be attributed to periods of climate change. In this study, we analyzed the possible link between short-term geomagnetic variability (jerks) and climate change, as well as the accelerated drift of the north magnetic pole and surface temperature variations.

The results do not rule out the possibility that geomagnetic field variations which modulate the cosmic ray flux could have played a major role in climate change in addition to previously induced by solar radiation.

DOI: 10.1134/S0016793212080063

1. INTRODUCTION

Concern over current global warming has received a great deal of attention from both the public and scientific communities. One reason for this may be the dramatic potential of global warming as a social problem. On the other hand, we need a better understanding of the mechanisms of global warming. Therefore, one of the most important issues in climate research is to distinguish natural causes of climate change from anthropogenic effects. The development of a climate theory is a very complex problem of physics since its general solution (calculating the function of climate) is related to the chaos theory and is not achievable yet. The key climate variables are temperature (as a major climate control element) and precipitation (far more complex than temperature). Thermometer measurements, which have only been conducted for the past ~150 years, indicate a clear warming trend for much of the time.

Recent reconstructions of global climate change based on a variety of natural proxy records, such as tree rings, ice cores, and speleothems over timescales from decades to millennia clearly indicate that natural processes are the main drivers of global climate change (e.g., (Dergachev, 1996)).

The natural factors that can shape climate include processes, such as variations in sunspot activity and global climate in response to glacial cycles, which are in turn caused by changes in the global distribution of solar radiation and changes in the Earth's orbit around the Sun.

However, the global variations in temperature from 1950 onwards cannot be explained by natural factors (solar activity (SA), variations in the Earth's orbital geometry and axial tilt, ocean–atmosphere interactions, volcanic activity, and cosmic rays) or human-induced changes. The Earth's climate has varied continuously in the past, but the causes of these variations are still not fully understood (even on centennial timescales); hence, no factor can be neglected at present.

Understanding the mechanisms and history of climate variability is of particular importance for improving predictions of climate change. All predictions of anthropogenic global warming are based on assumptions, which are almost entirely hypothetical with little or no evidence to support them. Paradoxically, there is no scientific evidence whatsoever that global warming is caused by human activities.

Some previous studies ((Vasiliev et al., 2004) and others) considered the impacts of multiscale solar activity on climate. In recent years, one of the most favored theories proposes a mechanism of indirect solar forcing of climate by galactic cosmic rays (GCRs), which continually bombard the atmosphere (e.g., (Scherer et al., 2006)) and provide a source of ionizing radiation of the lower atmosphere near the Earth's surface. Although variations in total solar irradiance and cosmic rays are closely related, the intensity of GCRs is also dependent on other factors, such as the Earth's magnetic field (EMF).

The possible connection between secular variations in the Earth's magnetic field and climate change has received much attention in a number of studies (e.g., (Petrova and Raspopov, 1998)). It is interesting to note that instrumental measurements have revealed that the intensity of the EMF varies with abrupt shifts in the position of the magnetic poles. This places a particular emphasis on understanding short- and long-term variations in the EMF and their possible effects on climate change.

In this study, we analyze data on the effects of solar and geomagnetic activity on climate variables. We use high-resolution records for the correlation between geomagnetic field changes, variations in the cosmic ray flux and global temperature at various timescales.

2. CLIMATE VARIATIONS OVER TIME AND INFLUENCE OF SOLAR VARIABILITY ON CLIMATE

Climate varies naturally on all timescales from decades to millions of years. Several rapid climate transitions occurred in the past. There are two large phases of climate oscillations—glacial and interglacial—which are recognized on longer timescales. These large-scale transitions are characterized by climate instability, and the mechanisms behind all past climate transitions are not completely understood. Climatic variability on timescale of decades to centuries or millions of years, as well as global glacial–interglacial climate oscillations, are defined by a strictly nonlinear relationship between changes in the amount of incoming solar radiation, its absorption by the atmosphere and oceans and ice sheet growth. On longer timescales, the evolution of the climate system is governed by the large-scale nonlinear dynamics of interactions between all climatic subsystems and external forcings.

Several glacial periods, when extensive ice sheets permanently covered landmasses in polar and midlatitude regions, are reliably recognized in the Earth's climate history. New data on the trends and climate variability provide further evidence that climate change may be due to natural causes. The amount of solar irradiance in response to changes in the Earth's orbit is a prime forcing factor responsible for much longer (decades and up to centuries and millennia) climate variability. The orbital theory has been successful in explaining global climate changes (at least over the past million years) by variations in global insolation due to changes in the shape (or eccentricity), axial tilt, and precession of the Earth's orbit. It should be noted that the calculated insolation values change gradually over long periods of time, but they may take the Earth's climate to a breaking point at which other factors or mechanisms will begin to amplify any change into a sudden climate transition. Although changes in orbital parameters have little impact on the total amount of solar radiation received by the Earth, they do alter the amount of seasonal radiation at different latitudes. In this respect, the amount of solar radiation received on the continents at northern latitudes is critical, as this determines whether snow and ice can persist through the following summer months.

Studies of deep ocean cores indicate that the duration of glacials (glacier advance) and interglacials (glacier retreat) over the last million years have been about 100 (Budyko, 1980) and 10 kyr, respectively. The last glacial period of the Quaternary ended about 10 ka. Recent data suggest that the present interglacial (the Holocene) lasting for more than 10 kyr will end soon and that the Earth may be entering a new ice age.

Ice cores, for example, are used in detailed temperature reconstructions over longer timescales. The most widely used proxies from ice core layers include stable oxygen isotopes in air and water, gases, and dust and dissolved matter, as well as physical properties of ice layers, such as ice thickness, etc. The relative isotope concentration of the condensate produced by the evaporation of water and subsequent condensation on ice caps can be used as a proxy for temperature during condensation. An analysis of data suggests that the beginning of a warmer or cooler period is forced by regular variations in the Earth's orbital parameters (eccentricity, obliquity, or the tilting of the Earth's axis and precession with periods of ~100 000, 40 000, and 23 000/19 000 years, respectively), which modify the amount of solar radiation received from the Sun over a range of timescales.

Detailed climate records from the Greenland and Antarctic ice cores and deep ocean cores provided evidence for several glacial events during the Earth's history. Climate oscillations have been recurring at an approximately 100 000-year-long quasi-periodicity for the last few hundred thousand years as long-term cold and short-term warm alternations.

Until now, ice core data have only been available for the past 420 kyr, with the longest records of atmospheric parameters coming from Vostok in Antarctica (Petit et al., 1999), whereas new data provide the longest record to date going back 800 kyr (Jouzel et al., 2007) (Fig. 1). For the four most recent glacial cycles (400 kyr), these data agree well with the records from Vostok.

Figure 1 shows a comparison of Antarctic ice core temperature profiles with yearly solar inputs at 65°N over the past 800 kyr. As can be seen, the 23–19 kyr period has large solar oscillations due to precession. Variations in obliquity with a period of about 41 kyr change the amplitude of oscillations, whereas changing eccentricity acting as an amplitude envelope with a period of about 100 kyr overlap these oscillations. In most cases, time periods with higher amplitudes of oscillations in the solar input seem to produce inter-

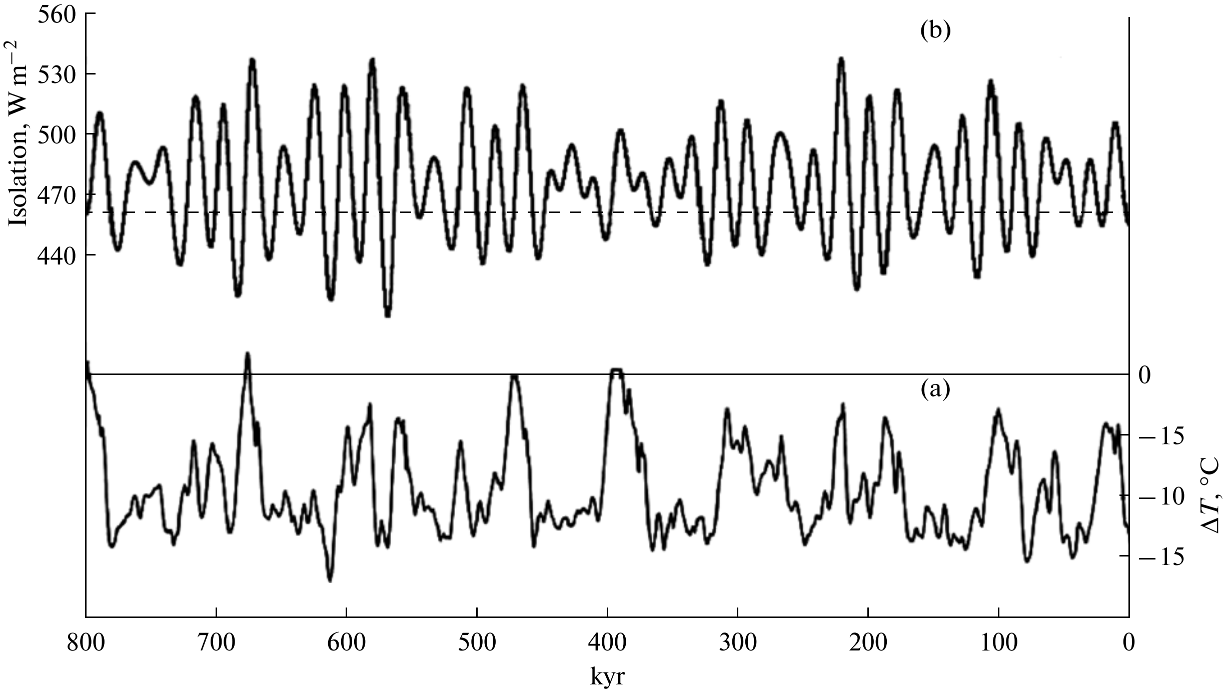


Fig. 1. Comparisons of (a) reconstructed temperature variability from EPICA Dome C ice cores over the past 800 kyr (Lüthi et al., 2008) and (b) calculated 65° N isolation (Laskar et al. 2004).

glacials, whereas periods with lower amplitudes tend to produce ice ages.

The last glacial period began at ~110 ka, reaching its maximum at about 20 ka, and was followed by rapid deglaciation or decay of ice sheets. Huge ice sheets covered most of North America and Scandinavia, northern Europe and East European plain, mountainous regions of South America and Australia, as well as the Alps and Himalaya. It should be noted that during the Holocene or under the current interglacial conditions (past ~10 kyr), climate has had a tendency towards remaining more stable and warmer than in the period before and after the last glacial.

After the retreat of the continental ice sheets, climate recovered for a long period of time and conditions became generally warmer than those of today (Fig. 2). Figure 2 shows the variability in solar intensity during the summer months at 65°N. The basic shifts in climate during the Holocene include the Holocene Climate Optimum, the Little Ice Age, and the Medieval Warm Period.

On shorter timescales ranging from decades to centuries, the natural forcing mechanisms responsible for climate change can be attributed to a number of other factors, such as solar variability or total solar irradiance, cosmic rays, geomagnetic field excursions, internal variability in the system the coupled atmosphere–ocean–ice, nonlinear feedbacks in the climate system, as well as volcanism. A number of forcing factors contribute to climate change, and it is difficult to isolate the contribution of each forcing.

Tree rings provide valuable data to track the natural variability in climate using high-resolution proxy climate records because they accurately portray multidecadal timescale changes. Such tree ring chronologies are provided by conifer and broadleaf species. Dendrochronology, i.e., the study of the annual growth increment in trees, is the only method of paleoenvironmental research that produces consistent proxy data with an annual resolution. When applied correctly, this method allows for the building of a continuous timescale covering the last few millennia (Dendrochronology and Dendroclimatology, 1986).

The unified dendrochronological timescale covers the period from 10 cal kyr BP. Another dating technique, which has proven to be successful, is radiocarbon dating. The results show (Dergachev and Veksler, 1991) that radiocarbon dates can be used as a reference to calibrate the age offset between dendrochronology and absolute ages and to obtain more accurate dates from peat bog and lake deposits.

The Sun is a prime source of energy for the Earth and its atmosphere. Because the amount of energy emitted from the Sun is the main heat input to the atmosphere, changing the levels of solar irradiance should affect the Earth's climate. The following mechanisms are thought to link changes in the Sun with climate: (a) changes in solar irradiance leading to changes in the heat input to the lower atmosphere; (b) solar UV radiation coupled with changes in the ozone concentration heating the stratosphere, which inter-

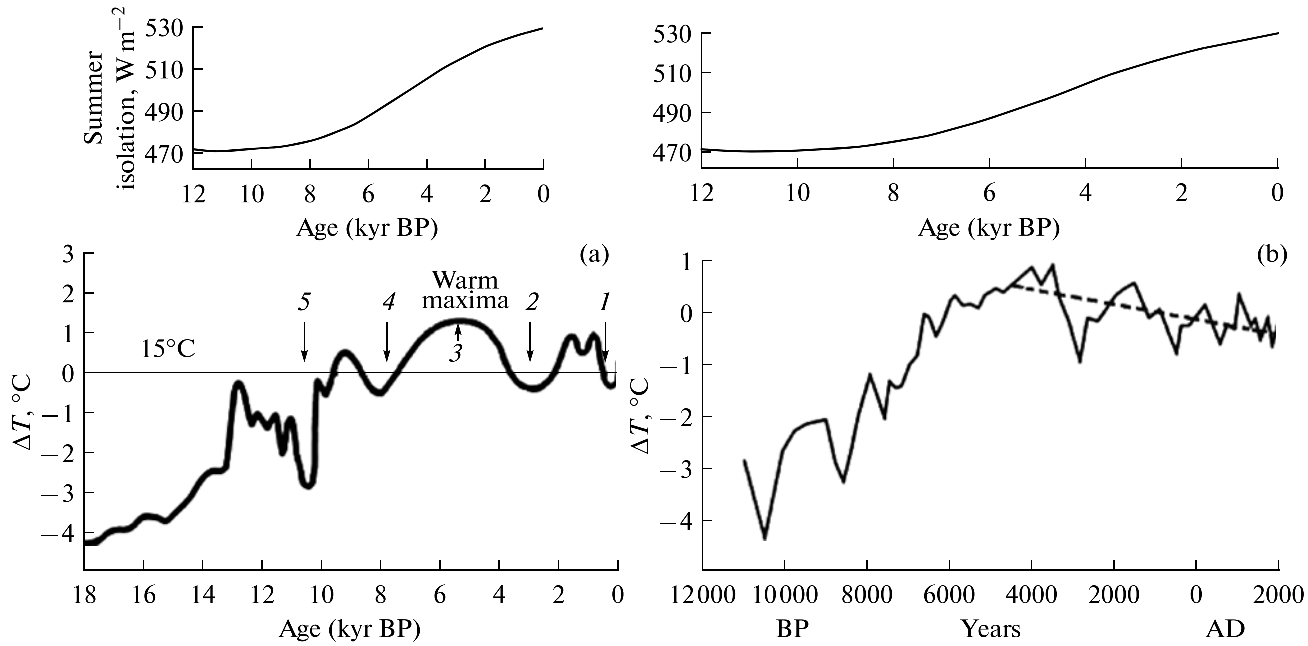


Fig. 2. Temperature variations against mean values from various paleodata: (a) (Dansgaard et al., 1969) (arrows *1*, *2*, *4*, and *5* indicate cooling and arrow *3* indicates warming cycles) and (b) (Energy, Nature, and Climate, 1997) (the dashed line corresponds to a cooling trend over the last 6.5 kyr. The upper panels show the calculated variations in 65° N summer insolation.

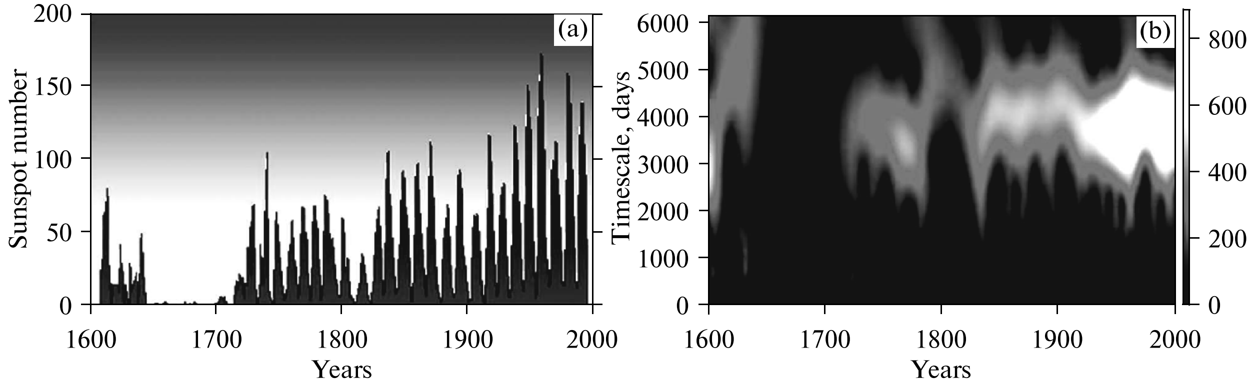


Fig. 3. (a) Time variations in the sunspot number (1610—1995) and (b) wavelet scalogram of the group sunspot number derived from instrumental measurements.

acts with the troposphere and lower atmosphere; and (c) GCRs modulated by solar activity.

Observational records of sunspots date back to 1610 (since Galileo's discovery) (Fig. 3a), but systematic observations had only begun by the 19th century. A wavelet analysis of the sunspot number (Fig. 3b) clearly shows the Maunder Minimum in 1645—1715 of extremely low solar activity and a very high level of solar activity after 1940. It should be noted that the 20th century is a period of unusually high solar activity, which is possibly unique for the past 400 years.

The cosmic ray flux into the atmosphere is another indicator of solar variability. Cosmogenic nuclides produced by cosmic rays (e.g., ^{14}C and ^{10}Be) can be stored in natural archives (tree rings, ice layers), which provide the absolute timescale. The most detailed radiocarbon data were obtained for the last 10 kyr. A spectral analysis of tree ring ^{14}C isotope records over this time period (Dergachev and Raspopov, 2000) indicates that the main periodicity in the solar cycle is ~210. There is therefore no doubt that variations in the atmospheric ^{14}C concentration in the past have differential time-varying impacts on solar activity and other natural forces on longer absolute timescales (e.g., (Dergachev, 2009)).

IPCC scenarios (e.g., IPCC, 2007) predict a significant increase in carbon dioxide, which will in turn cause an increase in temperature in this century as a

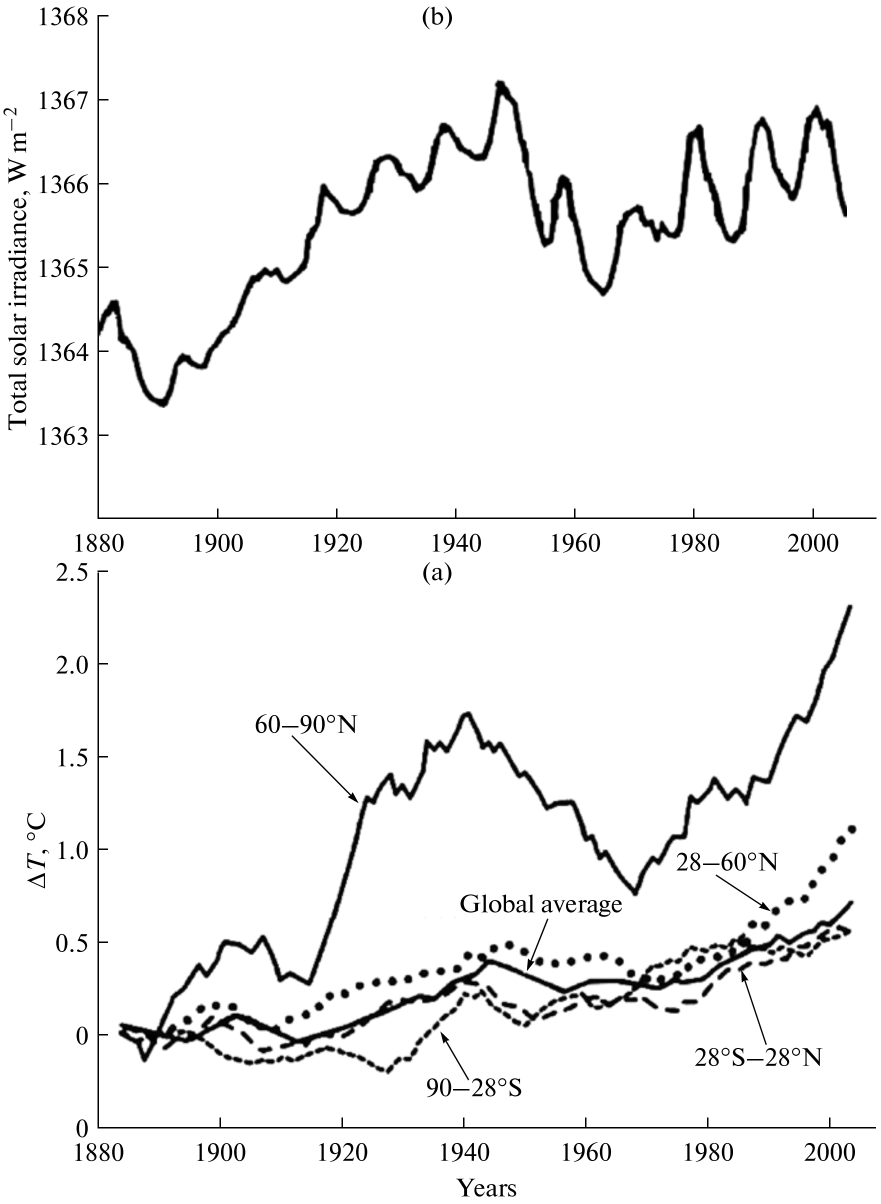


Fig. 4. (a) Observed temperatures over the indicated latitudes relative to 1880–1890 averaged by a running mean over a 4-year period (Shindell and Faluvegi, 2009) as compared to (b) variations in total solar irradiance (Hoyt and Schatten, 1993; Scafetta, 2009).

result of anthropogenic gas emissions. This may amplify the warming process in the Northern Hemisphere by the end of the 20th century. In this connection, we analyze the evolution of temperature reconstructed from instrumental data (Fig. 4).

As seen from Fig. 4a, the surface temperature increases from global warming over the past ~120 years should be particularly pronounced at northern high latitudes and less pronounced in the tropics and the least warming is observed at southern latitudes. An increase in temperature dates back to 1890 and continues until ~1940, followed by a slight drop in temperature from ~1940 to ~1978 and subsequent warming after ~1978.

A comparison of these temperature profiles with solar variability (Fig. 4b) suggests a strong correlation between solar activity and temperature (in particular, until ~1980). Based on the results of Krivova and Solanki (2008), the solar contribution became insignificant from 1980 which was possibly due to uncertainties related to the illumination of satellite solar irradiation sensors.

Therefore, analyses of both historical instrumental data on solar variability and global surface temperature records provide compelling evidence for connections

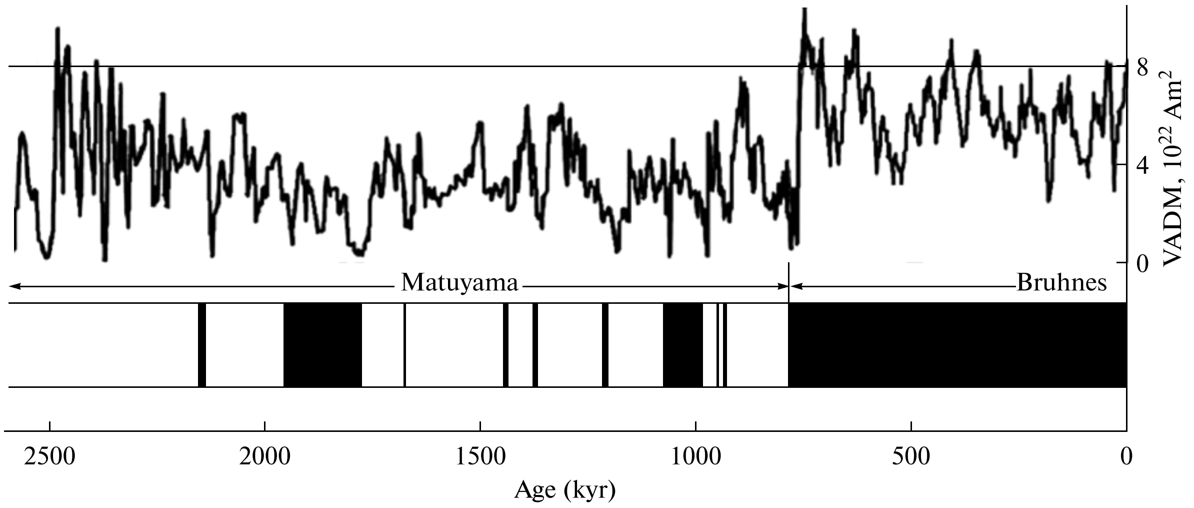


Fig. 5. Variations in the geomagnetic dipole moment over the past 2.5 Myr derived from oceanic relative paleointensity data (Valet et al., 2005). The normal (Brunhes) and reversed (Matuyama) polarity chrons are depicted by black/white bars, respectively. The present-day dipole moment is depicted by a solid line.

between natural processes on decadal, centennial, millennial, and multimillennial timescales.

Note that in addition to the direct solar effect, a number of indirect effects of solar activity are associated with time-varying cosmic rays—a continuous stream of particles bombarding the lower atmosphere and contributing to the atmospheric ionization level. Changes in the cosmic ray flux are modulated by geomagnetism. Therefore, variations in the geometry and strength of the geomagnetic field should in turn modify the solar impact on climate.

It should be noted that instrumental data have revealed that the strength of the magnetic field has varied significantly and the magnetic poles have abruptly changed their position over recent decades.

3. TIME VARIATIONS IN THE GEOMAGNETIC FIELD

According to modern understanding, 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 create a dynamo effect which sustains a system known as the Earth's magnetic field. The magnetic field exhibits complex spatiotemporal variations. The state of the magnetic field and time variations in the field's intensity provide important information on the processes in the coupled Sun–Earth system.

The most important information on geomagnetic field intensity variations were derived from instrumental and archeomagnetic data on timescales limited to the past 10–12 kyr. A record of changes in elements of the Earth's magnetic field is provided by the remanent magnetization of rocks. A paleomagnetic method can be used to extract the ancient remanent magnetization of rocks and to restore the present field direction and its variations over time. Continuous sedimentary sections provide a long record of magnetic field variations. A sediment-derived paleointensity record can be coupled with archeomagnetic data. Paleomagnetic data are used to reconstruct the history of the Earth's magnetic field over the past few million years. Recent measurements of the geomagnetic field intensity on longer timescales have shown 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 suggests numerous total reversals of the Earth's magnetic field such that the positions of the magnetic north and south (dipole) were interchanged. Long periods during which the magnetic field remains oriented in one direction are called chrons. (The nomenclature of magnetic polarity timescales includes epochs and events, superchrons and chrons, and subchrons and cryptochrons.) It should be noted that during a reversal the magnetic field does not disappear: it develops several poles at different locations and has a complex nondipole nature.

Let us consider some of the most important characteristics of the Earth's magnetic field. The plot in Fig. 5 shows the Earth's virtual axial dipole moment (VADM) for the last two million years (Valet et al., 2005; Dyachenko, 2003) for normal (Brunhes) and reversed (Matuyama) polarity periods. The last reversal occurred around 780 ka. This reconstruction is in good agreement with the absolute dipole moments derived from volcanic lavas, which were used for calibration.

Note that the time-averaged field intensity in the Brunhes chron, i.e., during periods without reversals, was higher than that during the Matuyama chron.

In the last 5 million years, the magnetic field has reversed it polarity roughly 20 times (Dyachenko, 2003). As can be seen in Fig. 5, the last reversal occurred around 780 ka, which preceded the current much longer period of normal polarity. Over the past 100 Myr, reversals have occurred with a remarkable irregularity: the time between them varied considerably from tens of thousands to millions of years. The normal-polarity epoch (Brunhes chron), which occurred at about 780 ka and still continues to the present day (Fig. 5), was preceded (from younger to older) by the following polarity epochs: Matuyama (mostly reversed), Gauss (mostly normal), and Gilbert (mostly reversed), etc. Shorter polarity intervals that occurred within the above epochs are called events or subchrons. For example, within the Matuyama chron, the Jaramillo, Olduvai, and reunion subchrons are clearly recognized.

Note that full polarity reversals have not been identified in the Brunhes epoch, although a number of short (on a millennial timescale) paleomagnetic excursions (or a flip of the poles towards southern latitudes) with short-lived episodes of variations in the geomagnetic field's characteristics have been recorded. For example, geomagnetic excursions during the Brunhes epoch include the Laschamp (~45 ka), Mono Lake (~29 ka), and Gothenburg (~12 ka) events (Petrova et al., 1992; Pospelova, 2000). During the latest Sterno–Etrussia geomagnetic excursion, which occurred at about 2.8 ka, the magnetic pole traveled during 100–200 years to the Southern Hemisphere and returned back along approximately the Greenwich meridian, and the intensity of the geomagnetic field decreased by a factor of 1.5 (Raspopov et al., 2003).

Our understanding of the evolution of the geomagnetic field and the recent advances in the theory of geomagnetism are built upon a common geomagnetic polarity timescale, which was derived by stacking many different records obtained by a number of methods and for a variety of timescales. Ground-based geomagnetic observatories perform continuous monitoring and registration of geomagnetic field components. Both direct and archeomagnetic measurements are used to derive components of the Earth's magnetic field, which include the following: (a) the main component of the Earth's magnetic field, which is slowly changing (secular variations) on timescales that range from 10 to 10000 years with periods of 10–20, 60–100, 600–1200, and 8000 years; (b) global magnetic anomalies with the foci located in Canada and Eastern Siberia in the Northern Hemisphere and in Brazil and Antarctica in the Southern Hemisphere (anomalies, the intensity of which is 20% of the intensity of the dipole field, occupying an area of up to 10000 km) ; (c) local magnetic fields generated by crustal magnetization from local rocks (e.g., the Kursk Magnetic Anomaly), which extend from a few kilometers to hundreds of kilometers; and (d) alternating (external) magnetic fields produced by electric fields external to the Earth's surface and atmosphere. For periods shorter than epochs, the Earth's magnetic field should be considered as the main magnetic field with a superimposed alternating magnetic field, the intensity of which is by several orders of magnitude lower than that of the main field. Field variations observed at the Earth's surface are influenced by processes operating in the crust and outer core.

The Earth's magnetic field varies over an extraordinary large range of timescales. Changes on a timescale from decades to millennia are called secular variations. These are closely linked 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 forced by the solar wind. The intensity of such variations depends on the latitude, season, time of the day, and solar wind parameters.

The schematic representation in Fig. 6a describes the major contributing sources of the Earth's magnetic field (Constable and Johnson, 2005). The contribution of each source to magnetic field variations can be estimated as a function of frequencies. This can be done by estimating the spectrum of geomagnetic variations. Power spectral density $S(f)$ is a measure of the power in geomagnetic field variations at frequency f. The power spectral estimation as a function of frequency has been previously discussed (see (Constable and Johnson, 2005)) (Fig. 6b).

Figure 7 shows a detailed reconstruction of the evolution of the geomagnetic dipole moment over the past 800 kyr (Valet et al., 2005; Guodo and Valet, 1999). Geomagnetic excursions during the Brunhes chron are shown by arrows (Fig. 7a). The horizontal dashed line corresponds to the critical value of intensity below which directional excursions were observed (Langereis et al., 1997).

Instrumental data from 1831 provide observations of sharp changes in secular variations of the field intensity coupled with sudden curvature changes in the direction (in the second derivative of the field with respect to time) over very short timescales ranging from a few months to a few years, which are separated by periods of nearly constant geomagnetic secular acceleration. This feature was first described by Courtillot (1978) as an impulse occurred around 1969. Subsequently, this feature was proved to be of global, although latitude-dependent, character based on similar observations in different parts of the world.

Sharp changes in the field's secular variations have been called "geomagnetic jerks" (Newit et al., 2002; Dormy and Mandea, 2003). The causes of these magnetic changes are not completely understood, but they are thought to be controlled by variations in the outer core. Three jerks are clearly observed globally in the

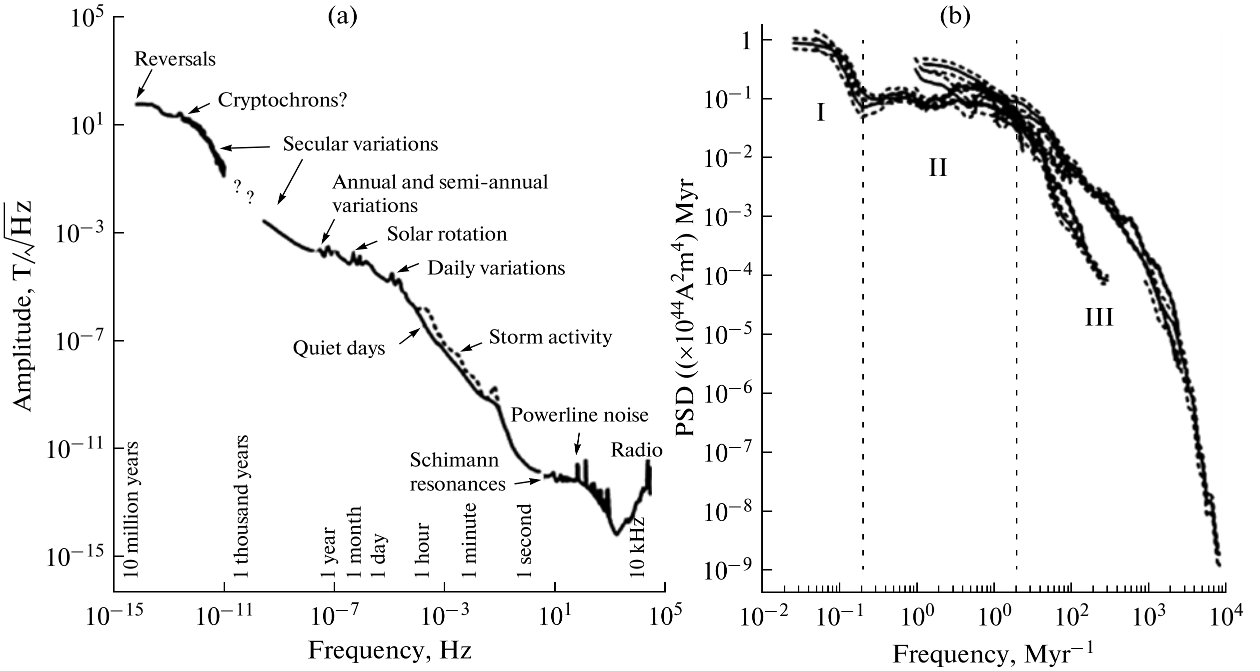


Fig. 6. (a) Composite amplitude spectrum of geomagnetic variations as a function of frequency: the annotations indicate the predominant physical processes at various timescales; (b) composite spectrum for the geomagnetic dipole moment constructed from various data: I, magnetostratigraphic reversal records with and without cryptochrons (frequencies from 10^{-2} to 20 Myr^{-1}), II, various sedimentary records of relative paleointensity (10^0 to 10^3 Myr^{-1}); III, from dipole moments of a 0–7 ka paleomagnetic field model (10^3 to 10^4 Myr^{-1}). The figure is reconstructed based on (Constable and Johnson, 2005).

second half of the 20th century (in 1969, 1972, and 1992).

The global network of magnetic observatories is too sparse to provide a continuous recording of geomagnetic field variations. Olsen and Mandea (2007) developed an approach, which has been used to extract monthly mean values from satellite data collected at a height of 400 km. This approach allowed the authors to detect a geomagnetic jerk in the first months of 2003. This jerk is clearly observed from ground-based observations. Although this jerk is clearly recognized from satellite data in the hemispheres, it is not a global phenomenon. 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.

Well-dated archeological material can be used for the reconstruction of geomagnetic secular variations, and these data can be further compared with a reference secular variation curve to allow for the dating of material of unknown age. The results collected over numerous well-dated archeological sites were used to generate a reference curve for Western Europe spanning the last 2100 years (Thellier, 1981), being extended to the past three millennia (Gallet et al., 2002).

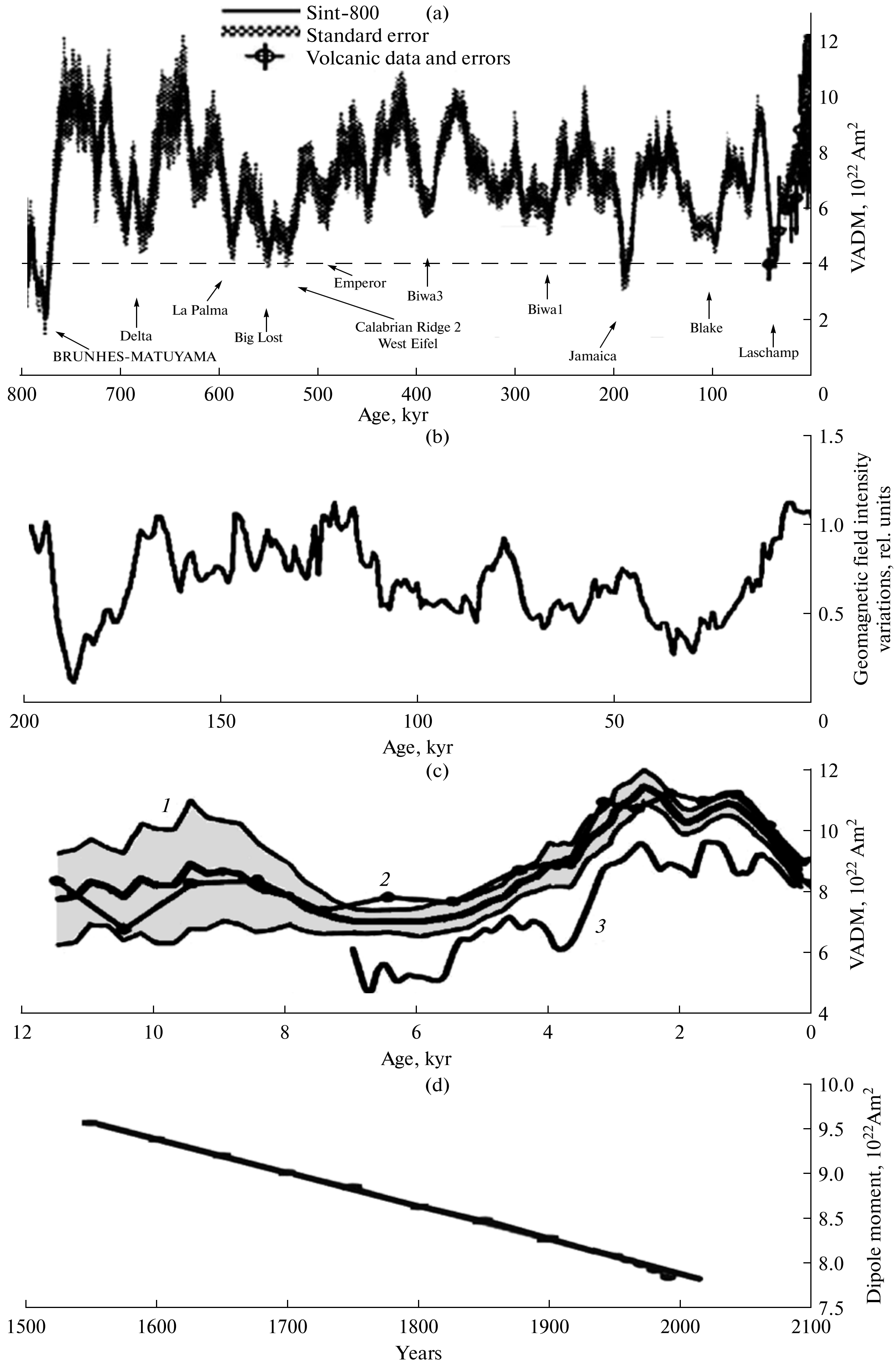
The geomagnetic secular variation curve for the last 3 millennia using data from Western Europe exhibits larger variations in the archeomagnetic direction with declination of ~50° and inclination of 15–20°, whereas the intensity shows an overall decrease with several minor peaks.

In addition to geomagnetic jerks, archeomagnetic jerks were also recorded on decadal—centennial timescales. An analysis of the archeomagnetic timescale over the past two millennia indicates that the appearance of archeomagnetic jerks can be correlated with events at ~1600, 1400, 800, 600, and 200 AD and around 350 BC.

Recent lake sediment paleomagnetic data (declination and inclination) from Korea, China, and Japan for the past three millennia (Yu et al., 2011) also

→

Fig. 7. (a) Variations in the virtual axial diploe moment obtained from a stack of 33 records of paleointensity in sedimentary rocks (SINT 800) (Valet et al., 2005; Guyodo and Valet, 1999) calibrated over the past 40 kyr using volcanic paleointensity data with standard errors and reversals (indicated by arrows). (b) Variations in the relative field intensity over the past 200 kyr reconstructed from ^{10}Be production variations in marine sediments (Frank et al, 1997). (c) Reconstructions of the geomagnetic dipole moment from archeomagnetic records by (1) Knudsen et al. (2008), (2) Yang et al. (2000), and (3) Korte and Constable (2005) (the shaded area is the 2σ uncertainty associated with the dipole moments (Knudsen et al., 2008)). The VADM (thick solid line) was determined as time windows of 500 yr back to 4000 BP and 1000 yr in the preceding period.


(a)
Sint-800
Standard error
Volcanic data and errors
VADM, 10^{22} Am^2
12
10
8
6
4
2
BRUNHES-MATUYAMA
Delta
La Palma
Big Lost
Emperor
Calabrian Ridge 2
West Eifel
Biwa3
Biwa1
Jamaica
Blake
Laschamp
800
700
600
500
400
300
200
100
0
Age, kyr
(b)
Geomagnetic field intensity variations, rel. units
1.5
1.0
0.5
200
150
100
50
0
Age, kyr
(c)
1
2
3
VADM, 10^{22} Am^2
12
10
8
6
4
12
10
8
6
4
2
0
Age, kyr
(d)
Dipole moment, 10^{22}Am^2
10.0
9.5
9.0
8.5
8.0
7.5
1500
1600
1700
1800
1900
2000
2100
Years

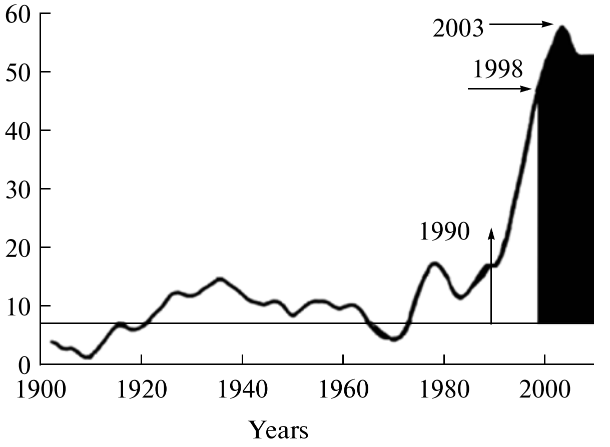


Fig. 8. Graph showing the drift of the north magnetic pole (Olsen and Mandea, 2007).

clearly indicate the occurrence of jerks, which coincide with those previously observed in Europe. The good correspondence between the jerk times gives way to debate regarding their global vs. regional nature. The results of previous studies show that archeomagnetic jerks correspond to episodes of a maximum geomagnetic field hemispheric asymmetry, which could explain some features of long-term geomagnetic field variations.

Detailed instrumental observations show that the geomagnetic field has varied significantly over the past 150 years. The field intensity has decreased, and the drift of magnetic poles has generally accelerated (Olson and Amit, 2006). Changes in the Earth's magnetic field also affect the transfer rate of solar wind energy to the Earth's atmosphere, whereas the movement of the poles changes the geographic distribution of galactic and cosmic rays, which interact with the atmosphere. Moreover, changes in the geomagnetic shielding of the GCR flux, resulting from changes in the Earth's dipole moment, is maximum at low latitudes and disappears at higher latitudes.

The movement of the magnetic poles has been observed since 1885. The data indicates that the north magnetic pole has been migrating towards the East Siberian Magnetic Anomaly across the Arctic Ocean at an accelerated rate, and the south magnetic pole has drifted some 900 km during the last 100 years and is presently located in the Indian Ocean.

Figure 8 shows the movement of the north geomagnetic pole. As can be seen, the rate of pole drift had increased almost fivefold by the late 1990s as compared to 1980. This fact may point to a substantial change in the dynamical processes in the core, which form the geomagnetic field. This may also be an obvious sign of the beginning of another cycle of surge in the Earth's endogenous activity. From 1980 to present, the rate of the north magnetic pole drift has increased by 500%. This might indicate the beginning of an increase in the Earth's geodynamic activity, since the Earth's magnetic field is generated as a result of complex energy processes in its inner and outer cores. According to a forecast by Olsen and Mandea (2007), the north magnetic pole will be the closest to the north geographic pole (~400 km) in 2018 and will continue to move towards Siberia.

This sudden acceleration of the magnetic pole drift from 1990 may become a significant driving force of changes in not only climate but also in the overall behavior of the Earth's inner and outer cores, which, as has already been mentioned, are responsible for generating the Earth's magnetic field. A synchronous decrease in the intensity of the magnetic field is also observed. Archeomagnetic data indicate that the field intensity has been decreasing over the past two millennia and a strong intensity decrease has been observed in the last centuries (Fig. 7d). Over the past 22 years, the field intensity has on average decreased by 1.7 and 10% in some regions (e.g., in the South Atlantic). However, in other regions, the field intensity has increased contrary to the observed trend. If the present-day intensity decrease and the motion of the poles continue at the same rate, this could lead to a polarity reversal in the near future.

4. CORRELATIONS BETWEEN MAGNETISM AND CLIMATE

Large volumes of data that are currently available provide evidence for long-term climatic changes through the Earth's geologic history. It should be noted that the temporal resolution of many natural archives of past climate conditions decreases sharply back in time, making it perilous to build on theories that explain climate change over long timescales.

Geomagnetic variations, which are observed on longer timescales, modulate the intensity of the cosmic ray flux. Since changes in the Earth's orbital parameters have a direct impact on geodynamo processes, this should primarily force variations in the geomagnetic field. Therefore, a comprehensive analysis of the potential connections between changes in orbital parameters, the cosmic ray flux, and climate on a variety of timescales is needed to fully understand such a large-scale climate variability.

In addition, while there is considerable evidence for a solar influence on the Earth's preindustrial and postindustrial climate, there is little agreement regarding the effects of the geomagnetic field and its components on climate change. Moreover, it has long been speculated that there are possible connections between climate changes and the secular trend in the Earth's magnetic field. There are however plenty of data that either challenge or support this link. The immediate aim in this respect is (1) to establish the robust correlations between climate and magnetic

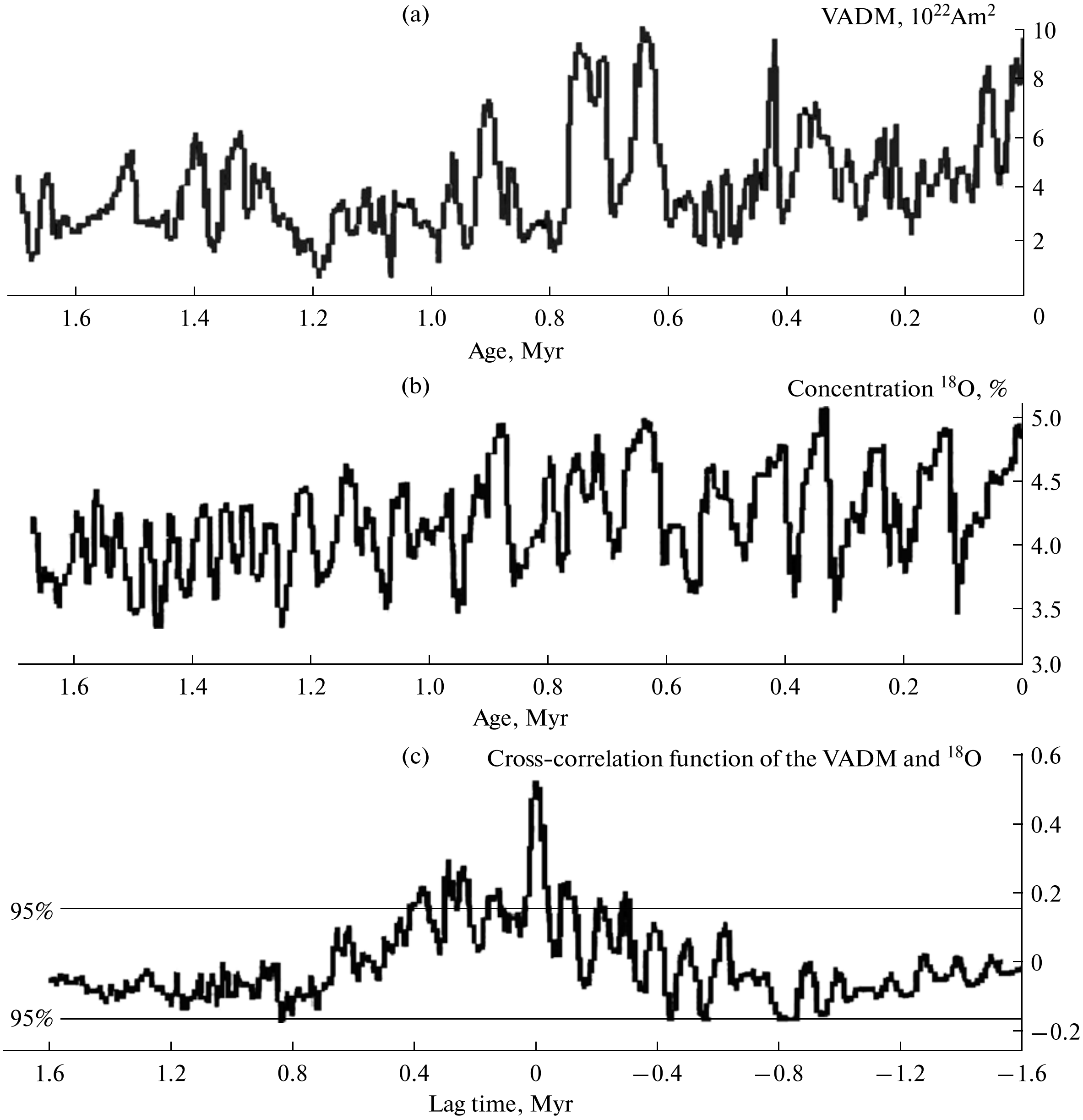


Fig. 9. Comparisons of (a) VADM (BADM) (Valet and Meynadier, 1993) and (b) ^{18}O variations in sediments (Shackleton et al., 1990) for the last 1.6 Myr over a 10-kyr running mean; (c) sample estimates of the cross-correlation function of the VADM and δ^{18}O.

field variations at various timescales and (2) to suggest a mechanism linking magnetism and climate.

We then summarize the evidence for variations in the virtual axial dipole moment (VADM) determined from paleointensity data on volcanic and sedimentary rocks (Valet and Meynadier, 1993) and the ^{18}O concentrations in sedimentary rocks of the Panama basin (Shackleton et al., 1990) at a longer timescale (Fig. 9). It should be noted that a quantitative relationship was established between variations in ^{18}O and temperature.

Figure 9 shows virtual axial dipole moment (Fig. 9a) and oceanic oxygen isotope (Fig. 9b) data and their cross-correlation function (Fig. 9c). A sample estimation of the cross-correlation function (CCF) for two series can be conducted following the procedure proposed by Jenkins and Watts (1972). To clarify the relationship, individual series should be first prewhitened to deal with the effects of autocorrelation of the estimated series, i.e., reducing the estimated time series to white noise (nonautocorrelated). If the hypothesis is correct, the number of the estimated CCF values for the two time series, exceeding a 95% significance level (2σ), should be less than 5% of all CCF values; otherwise, these series are autocorrelated.

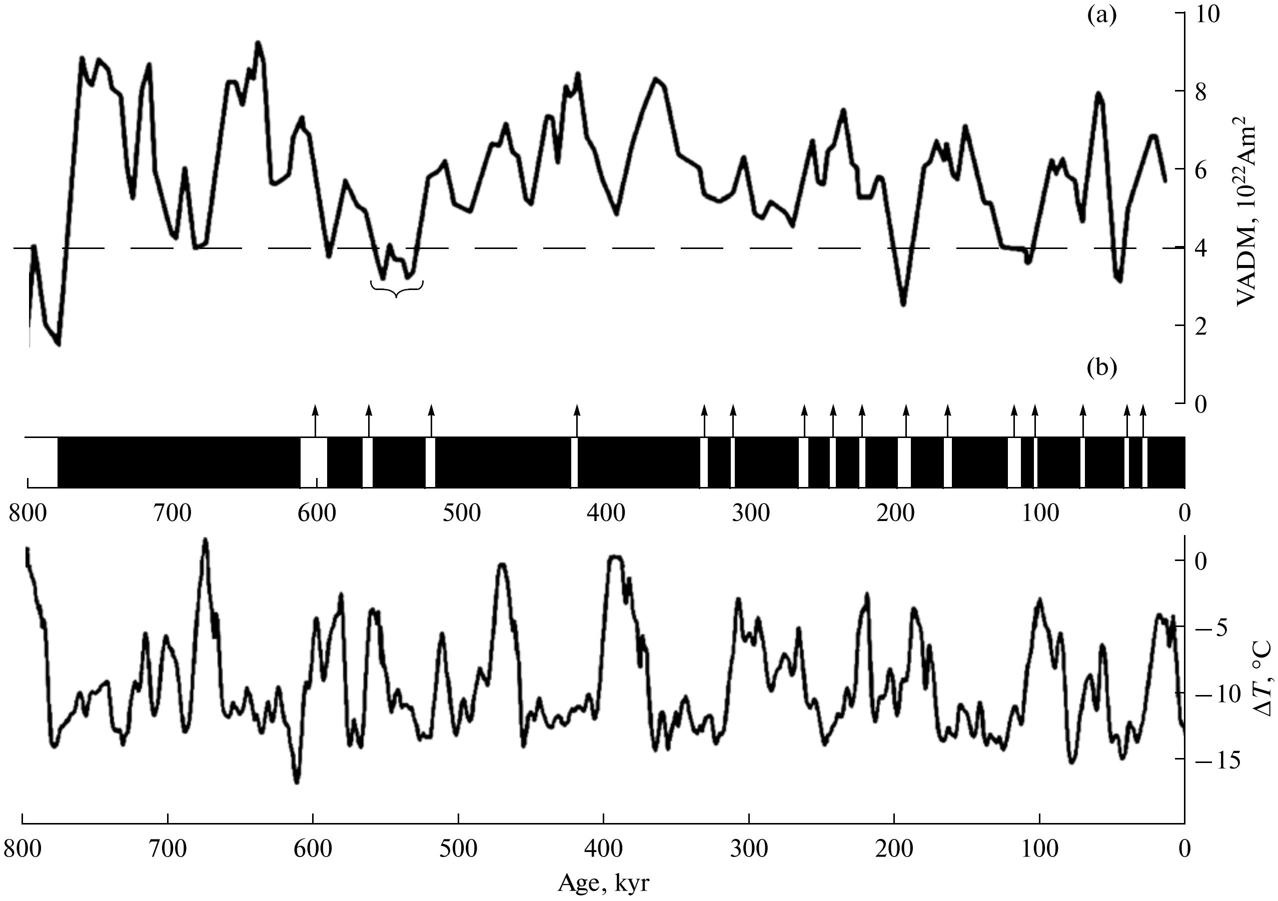


Fig. 10. Data on: (a) the VADM (Guyodo and Valet, 1999) and (b) geomagnetic excursion timescale (white bands); (c) oceanic ^{18}O values (Shackleton et al., 1990) for the last 800 kyr.

The CCF of the VADM and ^{18}O values (Fig. 9c) may reflect the direct impact of the Earth's magnetic field on climate. Calculations show that the hypothesis about a close relationship between VADM and climate can be considered significant at a 12% level as compared to the 5% critical level; the correlation coefficient is 0.525; i.e., an increase in the dipole moment leads to an increase in temperature. The lag between the time series is zero.

In our previous study (Dergachev et al., 2008), we addressed the question regarding whether an orbital fingerprint can be seen in geomagnetic time series. With this in mind, we have analyzed the cross-correlation functions of corresponding pairs of observations, i.e., variations in eccentricity and ^{18}O, VADM, as well as variations in ^{18}O and eccentricity and VADM for the past 1.5 Myr. The results showed that climate changes might be both orbitally and geomagnetically forced, so that the climate response lagged behind orbital forcing by10 ka and pulsed in rough unison with geomagnetic variations. For the 680–800 kyr interval, we have compared variations in climate and ^{10}Be production near the Brunhes–Matuyama paleomagnetic reversal. It was shown that the VADM values were very low at the Brunhes–Matuyama boundary at about 780 ka (less than 2×10^{22} Am^2), while the ^{10}Be values increased substantially, suggesting that geomagnetic field variations drive changes in climate.

In order to explore the possibility of a direct impact of the geomagnetic field on climate (caused by other factors in addition to orbital forcing), here we compare more precise higher resolution data obtained from a stack of 33 marine records of paleointensity (Guyodo and Valet, 1999) and oceanic ^{18}O (Shackleton et al., 1990) for the past 800 kyr (Fig. 10). Figure 10 shows a good correspondence between features according to the climate and geomagnetic records. As a rule, paleointensity maxima are expected to correlate with minima in temperature, i.e., VADM variations exhibit a fairly good correlation with climatic responses when the correlation coefficient reaches a value of 0.6).

As Fig. 10a shows, geomagnetic excursions are observed when the dipole moment decreases to a critical value of about 4×10^{22} Am^2. These excursions (indicated by arrows in Fig. 10b) are of a global nature. Note also that no stable periodicity due to orbital modulation was found in these paleointensity records

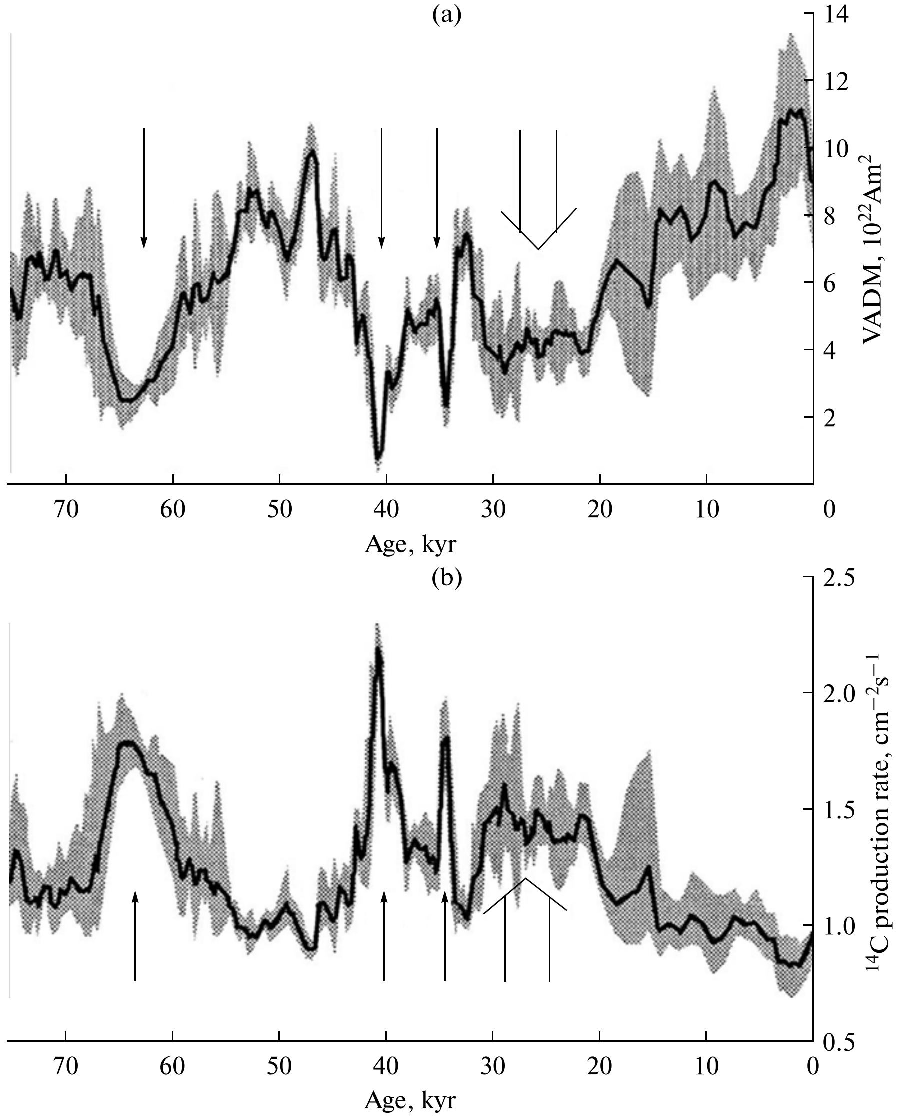


Fig. 11. (a) Comparison between VADM variations (Laj et al., 2002) and (b) the ^{14}C production rate over the past 75 kyr (Masarik and Beer, 1999). Arrows denote amplitude maxima and minima of the field parameters or the radiocarbon production rates coinciding with the geomagnetic field excursions.

over long time intervals, suggesting an insufficient resolution of this timescale.

Previous studies suggested that variations in the cosmic ray flux were correlated with climate changes over intervals 0–10 and 10–100 kyr ago (Dergachev et al., 2006, 2007). Therefore, an 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 as a potential forcing function of climate.

Figure 11 shows a comparison of high-resolution paleointensity stacks from sediments with high deposition rates (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 variations in the geomagnetic field derived from these records are consistent with variations in geomagnetic field components.

It is also interesting to note that the prominent lows in paleointensity at 41 and ~35 ka and minima at 60–65 and 20–30 ka more or less correspond to the following geomagnetic excursions (e.g., (Petrova et al., 1992)): Gothenburg (15–20 ka), Mono Lake (25–30 ka), Laschamp (35–45 ka), and Kargopolovo (60–70 ka).

As variations in the geomagnetic field control the cosmic ray intensity, Knudsen and Riisager (2008) provided a detailed reconstruction of variations in the geomagnetic dipole moment over the last ~10 kyr based on data derived exclusively from burned archeological materials and lava flows, which are unaffected by climatic biases (Fig. 7c).

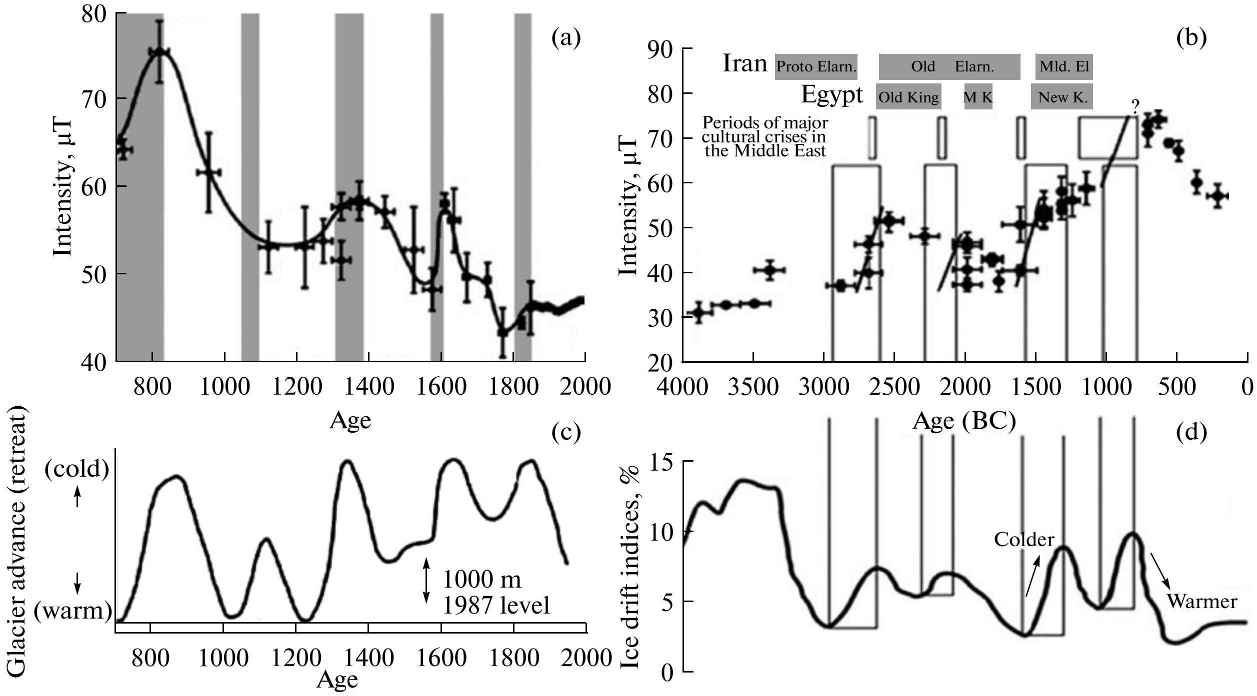


Fig. 12. (a, b) Geomagnetic field intensity variations in Paris and Mesopotamia derived from archeomagnetic records, (c) advance and retreat of alpine glaciers (Holzhauzer et al., 2005), and (d) climate change in the North Atlantic from ice drift indices (Bond et al. 2001). Shaded bands depict cooling periods.

Variations in the dipole moment intensity cause changes in the geomagnetic cutoff rigidity, hence deflecting incoming cosmic ray fluxes. Shea and Smart (2004) showed that these changes might have caused a variation of 21–34% in high-energy particle fluxes entering the Earth's atmosphere at ±35° latitudes during solar minima (similar to those occurred in 1965). Therefore, the production rate of cosmogenic nuclides depends on variations in the geomagnetic field intensity and direction.

In order to study the potential relationship between the geomagnetic dipole moment and climate, we focus our attention on high-resolution δ^{18}O data collected from caves in the vicinity of the ocean, which represent proxy records of past precipitation at low latitudes. Very high correlation coefficients (0.83 and 0.87) were reported by Knudsen and Riisager (2009) to exist between speleothem δ^{18}O data from southern China and Oman for the period from 5000 yr BP to the present time.

A comparison of a dipole moment reconstruction and an ^{18}O record from natural archives at low latitudes revealed that a lower dipole moment leads to a higher cosmic ray flux, resulting in higher monsoon precipitation, which can be explained by the differences in geomagnetic and solar modulations of the galactic cosmic ray flux.

The long-term decrease in the low-latitude monsoon precipitation observed in the records described above is in good agreement with observations from other regions of China, Australia, and Indonesia (see, e.g., (Cai et al., 2010; Griffiths et al., 2010)).

Recent archeomagnetic data allow for a detailed comparison of variations in the geomagnetic field and short-term climate changes for the last millennia. Evidence for the most recent and important climatic variations during the past millennia can be taken from many different sources, such as historical documents, tree rings, ice cores, stalagmites, pollen, glacier fluctuations, and continental and marine sediments. One of the most important indicators of climate cooling and warming cycles, such as advances and retreats of glaciers, provide very useful information on overall temperature variations in Western Europe, which might have impacted the history of ancient civilizations (Le Roy Ladurie, 1996).

The archeointensity results (Gallet et al., 2005) obtained from seven groups of French faience potsherds dated from the 17th to the 19th centuries confirmed that the mean intensity values have a sharp increase between ~1550 and 1600 AD, followed by a decrease until ~1750 AD when the intensity started to increase again.

The global coincidence between climatic proxies in different regions of the world suggests a causal relationship between climate change and the history of ancient civilizations. Figure 12 shows a comparison of paleointensity variations, advances of alpine glaciers (Holzhauzer et al., 2005), indices of ice drifts (Bond

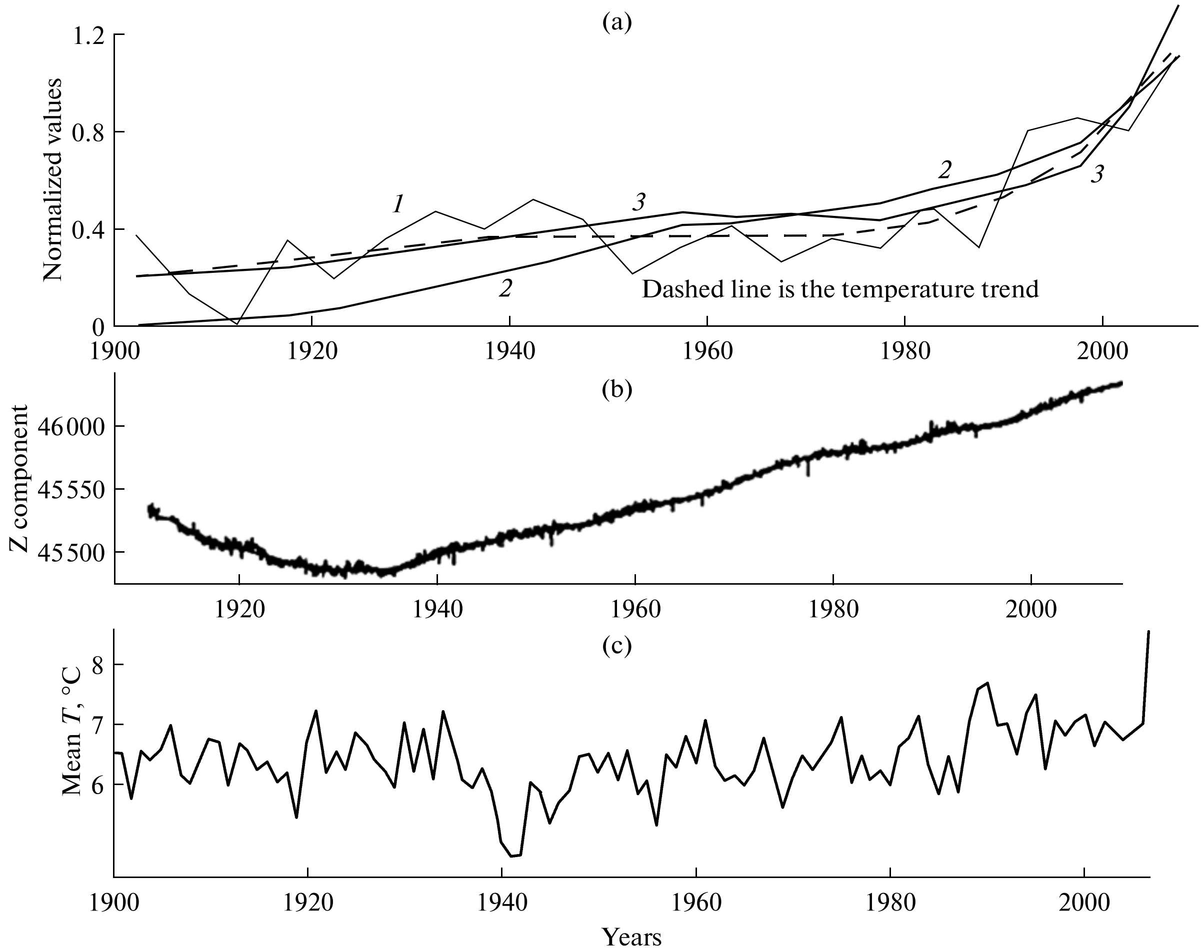


Fig. 13. Comparisons of variations: (a) *1*, temperature in the Northern Hemisphere and the north magnetic pole; *2*, latitude ($R^2 = 0.630$); and *3* longitude ($R^2 = 0.704$); (b) daily average values of the *Z* component in 1911–2008 from measurements at Eskdalemuir (Scotland); and (c) average European temperatures between 1900 and 2007.

et al., 2001), and social changes in the ancient Middle East.

New data on 31 sites mean that archeointensity values from Iranian and Syrian archeological excavations for the period from 3000 to 0 BC were used to construct a detailed geomagnetic field intensity variation curve for this region (Gallet et al., 2006). The results point to four potential geomagnetic events characterized by strong intensity increases at ~2800–2600, ~2100–1900, ~1750–1500, and ~750 BC (Fig. 12b). These events can be compared with the geomagnetic features from two lacustrine long cores from Sweden (Snowball and Sandgren, 2004), which were found to contain distinct paleointensity peaks around ~4500, 3900, 3700, and 2900 years ago. The agreement between these results is not fully satisfactory, which is most probably related to the differences in the high-precision archeointensity values and relative paleointensity estimates, as well as the different natures of the data and dating process.

Comparisons of the data in Fig. 12 show that both climatic variations and cultural crises in the Middle East can be connected to geomagnetic field fluctuations.

Kerton (2009) has studied variations in temperature and the positions of the magnetic poles from 1900 to 2005. The drift of the Earth's magnetic poles over the last 105 years show strong correlations between the position of the north magnetic pole and the Northern Hemisphere and global temperatures, suggesting a potential connection between these phenomena. Figure 13a in (Kerton, 2009) shows variations in the Earth's magnetic pole (latitude and longitude) in comparison with variations in temperature in the Northern Hemisphere and the corresponding R^2 values.

An analysis of daily variations in the Z component of the geomagnetic field measured in Scotland over the last ~100 years (Fig. 13b) show a steady increase in the component values with time, which is consistent with variations in annual average European temperature (Yiou P. et al., 2010) (Fig. 13c).

The underlying mechanisms of correlations between the drift of the magnetic poles and temperature and variations in the Z geomagnetic component and temperature remain difficult to understand. If solar activity does not affect the core and climate simultaneously, then geodynamo processes in the Earth's core may cause changes in the external geomagnetic field of the Earth, thus modulating the cosmic ray flux penetrating into the atmosphere, which could finally affect cloud formation.

The dramatic changes in climate over the past several decades raise possibility question that geomagnetic field fluctuations may not only contribute to long-term climate variations, but also to decadal, centennial, and millennial changes.

5. CONCLUSIONS

As we mentioned above, dramatic climate changes during the past centuries raise a question regarding whether there is a possible connection between the Earth's magnetism and climate over a range of timescales from decades to hundreds of thousands of years. Although there is convincing evidence for causal relationships between solar activity and climate both in the preindustrial and postindustrial ages, the influence of the geomagnetic field or its individual components on climate is often problematic.

The geomagnetic field can vary quite rapidly. A comparison between the most detailed reconstructions of the geomagnetic dipole moment for the past ~10 kyr and climate proxy records shows that dipole moment fluctuations influenced low-latitude precipitation in some regions of the world. An analysis of data over this timescale indicated that in addition to solar forcing mechanisms the geomagnetic field also modulates the cosmic ray flux interacting with the atmosphere. Understanding the causal connections between climate change at a variety of timescales and geomagnetic forcing requires a comprehensive study of the effects of geomagnetic paleointensity and directional variations on cosmogenic nuclide production.

The most recent archeointenisty results for the last ~5 kyr obtained in various regions of the world allowed one to ascertain the connection between climatic variations and the history of human civilizations. The periods of dramatic climate changes and cultural crises may have been coincident with geomagnetic features.

An analysis of the connections between sharp maxima in time variations in paleointensity (jerks) and climate change, as well as in the accelerated drift of the northern magnetic pole and variations in global surface temperature, suggests strong correlations between the positions of the magnetic and geomagnetic fields and the Earth's surface temperature.

Of prime importance is continuous monitoring of the present geomagnetic field variations, as it offers an opportunity to understand the underlying processes of geomagnetic field generation and its impact on climate.

ACKNOWLEDGMENTS

This study was partially supported by the Russian Foundation for Basic Research (grants nos. 10-05-00129, 10-02-00391, and 11-02-00755), the Presidium of the Russian Academy of Sciences (program no. 22), and a joint research program between the Russian Academy of Science and Finland (project no.16). We thank the reviewer for comments that helped improve the manuscript.

REFERENCES

Bond, G., Kromer, B., Beer, J., et al., Persistent Solar Influence on North Atlantic Climate during the Holocene, *Science*, 2001, vol. 294, pp. 2130–2136.

Budyko, M.I., *Klimat v proshlom i budushchem* (Climate in the Past and Future), Leningrad: Gidrometeoizdat, 1980.

Cai, Y., Tan, L., Cheng, H., et al., The Variation of Summer Monsoon Precipitation in Central China Since the Last Deglaciation, *Earth Planet. Sci. Lett.*, 2010, vol. 291, pp. 21–31.

Climate Change: The Physical Science Basis, Solomon, S. et al., Eds.., New York: Cambr. Univ. Press, 2007.

Constable, C.G. and Johnson, C.L., A Paleomagnetic Power Spectrum, *Phys. Earth Planet. Inter.*, 2005, vol. 153, pp. 61–73; doi:10.1016/j.pepi.2005.03.015.

Courtillot, V., Ducruix, J., and Le Mouël, Sur Une Acce'le'ration Re'cente de la Variation Se'culaire du Champ Magnetique Terrestre, *C.R. Acad. Sci., Paris: Ser. D,* 1978, vol. 287, p. 1095.

Dansgaard, W., Johnsen, S.J., and Moller, J., One Thousand Centuries of Climatic Record from Camp Century on the Greenland Ice Sheet, *Science*, 1969, vol. 166, no. 3903, pp. 377–381.

D'yachenko, A.I., *Magnitnye polyusa Zemli* (Magnetic Poles of the Earth), Moscow: MTsNMO, 2003.

Dendrokhronologiya i dendroklimatologiya (Dendrochronology and Dendroclimatology), Kairyukshtis, L.A., Galaziya, G.I., and Shiyatov, S.G., Eds., Novosibirsk: Nauka, 1986.

Dergachev, V.A., Concentration of Cosmogenic Radiocarbon in the Earth's Atmosphere and Solar Activity during the Last Millennia, *Geomagn. Aeron.*, 1996, vol. 36, no. 2, pp. 49–60 [*Geomagn. Aeron.* (Engl. transl.), 1996, vol. 36, pp. 179–186].

Dergachev, V.A., Cosmogenic Isotopes ^{14}C and ^{10}Be: Solar Activity and Climate, *Izv. Ross. Akad. Nauk, Ser. Fiz.*, 2009, vol. 73, no. 3, pp. 400–402.

Dergachev, V.A. and Veksler, V.S., *Primenenie radiouglerodnogo metoda dlya izucheniya prirodnoi sredy proshlogo* (Application of the Radiocarbon Method to the Study of the Natural Environment in the Past), Leningrad: FTI, 1991.

Dergachev, V.A. and Raspopov, O.M., Long-Term Processes on the Sun, Responsible for the Tendency toward a Change in the Solar Radiation and the Earth's Surface Temperature, *Geomagn. Aeron.* (Engl. transl.), 2000, vol. 40, pp. 9–14 .

Dergachev, V.A., Dmitriev, P.B., Raspopov, O.M., and Jungner, H., Cosmic Ray Flux Variations, Modulated by the Solar and Earth's Magnetic Fields, and Climate Changes. 1. Time Interval from the Present to 10–12 ka Ago (the Holocene Epoch), *Geomagn. Aeron.*, 2006, vol. 46, no. 1, pp. 123–144 [*Geomagn. Aeron.* (Engl. transl.), 2006, vol. 46, pp. 118–128].

Dergachev, V.A., Dmitriev, P.B., Raspopov, O.M., and Jungner, H., Cosmic Ray Flux Variations, Modulated by the Solar and Earth's Magnetic Fields, and Climate Changes. Part 2: Time Interval from ~10000 to ~100000 Years Ago, *Geomagn. Aeron.*, 2007, vol. 47, no. 1, pp. 116–125 [*Geomagn. Aeron.* (Engl. transl.), 2007, vol. 47, pp. 109–117].

Dergachev, V.A., Dmitriev, P.B., Raspopov, O.M., and Jungner, H., Cosmic Ray Flux Variations, Modulated by the Solar and Earth's Magnetic Fields, and Climate Changes. Part 3: A Time Interval of 1.5 Myr, Including the Pleistocene, *Geomagn. Aeron.*, 2009, vol. 49, no. 1, pp. 3–17 [*Geomagn. Aeron.* (Engl. transl.), 2009, vol. 49, pp. 1–13].

Dormy, E., Mandea. Asymmetric Behavior of Magnetic Dip Poles, *Earth Planet. Space*, 2003, vol. 55, pp. 153–157.

Energiya, priroda i klimat (Energy, Nature, and Climate), Klimenko, V.V. et al., Eds., Moscow: MEI, 1997.

Frank, M., Schwarz, B., Baumann, S., et al., A 200 kyr Record of Cosmogenic Radionuclide Production Rate and Geomagnetic Field Intensity from 10Be in Globally Stacked Deep-Sea Sediments, *Earth Planet. Sci. Lett.*, 1997, vol. 149, pp. 121–129.

Gallet, Y., Genevey, A., and Le Goff, M., Three Millennia of Directional Variation of the Earth's Magnetic Field in Western Europe as Revealed by Archeological Artifacts, *Earth Planet. Inter.*, 2002, vol. 131, pp. 81–89.

Gallet, Y., Genevey, A., and Fluteau, F., Does Earth's Magnetic Field Secular Variation Control Centennial Climate Change?, *Earth Planet. Sci. Lett.*, 2005, vol. 236, pp. 339–347.

Gallet, Y., Genevey, A., Le Goff, M., Fluteau, F. and Eshraghi, S.A., Possible Impact of the Earth's Magnetic Field on the History of Ancient Civilizations, *Earth Planet. Sci. Lett.*, 2006, vol. 246, pp. 17–26.

Griffiths, M.I., Drysdale, R.N., Michael, K., Gagan, M.K., et al., Evidence for Holocene Changes in Australian-Indonesian Monsoon Rainfall from Stalagmite Trace Element and Stable Isotope Ratios, *Earth Planet. Sci. Lett.*, 2010, vol. 292, pp. 27–38.

Guyodo, Y. and Valet, J.P., Global Changes in Intensity of the Earth's Magnetic Field during the Past 800 kyr, *Nature,* 1999, vol. 399, pp. 249–252.

Holzhauzer, H., Magny, M., and Zumbuhl, H., Glacier and Lake-Level Variations in West-Central Europe over the Last 3500 Years, *Holocene*, 2005, vol. 15, pp. 789–801.

Hoyt, D.V. and Schatten, K.H., A Discussion of Plausible Solar Irradiance Variations, 1700–1992, *J. Geophys. Res.*, 1993, vol. 98, pp. 18 895–18 906.

Jenkins, G. and Watts, D., *Spectral Analysis and Its Applications*, San Francisco: Holden-Day, 1966. Translated under the title *Spektral'nyi analiz i ego prilozheniya*, Moscow: Mir, 1972, vol. 2.

Jouzel, J., Masson-Delmotte, V., Cattani, O., et al., Orbital and Millennial Antarctic Climate Variability over the Past 800000 Years, *Science*, 2007, vol. 317, pp. 793–796.

Kerton, A.K., Climate Change and the Earth's Magnetic Poles, a Possible Connection, *Energy Environ.*, 2009, vol. 20, no. 1-2, pp. 75–83.

Knudsen, M. and Riisager, P., Is There a Link between Earth's Magnetic Field and Low-Latitude Precipitation?, *Geology*, 2009, vol. 37, pp. 71–74.

Knudsen, M.F., Riisager, P., Donadini, F., et al., Variations in the Geomagnetic Dipole Moment during the Holocene and the Past 50 kyr, *Earth Planet. Sci. Lett.*, 2008, vol. 272, pp. 319–329.

Korte, M. and Constable, C., The Geomagnetic Dipole Moment over the Last 7000 Years - New Results from a Global Model, *Earth Planet. Sci. Lett.*, 2005, vol. 236, pp. 348–358.

Krivova, N. and Solanki, S., Models of Solar Irradiance Variations: Current status, *J. Astrophys. Astron.*, 2008, vol. 29, pp. 151–158.

Laj, C., Kissel, C., Mazaud, A., et al., North Atlantic Paleointensity Stack Since 75 ka (NAPIS-75) and the Duration of the Laschamp Event, *Phil. Trans. R. Soc. London,* 2000, vol. 358, pp. 1009–1025.

Langereis, C.G., Dekkers, M.J., de Lange, G.J., et al., Magnetostratigraphy and Astronomical Calibration of the Last 1.1 Myr from an Eastern Mediterranean Piston Core and Dating of Short Events in the Brunhes, *Geophys. J. Int.*, 1997, vol. 129, pp. 75–94.

Laskar, J., Robutel, P., Joutel, F., et al., A Longterm Numerical Solution for the Insolation Quantities of the Earth, *Astron. Astrophys.*, 2004, vol. 428, pp. 261–285.

Le Roy Ladurie, E., *Histoire du climat depuis l'an mil,* Paris: Flammarion, 1967.

Lüthi, D., Le Flock, M., Bereiter, B., et al., High-Resolution Carbon Dioxide Concentration Record 650000–800000 Years before Present, *Nature,* 2008, vol. 453, pp. 379–382.

Masarik, J. and Beer, J., Simulation of Particle Fluxes and Cosmogenic Nuclide Production in the Earth's Atmosphere, *J. Geophys. Res.*, 1999, vol. 104D, pp. 12099–12111.

Newitt, L.R., Mandea, M., McKee, L.A., and Orgeval, J.J., Recent Acceleration of the North Magnetic Pole Linked to Magnetic Jerks, *EOS*, 2002, vol. 83, pp. 381–388.

Olsen, N. and Mandea, M., Investigation of a Secular Variation Impulse Using Satellite Data: The 2003 Geomagnetic Jerk, *Earth Planet. Sci. Lett.*, 2007, vol. 255, pp. 94–105.

Olson, P. and Amit, H., *Changes in Earth's Dipole. Naturwissenschaften*, 2006, vol. 93, pp. 519–542.

Petit, J.R., Jouzel, J., Raynaud, D., et al., Climate and Atmospheric History of the Past 420000 Years from the Vostok Ice Core, Antarctica, *Nature*, 1999, vol. 399, pp. 429–436.

Petrova, G.I. and Raspopov, O.M., Relation between the Changes in the Geomagnetic Moment and Paleoclimate for the Past 12 kyr, *Geomagn. Aeron.*, 1998, vol. 38, no. 5, pp. 141–150 [*Geomagn. Aeron.* (Engl. transl.), 1998, vol. 38, pp. 652–658].

Petrova, G.N., Nechaeva, T.B., and Pospelova, G.A., *Kharakternye izmeneniya geomagnitnogo polya v proshlom* (Characteristic Geomagnetic Field Variations in the Past), Moscow: Nauka, 1992.

Pospelova, G.A., Brunhes Chrone Geomagnetic Field Excursions and Global Climate Changes, *Fiz. Zemli*, 2000, no. 8, pp. 3–14.

Raspopov, O.M., Dergachev, V.A., and Gooskova, E.G., Ezekiel's Vision: Visual Evidence of the Sterno–Etrussia Geomagnetic Excursion (2700 BP)?, *EOS. Trans. AGU*, 2003, vol. 84, no. 9, pp. 77–79.

Scafetta, N., Empirical Analysis of the Solar Contribution to Global Mean Air Surface Temperature Change, *J. Atmos. Sol.–Terr. Phys.*, 2009, vol. 71, pp. 1916–1923.

Scherer, K., Fichtner, H., Borrmann, T., et al., Interstellar–Terrestrial Relations: Variable Cosmic Environments, the Dynamic Heliosphere, and Their Imprints on Terrestrial Archives and Climate, *Space Sci. Rev.*, 2006, vol. 127, pp. 327–465.

Shackleton, N.J., Berger, A., and Peltier, W.R., An Alternative Astronomical Calibration of the Lower Pleistocene Timescale Based on ODP Site 677, *Trans. R. Soc. Edinburgh, Earth Sci.*, 1990, vol. 81, pp. 251–261.

Shea, M.A. and Smart, D.F., Preliminary Study of Cosmic Rays, Geomagnetic Field Changes and Possible Climate Changes, *Adv. Space Res.*, 2004, vol. 34, pp. 420–425.

Shindell, D. and Faluvegi, G., Climate Response to Regional Radiative Forcing during the Twentieth Century, *Nat. Geosci.,* 2009, vol. 2, p. 294.

Snowball, P. and Sandgren, P., Geomagnetic Field Intensity Changes in Sweden between 9000 and 450 Cal BP: Extending the Record of "Archeomagnetic Jerks" by Means of Lake Sediments and the Pseudo-Thellier Technique, *Earth Planet. Sci. Lett.*, 2004, vol. 227, pp. 361–375.

Thellier, E., Sur la Direction du Champ Magnetique Terrestre, en France, Durant les Deux Derniers Millenaires, *Phys. Earth. Planet. Inter.,* 1981, vol. 24, pp. 89–132.

Valet, J.P. and Meynadier, L., Geomagnetic Field Intensity and Reversals during the Past Four Million Years, *Nature*, 1993, vol. 366, pp. 234–238.

Valet, J.-P., Meynadier, L., and Guyodo, Y., Geomagnetic Dipole Strength and Reversal Rate over the Past Two Million Years, *Nature*, 2005, vol. 435; doi:10.1038/nature03674.

Vasiliev, S.S., Dergachev, V.A., and Raspopov, O.M., Reconstruction of the Greenland Temperature for the Last Millennium, Solar Activity, and the North Atlantic Oscillations, *Geomagn. Aeron.*, 2004, vol. 44, no. 1, pp. 123–128 [*Geomagn. Aeron.* (Engl. transl.), 2004, vol. 44, pp. 110–114.

Yang, S., Odah, H., and Shaw, J., Variations in the Geomagnetic Dipole Moment over the Last 12000 Years, *Geophys. J. Int.,* 2000, vol. 140, pp. 158–162.

Yiou, P., Bard, E., Dandin, P., et al., Statistical Issues about Solar–Climate Relations, *Clim. Past,* 2010, vol. 6, pp. 565–573.

Yu, Y., Doh, S.-E., Kim, W., et al., Archaeomagnetic Secular Variation from Korea: Implication of the Occurrence of Global Archaeomagnetic Jerks, *Earth Planet. Sci. Lett.*, 2011 (in press).