ON A COMBINED INFLUENCE OF LONG-TERM SOLAR ACTIVITY VARIATIONS AND GEOMAGNETIC DIPOLE CHANGES ON CLIMATE CHANGE

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Abstract. The influence of variations in galactic cosmic rays (GCR) on climate change has been analyzed for the time intervals of thousands and tens of thousands of years. It has been shown that in the last millennium quasi-two-hundred-year variations in the GCR intensity (variations in the cosmogenic ^{14}C isotope concentration in dated tree rings) modulated by solar cyclicity (the ~210-year cycle) correlated well with climate change (temperature and precipitation variations). The correlation coefficient between variations in GCR and climate parameters for different regions of the Earth has been found to range from 0.58 to 0.95. Analysis of variability in the concentration of the cosmogenic ^{10}Be isotope (that also reflects the GCR flux variability) in Greenland ice for the time interval from 20,000 to 50,000 years ago has revealed that the ^{10}Be concentration is modulated by the quasi-two-hundred-year solar cycle. Comparison of variations in the cosmogenic ^{10}Be isotope concentration with changes in the magnitude of the virtual axial dipole moment (VADM) of the geomagnetic field has shown that the envelope of the ^{10}Be concentration amplitude correlates well with the VADM variations. Thus, it can be concluded that long-term solar activity and geomagnetic dipole variations exert a combined influence on the GCR fluxes that enter the Earth's atmosphere and affect the climate. A decrease in the geomagnetic dipole leads to an enhancement of the total GCR flux on the one hand and an increase in the depth of modulation of the GCR fluxes caused by solar activity variability on the other hand.

1 Introduction

The problem of the influence of variable cosmic ray fluxes on atmospheric processes and meteorological and climatic parameters has been intensely studied in recent years [Pudovkin and Raspopov, 1992; Pudovkin, 2004; Dergachev et al., 2006, 2007; Raspopov et al., 2007, 2008]. Major attention has been paid to the effect of solar activity on amplitude modulation of the galactic cosmic ray fluxes (GCR) entering the atmosphere. However, there also exists another geophysical factor that affects the amplitude modulation of GCR fluxes and thus exerts influence on climate parameters. This is the magnitude of the geomagnetic dipole. The geomagnetic field is a peculiar umbrella that prevents GCR penetration into the magnetosphere. The fact of amplitude modulation of GCR fluxes in the atmosphere caused by variations in the geomagnetic dipole is evidenced by experimental data on the concentration of cosmogenic ^{10}Be isotope in the terrestrial archives whose production in the atmosphere occurs under the influence of cosmic rays [Masarik and Beer, 1999]. The time scale of these variations is thousands and tens of thousands of years, while variations in solar activity have a much smaller scale.

The goal of our paper is to consider a combined effect of long-term variations in solar activity and changes in the geomagnetic dipole on climate.

2 Data used

To analyze the climate change caused by long-term solar activity variations and changes in the geomagnetic dipole, we used the data on the concentrations of cosmogenic ^{14}C and ^{10}Be isotopes and stable ^{18}O isotope in the terrestrial archives (ice caps of Greenland and Antarctica, bottom sediments) and also on summer temperatures and precipitations reconstructed from variations in ring widths of different species of juniper in Tien Shan and Tibetan Plateau and ring widths of *Fitzroya cupressoides* in Chile.

2.1 Data on solar activity

To analyze solar activity variations, data on the ^{14}C variations in tree rings for the last 8,000 years [Stuiver at al., 1998] and also measurements of the ^{10}Be concentration in Greenland ice for the time interval from 50,000 to 25,000 years ago [Masarik and Beer, 1999] were used.

2.2 Data on changes in the geomagnetic dipole

Changes in the geomagnetic dipole were analyzed by using data on changes in the dipole moment M for the last 40,000 years [Lehman et al., 1996] and palaeomagnetic high-resolution data (SAPIS-8) on changes in M for the last 100,000 years obtained at the continental edge of the Antarctic peninsula (65^{O}S, 78^{O}W) [Sagnotti et al., 2001] were used.

2.3 Data on climate change

To analyze the influence of long-term solar activity variations on climate, we used data on ~200-year solar activity cyclicity (de Vries cycle) in the time interval of the last 1,000 years and also the 1,229-year chronology around 50,000 years ago. For these intervals, data on annual variations in tree ring widths are available. For the last millennium, data on variations in ring widths of juniper *Junipedrus turkestanica* from two regions of Tien Shan [Maksimov and Grebenyuk, 1972; Esper at al., 2003; Mukhamedshin and Sarbaev, 1988] and juniper *Sabina przewalskii* growing on the Tibetan Plateau [Shao et al., 2005] are available. The growth of *Junipedrus turkestanica* was found to be affected by summer temperatures and independent of precipitations. The radial growth of *Sabina przewalskii* was governed by the amount of precipitations.

For the time interval around 50,000 years ago, a floating 1,229-year chronology developed from subfossil stumps of *Fitzroya cupressoides* from the mid-latitude region of Chile has been reported [Roig et al., 2001]. The trees were buried by a landslide and were well preserved. Analysis of variations in the ring widths of living trees of this species showed that their radial growth was governed by summer temperatures.

To analyze the intercorrelation between climate change and changes in the magnitude of the geomagnetic dipole, the data of the concentration of stable oxygen ^{18}O isotope in Greenland ice for the time interval of 40,000 years [Grootes and Stuiver, 1997] and in the Antarctic ice for the time interval to 100,000 years [Steig et al., 2000] were used. Variations in the relative ^{18}O isotope concentration give information on relative temperature variations [Souchez, 1997].

3 Results of analysis and discussion

To examine the interrelation between changes in the geomagnetic dipole and temperature oscillations in the past, a cross-correlation analysis of the curves (series) characterizing these variations was carried out. Fig. 1a and 1b show changes in the Earth's dipole [Lehman et al., 1996] and variations in the ^{18}O concentration [Grootes and Stuiver, 1997] in Greenland ice for the time interval from 39,900 to 3,400 years ago, respectively. Fig. 1c gives estimates of the cross-correlation function between changes in the Earth's magnetic moment and ^{18}O concentration (temperature). The correlation coefficient between these series was found to be rather high and equal to 0.71.

It is evident from Fig. 1 that there is a similarity between the curves shown in Fig. 1a and 1b and Fig.1d and 1e, respectively, and the high correlation coefficients (Fig. 1c and 1f) for the curves plotted independently indicate that a relation between variations in temperature and intensity of the cosmic ray fluxes modulated by the geomagnetic field does exist.

Let us now consider the interrelation between climate change and ~200-year solar cyclicity. Fig. 2 shows results of wavelet transformation (Morlet basis) in the range of 100-300-year periods of solar activity (^{14}C) (a), variations in summer temperatures in three regions of Tien Shan (b), and variations in precipitations on the Tibetan Plateau in the same range of periods (c) for the last millennium. The variations in summer temperatures and precipitations were reconstructed from variations in tree ring widths of the junipers mentioned in Section 2.3. As one can see from Fig.2, the behavior of climate characteristics correlates well with the ~200-year solar activity variations. The correlation coefficients between the series of solar activity and climate parameters shown in Fig. 2 were found to be 0.94, 0.78, and 0.84. This indicates that the 200-year solar cyclicity strongly affects climate parameters.

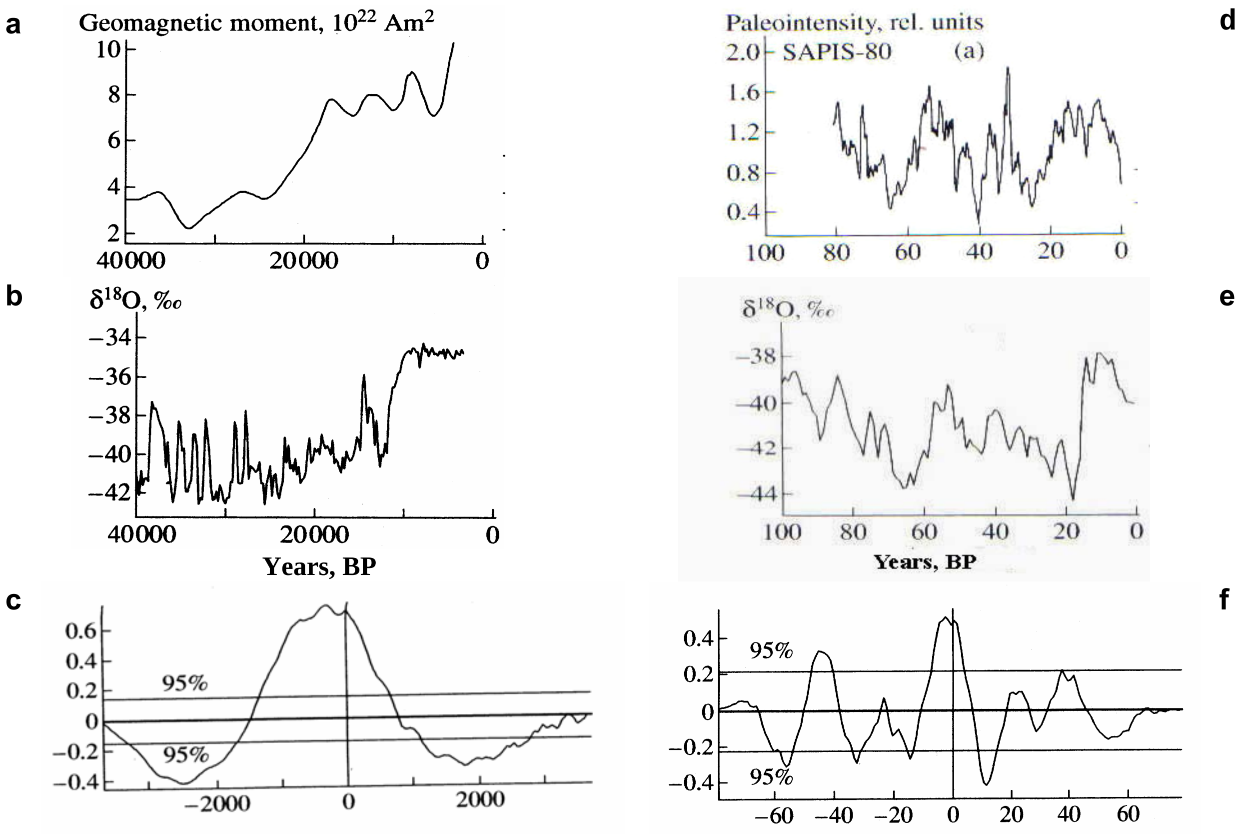

Fig. 1 (a) changes in the Earth's dipole moment [Lehman et al., 1996]; (b) variations in the ^{18}O concentration [Grootes and Stuiver, 1997] in Greenland ice for the time interval from 39,900 to 3,400 years ago; (c) cross-correlation function between changes in the Earth's magnetic moment and variations in the ^{18}O concentration; (d) changes in palaeointensity of the Earth's magnetic field (SAPIS-80) reconstructed by using sediment cores from the Antarctic peninsula for the last 100,000 years [Sagnotti et al., 2001]; (e) variations in ^{18}O concentration in ice cores from the Taylor Dome station, Antarctica [Steig et al., 2000]; (f) cross-correlation function between the series presented in Fig. (d) and (e).

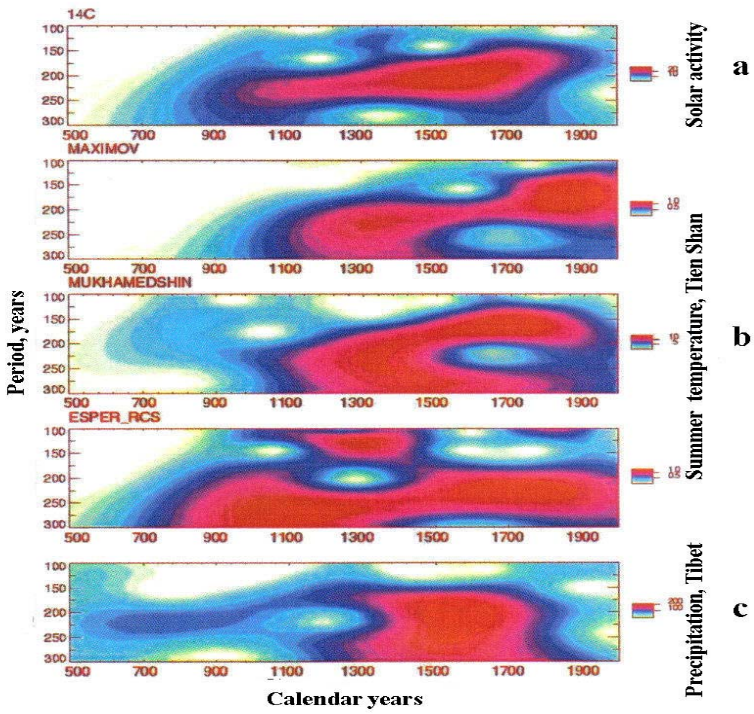

Fig. 2 (a) results of wavelet transformation (Morlet basis) in the range of solar activity periods of 100-300 years (^{14}C), (b) variations in summer temperatures in three regions of Tien Shan, and (c) variations in precipitations on the Tibetan Plateau in the same range of periods for the last millennium.

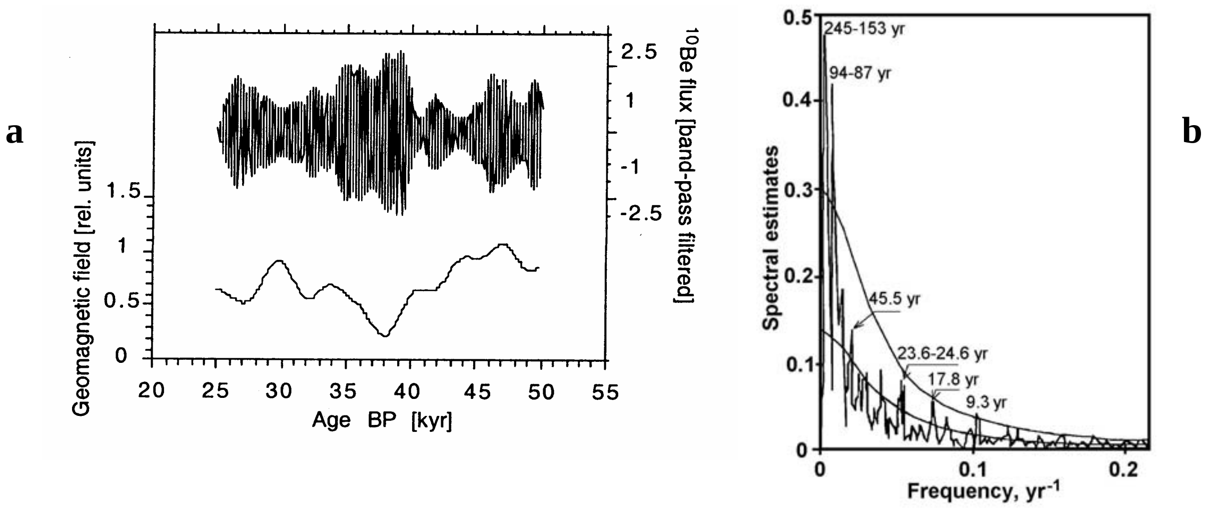

Fig. 3 (a) 208-year variations in the ^{10}Be concentration in cores from Greenland glaciers; (b) results of spectral analysis of variations in ring widths of *Fitzroya cupressoides* buried by a landslide around 50,000 years ago in Chile

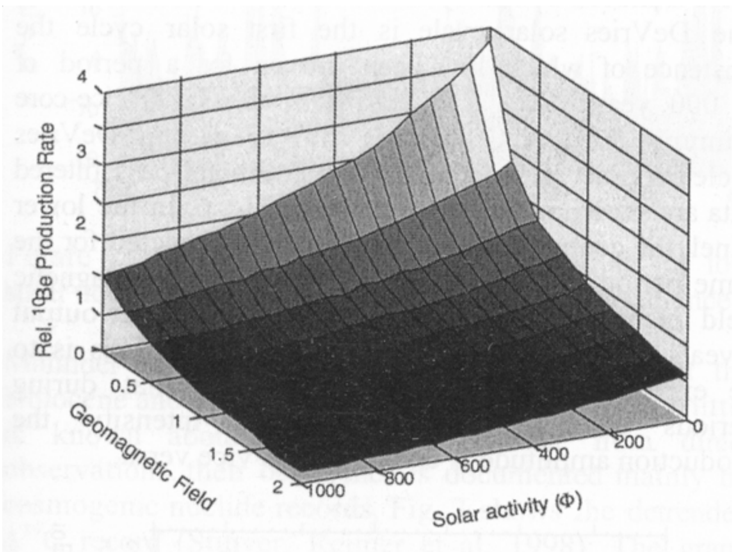

Fig. 4 Simulated rate of production of ^{10}Be in the atmosphere in the case of changes in the geomagnetic dipole and variations in solar activity [Masarik and Beer, 1999]. The measure of solar activity in the figure in coefficient Φ which is zero in the absence of disturbances and equals 1,000 at a high solar activity. The limits of variations in the geomagnetic dipole M in the graph are taken to be from 0 to 2, where 1 is the modern value of the geomagnetic dipole.

By examining cores of Greenland ice with the aim of tracing variations in the ^{10}Be concentration, Masarik and Beer (1999) revealed the 208-year solar cycle in the time interval from 50,000 to 25,000 years ago. They found that the amplitude of these variations was modulated by changes in the geomagnetic field intensity (Fig.3a). The efficiency of the effect of the ~200-year solar cycle during this time interval is confirmed by spectral analysis of the variations in tree ring widths of *Fitzroya cupressoides* buried by a landslide around 50,000 years ago in Chile. Fig. 3b shows results of spectral analysis of the variations in ring widths of the trees mentioned above. The spectrum clearly exhibits the quasi-two-hundred-year climatic cycle and also other solar cycles, i.e., 80-90 years (Gleissberg cycle) and 23 years (Hale cycle). This result, together with the data on the quasi-two-hundred-year solar cycle around 50,000 years ago shown in Fig.3a, points to a combined influence of the geomagnetic field intensity and solar activity on climate during the time intervals from hundreds to tens of thousands of years.

The experimental result obtained is in good agreement with the simulated global pattern of the rate of production of ^{10}Be in the atmosphere in the case of varying magnitude of geomagnetic dipole and solar activity (Fig. 4) [Masarik and Beer, 1999]. In Fig. 4 the measure of the solar activity is coefficient Φ which is zero in the absence of disturbances and equals 1000 at a high solar activity. The limits of changes in the geomagnetic dipole in the graph are from 0 to 2. The rage of production of ^{10}Be equal to 1 corresponds to the modern magnitude of the geomagnetic field (M = 1) and its average disturbance (Φ = 550). As one can see from the graph, in the limits of the given M and Φ the intensity of the integral cosmic ray flux in the atmosphere can vary by an order of magnitude. A decisive factor in the enhancement of the SCR flux in the atmosphere is a decrease of the geomagnetic dipole by a factor of 2 and more and a low solar activity.

4 Conclusions

Experimental data and simulation have shown that changes in the geomagnetic dipole magnitude and long-term variations in solar activity exert a combined effect on climate change and, hence, confirm the idea of the influence of cosmic ray fluxes on climate change.

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