Long-term solar activity variations as a stimulator of abrupt climate change

O. M. Raspopov[1], A. V. Dergachev[2], T. Kolström[3], A. V. Kuzmin[4], E. V. Lopatin[3,5], and O. V. Lisitsyna[6]

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[1] Analysis of solar forcing of climate on long time scales has shown that it is necessary to take into consideration the influence of long-term solar cyclicity, such as 200 and 2300–2400-year cycles, on climate. Even in the relatively warm climate of the last 10,000 years, a tendency to climate cooling at deep minima of long-term solar cyclicity is observed. Along with this, a long-term solar forcing of climate manifests itself not only as an external factor due the influence of solar irradiance variations on the atmosphere-ocean system, but also as a stimulator of internal processes in the climatic system, which, in turn, can lead to abrupt climate change. Large-scale abrupt climate oscillations – warmings and subsequent coolings (Dansgaard-Oeschger cycles) – have been revealed in cores of Greenland ice for the interval 60,000–10,000 years BP. They are attributed to the ice-rafting events in the North Atlantic. A comparative analysis of the development of Dansgaard-Oeschger events and solar activity variations (variations in the ^{10}Be concentration in Greenland ice) has shown that these climatic and solar processes developed simultaneously. It is evident that ice-rafting events were stimulated by an increasing ambient temperature and, hence, they are associated with a high solar activity level. A similar effect of solar activity has been revealed for the time interval of the Holocene. Thus, not only a low, but also a high level of solar activity was in the past a stimulator of abrupt climate changes. *INDEX TERMS:* 1616 Global Change: Climate variability; 1650 Global Change: Solar variability; 7536 Solar Physics, Astrophysics, and Astronomy: Solar activity cycle; *KEYWORDS:* solar activity variations, abrupt climate change, ice-rafting events.

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1. Introduction

[2] Extreme weather conditions observed at present that occur on the background of global warming, which is typically interpreted as a result of anthropogenic effects, can be a manifestation of a global rearrangement in the atmospheric circulation. Attention should also be paid to development of extreme solar events in recent years [see, e.g., a special issue of Geomagnetism and Aeronomy, 2006, vol. 45, no. 1], which can be attributed to the fact that now we are in the vicinity of the maximum of the quasi-two-hundred-year solar cycle [*Raspopov and Dergachev,* 2005]. Thus, anthropogenic and long-term natural factors simultaneously affect large-scale atmospheric processes. A natural question then arises as to whether the development of extreme meteorological conditions converts into variations in climatic parameters on the global scale under these conditions. In this respect it is reasonable to inquire into the effects of solar activity and its variability on large-scale climate changes in the past. Analysis of climatic data and effects of both the 200- and 2300–2400-year solar cycles has shown that they indeed can result in abrupt climate change. Note that there is a tendency to cooling or abrupt climate change at deep solar minima [*Dergachev et al.,* 2005; *Eddy,* 1976; *Mayewsky et al.,* 2004; *Raspopov et al.,* 2005, 2007; *Soon and Yaskell,* 2003]. A striking example is the Little Ice Age in 1600–1880-ies

[1]St.Petersburg Filial of Pushkov Institute of Terrestrial Magnetism, Ionosphere, and Radiowave Propagation of RAS, St.Petersburg, Russia
[2]Ioffe Physico-Technical Institute of RAS, St.Petersburg, Russia
[3]Mekrijärvi Research Station, University of Joensuu, Joensuu, Finland
[4]Polar Botanical Garden-Institute KolaSC RAS, Kirovsk, Murmansk Region, Russia
[5]Biology Institute of KomiSC of Ural Branch, RAS, Syktyvkar, Russia
[6]Oulu University, Oulu, Finland

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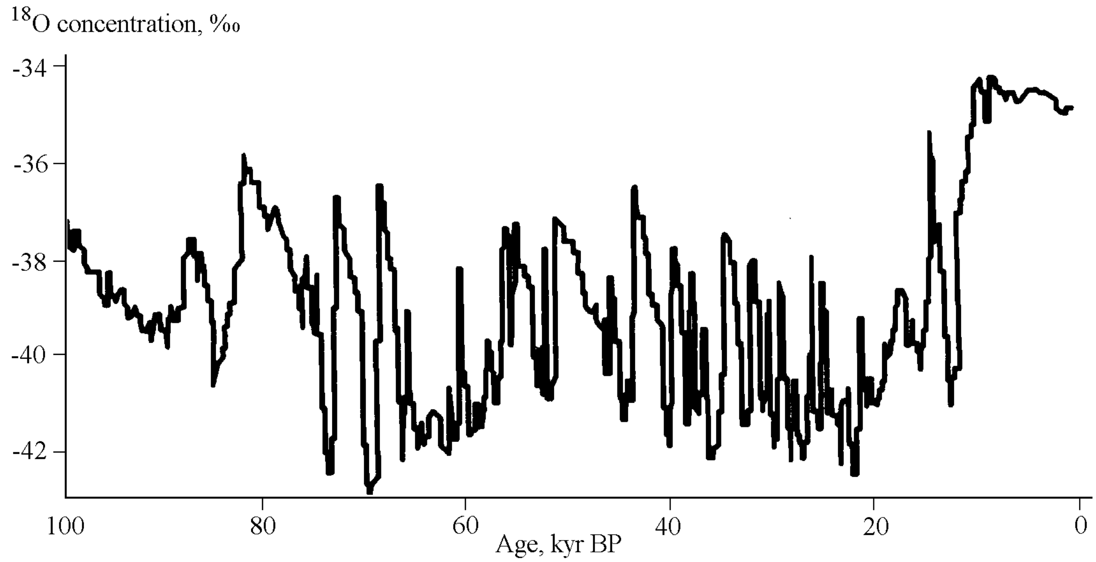

Figure 1. Temperature variations in Greenland for the last 100,000 years.

that started from development of the Maunder solar minimum (1638–1715) [*Eddy,* 1976; *Shindell et al.,* 2001; *Soon and Yaskell,* 2003]. However, it is necessary to analyze not only the results of a direct effect of solar activity and its variability on atmospheric processes, but also the probability of stimulation of internal processes in the atmosphere-ocean system by the events that occur at the Earth's surface. This paper is devoted to the consideration of this problem.

2. Long-Term Solar Activity Variations in the Pleistocene and Their Connection With Abrupt Climate Change

[3] It is well known that the North Atlantic region is one of the key regions where conditions for abrupt climate change of the global scale can arise [*Meeker and Mayewsky,* 2002; *Rogers and Van Loon,* 1979; *Van Loon and Rogers,* 1978]. One of stimulators of abrupt climate change can be dynamics of the North Atlantic overturning circulation (NAOC), i.e., the dynamics of the position of the Gulf Stream edge when the surface current converts into deep-water current of an opposite direction. The position of the northern edge of NAOC is governed by the temperature factor, when waters increase their density on cooling and sink into the ocean depths, and desalination of the ocean surface layer under the action of increasing precipitation in the Arctic or considerable ice rafting from Greenland and North America glaciers. Note that these are the processes with positive feedback because southward displacement of the Gulf Stream tongue contributes to even a greater temperature decrease in the Arctic region.

[4] Analysis of variations in the surface temperature of the Atlantic Ocean and also temperature variations in Greenland for the last ice age revealed sharp and large temperature variations, the so-called Dangaard-Oeschger (D-O) and Henrich events with a periodicity of around 1570 and 4800 years, respectively [*Dansgaard et al.,* 1993; *Grootes and Stuiver,* 1997] (Figure 1). Later analysis of bottom sediments from the North Atlantic showed that these temperature oscillations are associated with ice rafting from glaciers of Greenland and the North American continent [*Bond and Lotti,* 1995; *Bond et al.,* 1999]. For the time intervals indicated above, large amounts of gravel and sand carried from the continent were found in bottom sediments. It is natural to suppose that warming periods corresponded to the time intervals preceding ice-rafting events. In this respect it is reasonable to compare the development of D-O events with the solar activity periodicity. As a criterion of solar activity oscillations with durations of hundreds and thousands of years, variations in the concentrations of cosmogenic isotopes ^{14}C and ^{10}Be in dated terrestrial archives can be used.

[5] Generation of cosmogenic isotopes occurs in the atmosphere under the action of high-energy cosmic rays. In its turn, the intensity of cosmic rays in the Earth's atmosphere depends on the degree of turbulization of the solar wind and, hence, solar activity. Thus, the periodicity in solar activity oscillations governs the periodicity of variations in the cosmic ray flux intensity in the atmosphere. Galactic cosmic rays and high-energy solar cosmic rays entering the Earth's atmosphere form a number of cosmogenic nuclides, such as carbon isotope ^{14}C (radiocarbon) and beryllium isotope ^{10}Be. Radioisotopes ^{14}C and ^{10}Be are suitable for studying natural processes, such as time variations of the geomagnetic field and solar activity. As a result of exchange processes in the environment, these isotopes are recorded in dated natural archives: ^{14}C is found in tree rings and ^{10}Be is contained in glaciers and bottom sediments. Studies of dated natural archives is a unique tool of the investigation

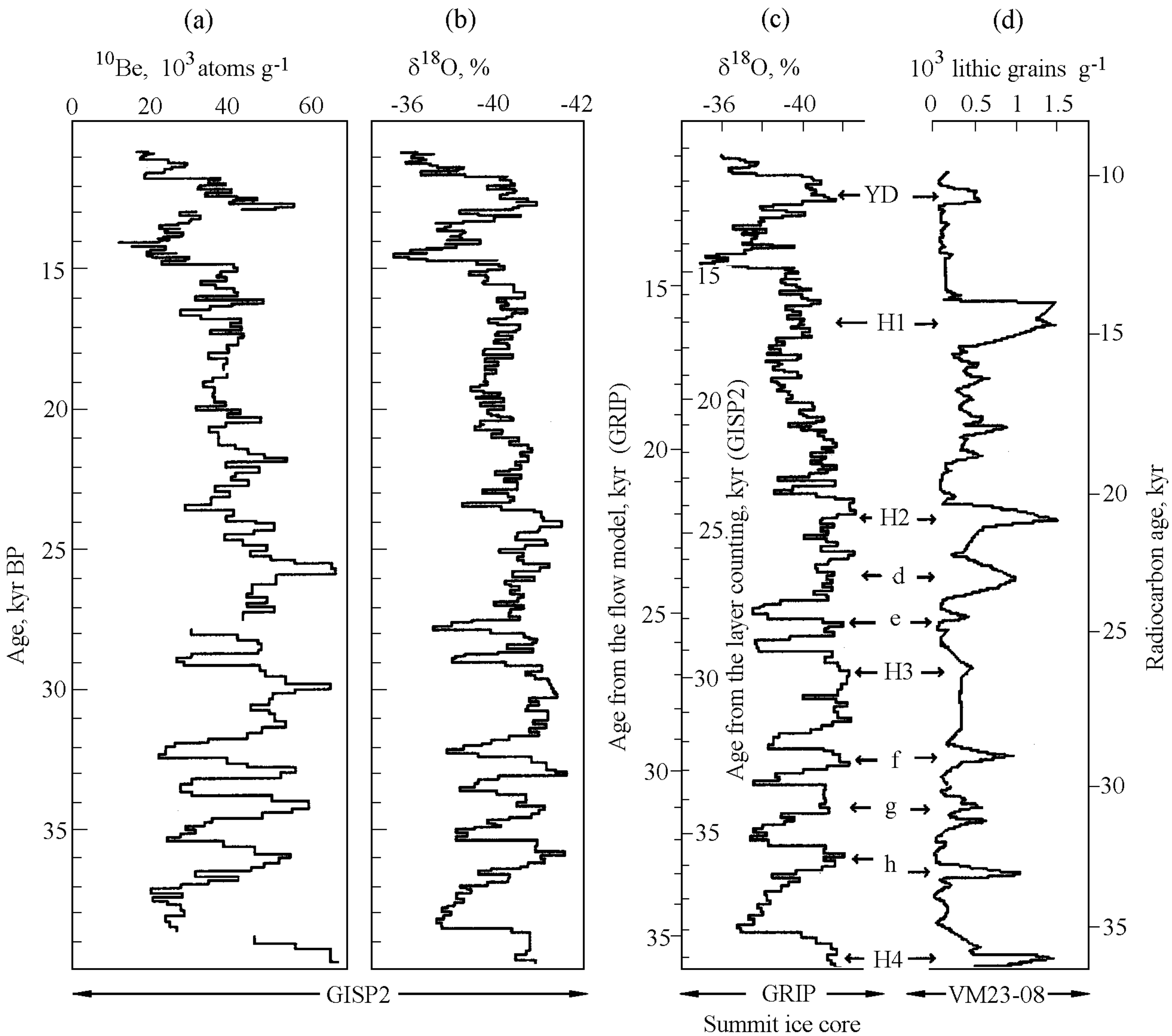

Figure 2. a – variations in the ^{10}Be content in Greenland ice for the last 40,000 years from the data of the GRIP2 borehole [*Finkel and Nishiizumi,* 1997]; b – temperature variations in Greenland ice (δ^{18}O) for the last 40,000 years from the data of the GRIP2 borehole [*Grootes et al.,* 1993]; c – temperature variations in Greenland from the data of the GRIP borehole [*Dansgaard et al.,* 1993]; d – ice-rafting events in the North Atlantic [*Bond and Lotti,* 1995].

of dynamic processes at the Earth and in the near-Earth space on the time scales from tens to several thousands of years on the basis of ^{14}C data (the half-life of ^{14}C is around 5730 years) and to hundreds of thousands of years on the basis of ^{10}Be data (the half-life of ^{10}Be is around 1.5 million years). For the time interval of tens of thousands of years, it is reasonable to use the data on the ^{10}Be concentration to characterize the solar activity level. Note that variations in concentrations of both ^{14}C and ^{10}Be depend on not only solar activity, but also on the exchange processes. Along with this, *Bard et al.* [1997], by comparing variations in ^{14}C and ^{10}Be for the last millennium, have shown that variations in ^{14}C and ^{10}Be trace well solar activity variations. *Beer* [2000] has shown that variations in ^{14}C and ^{10}Be give information on solar activity variations for the Holocene as well. In addition, *Finkel and Nashiizumi* [1997] have demonstrated that variations in the ^{14}C and ^{10}Be concentrations in time intervals from 8000 to 30,000 years are similar. For this reason, it can be believed that the data on ^{10}Be trace solar activity variations, at least qualitatively, in the Pleistocene.

[6] The presently available experimental data allow one to compare solar activity variations (variations in the ^{10}Be concentration) and variations in surface temperature (δ^{18}O) [*Finkel and Nishiizumi,* 1997; *Grootes et al.,* 1993] for the last 40,000 years by using cores from one and the same borehole in Greenland (GISP2). These data are presented in Figure 2. As can be seen, the graphs are similar, the intervals of a sharp temperature decrease are preceded by the

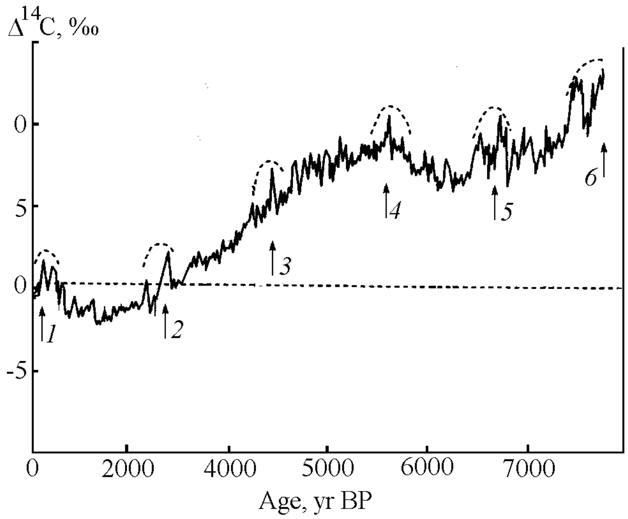

Figure 3. Variations in the ^{14}C concentration in tree rings for the last 11,400 years from the data of *Stuiver et al.* [1998]. The figures mark the epochs of deep solar minima.

intervals of an enhanced solar activity. Figure 2 also shows temperature variations ($\delta^{18}O$) for another Greenland borehole (GRIP) [*Dansgaard et al.,* 1993] and the graph of development of ice-rafting events (IRE) in the North Atlantic derived from the data of borehole VM23-081 in the ocean bottom [*Bond and Lotti,* 1995; *Bond et al.,* 1999]. It is apparent from Figure 2 that the variations in surface temperature inferred from the data of both boreholes are similar. Each development of the D-O event corresponds to the formation of layers with an increased content of gravel as evidenced by the data for the borehole in the ocean bottom, which indicates that ice-rafting events occurred in relevant time interval. Thus, the data presented in Figure 2 show that the IRE are preceded by the time intervals of a high solar activity and, hence, a stronger heating of the ocean surface. This suggests that in the Pleistocene, when the ice age developed, a high solar activity level and, most probably, a high solar irradiance stimulated development of such surface processes as ice-rafting events in the Northern part of the Atlantic ocean, and thereby caused abrupt climate changes. Note that the experimental data given above are confirmed by simulation of the IRE development [*Shaffer et al.,* 2004]. The results of simulation point to a periodicity in the occurrence of ice-rafting events, consistent with experimental data, and also to the fact that the IRE onset is preceded by an increase in the ocean temperature.

3. Long-Term Solar Activity Variations in the Holocene and Their Connection With Abrupt Climate Change

[7] Data with a high time resolution of the order of 10–20 years are available for the Holocene for both climate change and solar activity variations. This allows a more precise comparison of the development of climatic processes and solar activity variations than for the Pleistocene. Information on solar activity variations in the Holocene is obtained from measurements of the concentration of radiocarbon ^{14}C (Δ^{14}C) in dated tree rings. At present a series of ^{14}C data has been built for the last 11,400 years [*Stuiver et al.,* 1998]. This series is shown in Figure 3. Variations in the ^{14}C concentration in tree rings reflect slow variations in the geomagnetic field magnitude and also, as indicated above, faster solar activity variations. It can be seen from Figure 3 that the periodicity of occurrence of deep solar minima (maxima in the ^{14}C density) is 2300–2400 years. The first of these minima corresponding to the Maunder minimum was accompanied by a sharp cooling in Europe and the start of development of the so-called Little Ice Age [*Eddy,* 1976; *Shindell et al.,* 2001; *Soon and Yaskell,* 2003]. During the next, Homeric, minimum around 2700–2800 years BP, cooling and increase in humidity in Europe and climate change on other continents were also observed [*Dergachev et al.,* 2005; *Raspopov and Dergachev,* 2003; *Raspopov et al.,* 1998, 2000, 2005; *van Geel et al.,* 1998]. The solar minimum around 5400–5200 years BP was also accompanied by abrupt climate change [*Thompson et al.,* 2006]. At present data on climate change during the next deep solar minimum ∼7000 years BP are available: advance of glaciers occurred in Alaska and Canada [*Koch and Clague,* 2006]. However, it should be borne in mind that the development of this solar minimum took place on the background of the climatic optimum of the Holocene, and cooling could be not so noticeable. The next two deep solar minima also fall on the years of abrupt climate changes, i.e., near the boundary of the Holocene and Younger Dryas. Thus, almost all deep solar minima that occurred with a periodicity of 2300–2400 years were accompanied by large-scale climate changes. Along with this, analysis of abrupt climate changes in the Holocene has shown that not only deep solar minima. but also other processes caused coolings and abrupt climate changes. This is evident from the data presented in Figure 4. The upper panel of Figure 4 shows 200-year averaged data on the content of potassium (K) and sodium (Na) aerosols in Greenland ice for 11,400 years [*Mayewsky et al.,* 2004]. These data contain information on the character of atmospheric circulation in the North Atlantic region. A 2300–2400-year periodicity in the atmospheric circulation is clearly seen in the figure. The lower panel shows results of wavelet filtering (Morle basis) of variations in the ^{14}C concentration shown in Figure 3 for the range of periods 2000–3000 years. It can be seen that the solar minima repeating with a periodicity of 2300–2400 years coincide with increases in the contents of aerosols in Greenland ice, which points to intensification of the atmospheric circulation during these time intervals. Figure 4 also shows time intervals of glacier advance in Central Asia, the Southern Hemisphere, North America, and Scandinavia [*Denton and Karlén,* 1973; *Haug et al.,* 2001] and also the time intervals of glacier retreat in Switzerland [*Hormes et al.,* 2001]. It is evident from Figure 4 that the 2300–2400-year solar activity variations in the years of solar minima are accompanied by glacier advance. However, there are also the time intervals of cooling (glacier advance) that occurred at a high solar ac-

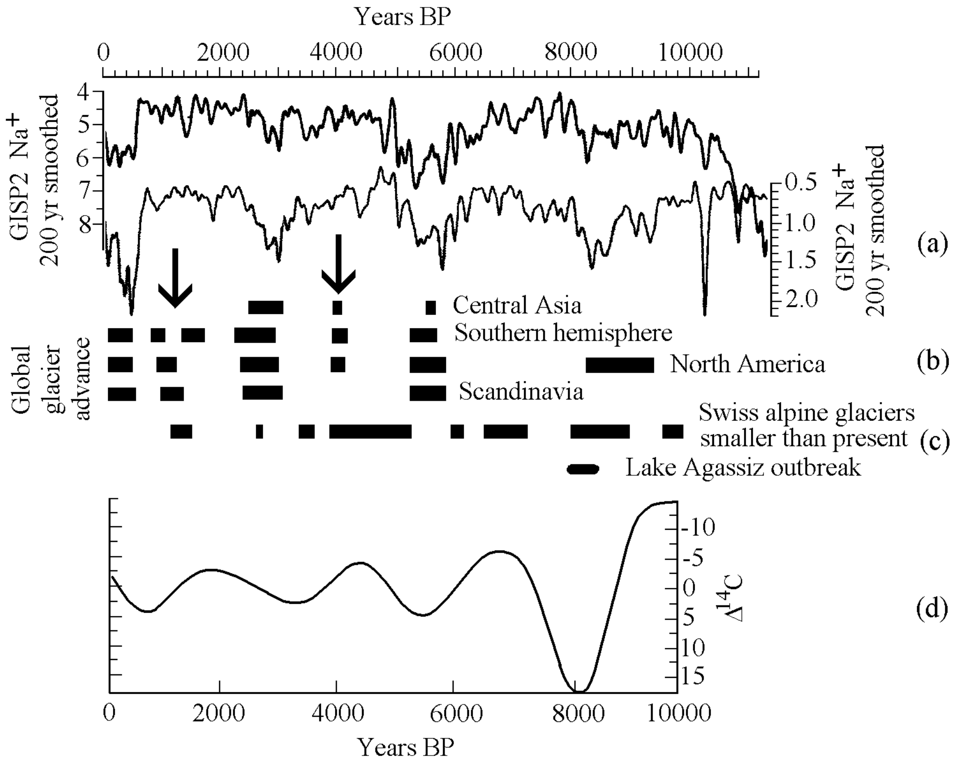

Figure 4. a – variations in Na and K aerosols in Greenland ice for the last 11,000 years [*Mayewsky et al.,* 2004]; b – time intervals of glacier advance [*Denton and Karlén,* 1973; *Haug et al.,* 2001]; c – time intervals of glacier retreat in the Alps [*Hormes et al.,* 2001]; d – variations in the ^{14}C concentration wavelet filtered in the range of periods 2000–3000 years (Morle basis) for the last 10,000 years.

tivity level. These intervals (around 1200–1400, 4000 years BP) are marked by arrows in Figure 4. Coolings during these time intervals are evidenced by the data on displacement of the Northern timberline in Northern Scandinavia and Canada [*Grudd,* 2006; *Helamma et al.,* 2004]. The timberline is a sensitive indicator of climatic conditions and ecological situation on the whole. It corresponds to a mean July isotherm of +11.5°C. A number of authors reported on multiple variations in the latitudinal and altitudinal timberline in Scandinavia and North European part of Russia derived from palynological and dendrochronological data [*Bjune et al.,* 2004; *Kultti et al.,* 2006; *MacDonald et al.,* 2000]. The maximum northward extent of forest was observed in the interval 4300–4000 years BP. Beginning from 4000 years BP, a southward retreat of the timberline associated with cooling has been taking place everywhere.

[8] Figures 5a,c show variations in the altitudinal timberline in Northern Finland and Northern Sweden, respectively, for the Holocene. Figure 5d presents time distribution of the number of subfossil logs used for plotting Figure 5a. In essence, this distribution also gives information on the timberline displacement in Northern Finland. The curves demonstrate that the timberline displaced around 5400–5200, 4200–3800, 2700–2200, 1500–1400, and 800–600 years BP. The first, third, and fifth time intervals correspond to deep solar minima, and the second and forth intervals correspond to advance of glaciers shown in Figure 4. Figure 5e presents variations in the high-latitude timberline in Canada, and Figure 5f shows reconstructed temperature variations in this region. Like in Scandinavia, coolings around 5000, 3800, 2500 and 800 years BP are observed. Note that the curves of average annual temperature in Scandinavia plotted on the basis of palynological data by *Seppä and Poska* [2004] and *Heikkila and Seppä* [2003] demonstrate temperature variations in the time intervals 5400–5100, 4300–3800, and 2800–2200 years BP. During these periods, a slight temperature increase was at first observed, then the temperature sharply fell, and after this an abrupt warming occurred.

[9] Analysis of palaeoclimatic data has shown that climate changes around 4200–3800 and 1500–1300 years BP had a global character [*Mayewsky et al.,* 2004; *Ristvet,* 2003]. While in Northern regions, such as Scandinavia and Canada, they were accompanied by coolings, in southern regions, such as, for example, Mesopotamia and Mexico, they were accompanied by the droughts that led to collapse of civilizations, such as the Akkadian Empire and Maya civilization, respectively [*Gill,* 2000; *deMenocal et al.,* 2000; *Hodell et al.,* 1991]. It is likely that the reason for such abrupt climate changes, which are not associated with deep solar minima of the Maunder type, is the development of internal processes in the atmosphere-ocean system.

[10] Analysis of bottom sediments of the North Atlantic has shown that ice-rafting events occurred in the North

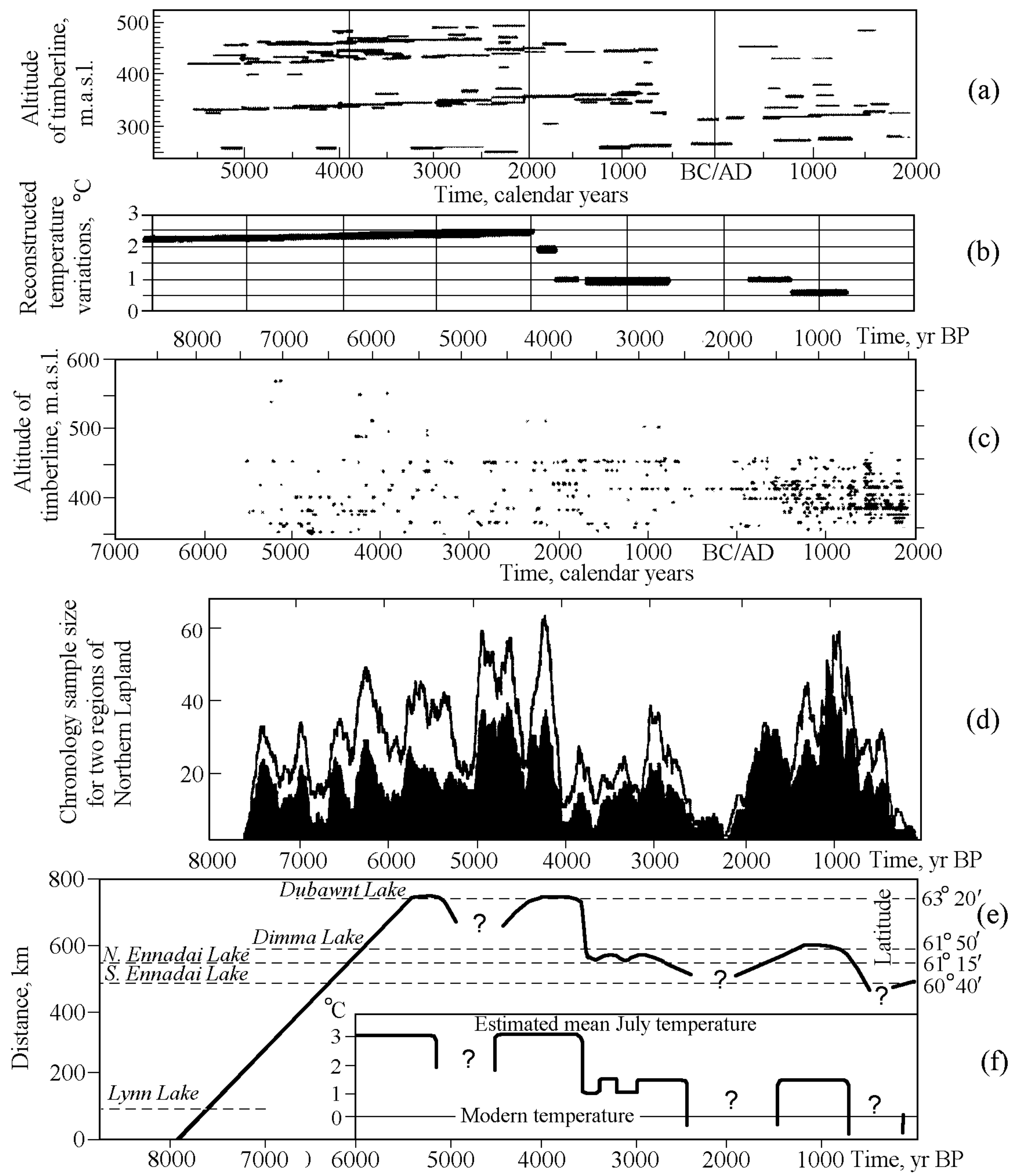

Figure 5. a – variations in the altitudinal timberline in Finnish Lapland for the last 8000 years [*Helamma et al.,* 2004]; b – variations in summer temperatures in Finnish Lapland for the last 8000 years reconstructed from dendrochronological data [*Kultii et al.,* 2006]; c – variations in the altitudinal timberline in Northern Sweden [*Grudd,* 2006]; d – the number of collected and dated subfossil logs in two regions of Finnish Lapland [*Helamma et al.,* 2004]; e – variations in the high-latitude timberline in Canada for the last 8000 years; f – variations in summer temperatures in Canada reconstructed from dendrochronological data.

Atlantic during both the Holocene and Pleistocene. A vivid example of ice rafting and a massive freshwater outburst is the outbreak of Lake Agassiz from the North American continent around 8200 years BP, which is well fixed in different palaeodata [*Renssen et al.,* 2001; *Rohling and Palike,* 2005]. This outbreak resulted in cooling on the global scale and was recorded in bottom sediments in the North Atlantic by an increase in the density of haematite grains and Iceland spar [*Bond et al.,* 2001].

[11] Comparison of the IRE development and solar activity variations (Figure 6) indicates that the IRE onsets coincide with or follow the time intervals of a high solar activity.

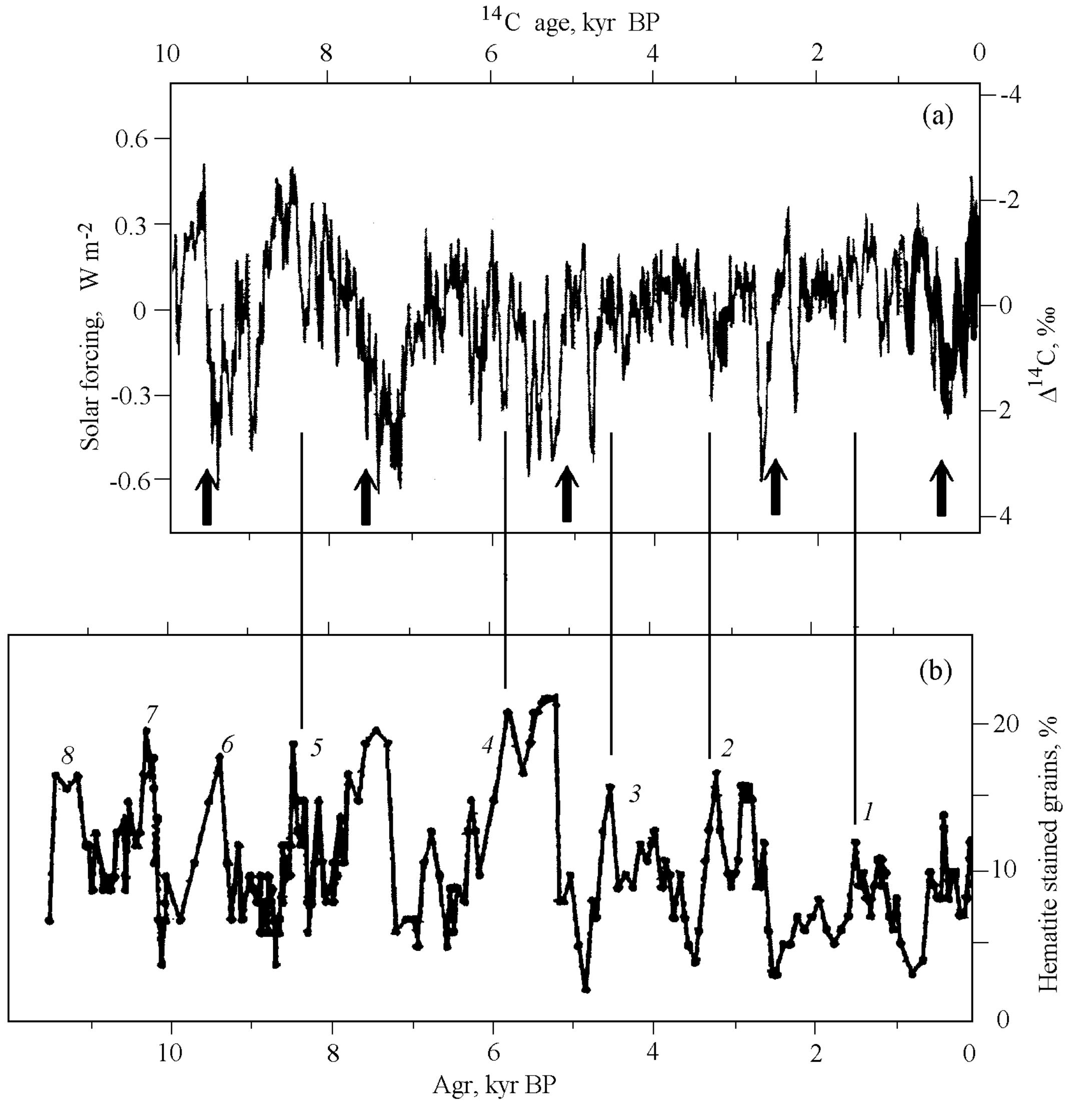

Figure 6. a – variations in Δ^{14}C for the last 10,000 years from the data of *Stuiver et al.* [1998] after removing the effect of variations in the geomagnetic dipole; b – ice-rafting events during the Holocene [*Bond et al.,* 1999]. The arrows show the time intervals of deep solar minima.

This is logical because, as simulation has shown, the IRE development results in an increase in the ocean surface temperature [*Shaffer et al.,* 2004], which must indeed occur in the case of a higher solar activity and, hence, a higher level of solar irradiance. It becomes evident from comparison of the times of glacier advance (Figure 4b) and time intervals of IRE (Figure 6) that the time intervals 1500–1400 and 4200–3800 years BP correspond to development of IRE (no. 1 and 3 in Figure 6) and, hence, the IRE could be stimulaters of abrupt global climate changes during these time intervals. Thus, abrupt climate changes in the past could be caused by not only a low but also a high level of solar activity.

4. Conclusions

[12] Analysis of the effect of long-term solar activity variations on climatic parameters on the time scales from 40,000 to 10,000 years BP (the Pleistocene) and from the modern times to 10,000 years BP (the Holocene) has been carried out. A comparative analysis of temperature and solar activity variations (variations in the contents of cosmogenic ^{10}Be isotopes in Greenland ice and ^{14}C in tree rings) has revealed two kinds of solar forcing of climate. On the one hand, deep solar minima create conditions for abrupt climate

change manifesting themselves in the most pronounced manner in the Holocene with a 2400–2300-year periodicity. On the other hand, a high level of solar activity and, hence, solar irradiance give rise to conditions for the development of dynamic processes at the Earth's surface, such as ice-rafting events in the North Atlantic. Simulation has shown that ice-rafting events can be stimulated by an increase in the ocean surface temperature, i.e., the conditions produced by a high solar activity level and a high level of solar irradiance. Ice-rafting events sharply change the character of the North Atlantic overturning circulation (NAOC) by moving the northern edge of the Gulf Stream southwards, which leads to abrupt climate change of the global nature.

[13] Analysis of experimental data has revealed that a high solar activity level stimulated development of ice-rafting events in both the Pleistocene and the Holocene. Thus, it can be concluded that both deep solar minima and a high solar activity level can create conditions for abrupt climate change.

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O. M. Raspopov, St.Petersburg Filial of Pushkov Institute of Terrestrial Magnetism, Ionosphere, and Radiowave Propagation of RAS, St.Petersburg, Russia, fax (812) 310 50 35, e-mail: oleg@or6074.spb.edu

V. A. Dergachev, Ioffe Physico-Technical Institute of RAS, St.Petersburg, Russia, e-mail: v.dergachev@mail.ioffe.ru

T. Kolström, Mekrijärvi Research Station, University of Joensuu, Finland

A. V. Kuzmin, Polar Botanical Garden-Institute KolaSC RAS, Kirovsk, Murmansk Region, Russia

E. V. Lopatin, Mekrijärvi Research Station, University of Joensuu, Finland; Biology Institute of KomiSC of Ural Branch, RAS, Syktyvkar, Russia

O. V. Lisitsyna, Oulu University, Finland