The nature of the storm activity in the northwest Atlantic during the Holocene and its possible connection with variations in the Earth's magnetic field

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Abstract. The data on the concentration of ions in the core of the Greenland Ice Sheet Project 2 (GISP2) were analysed to find the cause of storm activity in the north-west Atlantic during the Holocene. It was shown that there is cyclical transfer of ionic components with a period of \(\sim 2700\) years due to changes in storm activity. As a possible cause of storm changes, secular variations in the position of the geomagnetic pole over the past several thousand years have been considered. In particular, the periodicity of fluctuations in the longitude of the north geomagnetic pole was compared with the frequency of intensification of storm activity. It has been demonstrated that the spectra of these variations are similar, from which it is concluded that secular variations in the magnetic field are the basis of the processes that determine the variability of storm activity and climate in the north-west Atlantic during the Holocene.

1. Introduction

Until the end of the 20th century, it was believed that the climate in the Holocene was stable without significant changes in such manifestations as temperature fluctuations, precipitation and the transfer of atmospheric masses by wind.

Records from glacial cores of Greenland showed that climate variability was markedly more suppressed during the Holocene than it was during the last glaciations, although there is significant climatic diversity (see [1]–[3]).

The change in storm activity in the north-west Atlantic during the Holocene has attracted attention since the publication of O''Brien et al. [4]. When studying time series from the Greenland Ice Sheet Project 2 (GISP2) ice core, chemical concentrations of ions were determined. These concentrations were used to estimate the rate of accumulation of sea and terrestrial salt ions. O'Brien et al. showed that during the formation of ice cores in Greenland, the rate of accumulation of water-soluble components and continental dust varied significantly. The nature of these changes is associated with variations in wind speed and direction. Fluctuating fluxes of ions have changed significantly over several thousand years. Changes in ion fluxes are apparently related to climate variations in the North Atlantic. The study of this problem has been the subject of several works.

2. Mixing the atmosphere over Greenland

Information on climatic changes over the past several tens of thousands of years has been accumulated in the cores of the glaciers of Greenland. The most important ion composition analysis information was obtained as part of the Greenland Ice Sheet Project 2 (GISP2). These data contain information on the concentration in ice of cations such as \(\text{Na}^+\), \(\text{K}^+\), \(\text{Mg}^+\), \(\text{Ca}^{2+}\) and the anions \(\text{NH}_4^+\), \(\text{Cl}^-\), \(\text{NO}_3^-\), \(\text{SO}_4^{2-}\).
There are two ways for ions arrival in the atmosphere. The first way is receive aerosols from the sea surface. Another way is the transfer of continental dust by the wind. Both in the first and in the second case, intensive transport of the substance by air flows is necessary. The concentration of ions in the ice core shows how effective the transfer is. Figure 1 shows the concentration of $K^+$ ion after the removal of a long-term trend.

![Figure 1. The concentration of K$^+$ ions from the GISP2 project data for 10 thousand years. Concentration is given in ppb units (parts per billion). The upper and lower lines are spaced from average value (middle line) at a standard deviation distance.](image)

It can be seen that the ion concentration had varied cyclically. Apparently, the speed of the wind, carrying dust or aerosols, also had varied. To find out how common the phenomenon of cyclic changes in the transfer rate is, we examined the data for all anions and cations, with the exception of sulfates, the main source of which are volcanic eruptions.

![Figure 2. Periodogram of averaged ion concentration. The upper smooth curve limits the amplitudes, the significance of which is less than 0.95. The lower curve shows the amplitudes in red noise model.](image)

To calculate the mean cycle length, subtracting long-term trends was performed. Relative concentrations for all ions were calculated, then they were averaged and a periodogram of averaged values was calculated (see Figure 2). It is shown that the average cyclicity length is 2,700 years. The line present on the periodogram with a period of 1,350 years is apparently the harmonic of the main periodicity. To clarify the nature of concentration variations with a period of ~ 2700 years, some forcing mechanisms influencing changes in climatic processes should be considered. The most promising, in our opinion, are the phenomena associated with changes in the Earth's magnetic field.

3. Some mechanisms of magnetic field impact
Several mechanisms have been proposed in recent decades that could explain the relationship of the geomagnetic field to climate. The most interesting explanation is related to the flow of galactic cosmic rays penetrating the Earth's atmosphere. The flux of galactic cosmic rays is modulated by both the magnitude of solar activity and the strength of the dipole magnetic moment of the Earth, which acts as a protective shield. High values of the solar activity and magnetic field of the Earth reinforce shielding, as a result of which a low density of galactic cosmic rays entering the Earth’s atmosphere is expected [5].
Cosmic rays (CR) can play an important role in cloud formation [6], and thus the geomagnetic field can participate in climate processes. Thus, a decrease in the geomagnetic field strength and the magnitude of solar activity would increase the arrival of galactic cosmic rays to the Earth, which could enhance the formation of low-lying clouds [7], [8] or increase the global cloud cover, which will lead to cooling of the troposphere [9].

In the work of Kilifarska et al. [10], geomagnetic field variations are used to explain the variability of weather and climate phenomena. A physical mechanism is discussed explaining how the Earth's magnetic field can affect the spatial distribution and temporal changes in surface air temperature. The process is determined by the magnetic field modulation of the intensity and depth of penetration of energetic particles into the Earth’s atmosphere, which initiates ion-molecular reactions.

4. Changes in the position of the geomagnetic pole and climate

In addition to changing the magnitude of the geomagnetic field, the position of the geomagnetic pole can affect the climate. Bucha and Zikmunda [11] suggested that drifts of geomagnetic poles could cause displacements of the regions of increased pressure in the Earth’s atmosphere, which is associated with an increase in cyclonic activity and sudden changes in climate. And in the works of Bucha and Bucha [12] it was shown that the position of the geomagnetic pole and the corpuscular radiation of the Sun causing geomagnetic activity have a significant effect on the atmospheric circulation in Europe.

Bakhmutov [13] calculated the drift of virtual geomagnetic poles (VGP) for a time interval of 13,000–5,000 years ago. Paleomagnetic data from northern Russian lake sediments were used, mainly from Karelia and the Kola Peninsula. Based on the data obtained and within the framework of the hypothesis of Bucha and Bucha [12], the relationship between long-term climate changes and variations in the geomagnetic field with a characteristic time of \((10^2–10^3)\) years is discussed. It was found that the alternation of cold and warm periods correlates with the approach of VGP to Northern Europe or the moving away from it.

Similar conclusions follow from the results of Kovaltsov and Usoskin [14], where cosmic ray-induced ionization (CRII) is considered, which is an important factor in the cosmic influence on atmospheric processes. CRII variations are caused by two different processes: variations in solar activity that modulate the flux of cosmic rays in interplanetary space, as well as a change in the geomagnetic field, which affects the access of cosmic rays to the Earth. The migration of the axis of the geomagnetic dipole can greatly change the ionization process (CRII) over a time interval of the order of several centuries. It was shown that the regional effects of migration of the axis of the geomagnetic dipole can exceed the changes due to variations in solar activity.

Vasiliev and Dergachev [15] discussed the mechanisms of long-term climate change on Earth. Long-term changes in temperature are usually associated with an increase in the concentration of carbon dioxide in the atmosphere. It follows from the analysis that the increase in temperature is ambiguously associated with an increase in the concentration of CO2. A regression analysis of data on temperature, carbon dioxide concentration and latitude of the north magnetic pole (NMP) for 1970–2010 was carried out. It is shown that the dependence of zonal temperature on the latitude of the pole increases significantly for the polar zone (N 90° – N 64°) in comparison with the zones covering middle and subtropical latitudes (N 90° – N 24°, N 90° – 0°). This allowed us to conclude that processes that additionally affect the temperature change are localized in the polar zone. The relationship of arctic oscillations (AO) with a change in the latitude of the NMP was considered. It is shown that a change in the AO phase occurs during periods of an increase in the speed of the NMP movement.

5. Fluctuations in the position of the north geomagnetic pole over the past 7,000 years

In what follow, we will consider data on the change in the position of the geomagnetic pole over the past 7,000 years according to Korte and Mandea [16]. The position of the pole is counted in the positive direction, i.e. to the East. For convenience, a value of 360° has been added to longitude.

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last 4 centuries, there was a western drift of the north geomagnetic pole. As noted by Korte and Mandea, during the considered time interval, North pole moved, both west and east. On average, eastern drift prevailed. The magnitude of the drift, estimated by the linear trend, is (0.05–0.06)°/year. Figure 3 shows the change in longitude of the North Geomagnetic Pole (NGP) after subtracting a linear trend. In addition to its eastward displacement, the NGP deviates from the trend and performs swings.

To study the possible relationship between secular variations of the magnetic field and climate variations, we have analysed the periodogram of longitude fluctuations of the north geomagnetic pole.

Figure 4 shows the main features of these fluctuations. The spectrum contains spectral lines with multiple periods: 2700, 1350 and 710 years. Lines with periods of 2700, 1350 years are also present on the periodogram of the averaged ion concentration for GISP2 data (see Figure 2). The fact that the lines coincide in these two periodograms indicates a possible physical connection between these processes. For the coincidence and synchronism of processes of changes in the ion concentration and fluctuations in the position of the geomagnetic pole, it is important not only the identity of the lines, but also the significance of the appropriate lines of the cross-spectrum.

To verify the relationship between the position of the geomagnetic pole and climate change, it would be interesting to find other arguments in favor of this relationship. To explore this possibility, you can use some archaeological artifacts (see the next section).

6. Change in the intensity of the magnetic field in Paris and the climate over the past 3000 years

Gallet et al. [17] obtained new archaeological data from French’s faience fragments dated to the 17-19th centuries. These data made it possible to establish the occurrence of sharp changes in the secular fluctuations of the geomagnetic field in Western Europe over the past three millennia. The intensity change curve shows several maxima. The characteristic time of increase and decrease in intensity was ~ 100 years. The ascending parts of intensity coincide in time with the occurrence of cooling, recorded in this region in natural and historical data (see Gallet et al. [17], figure 2). This coincidence indicates
a causal relationship between the secular change in the geomagnetic field and climate change over a hundred-year time scale.

We compared changes in the magnetic field intensity in Paris with variations in the NGP longitude (see Figure 3). For this, a long-term trend was removed from the intensity data, and then a cross-spectrum (amplitude spectrum) was calculated. It is shown that the common cyclic components have periods of ~ 1350 and ~ 710 years (see Figure 5). There is no component with a period of ~ 2700, because the length of the series in intensity is insufficient. From the results it follows that there is a relationship between the position of the north geomagnetic pole, the regional intensity of the magnetic field and climate changes in the north-west Atlantic.

An analysis of the data on changes in the magnetic field intensity in Paris over the past 3,000 years confirms the idea of the relationship between secular changes in the magnetic field and climate variations.

7. Conclusions
An analysis of the data on individual ions shows that the time intervals of intensive transfer are repeated on average after 2,500-3,000 years. It has been shown that there is a cyclical process of ion transfer, and the average cycle length is 2,700 years.

It is shown that the most probable is the connection between fluctuations in the longitude of the north geomagnetic pole and the variability of storm activity, since the periodograms of these processes are similar. The similarity of periodograms is a convincing argument in favor of the existence of a causal relationship of these processes. As an additional argument confirming the influence of secular variations of the magnetic field on storm activity, we considered the relationship between variations in the regional intensity of the magnetic field (Gallet et al. [17]) and fluctuations in the longitude of the north magnetic pole. The cross-spectrum of these data was calculated and the statistical significance of the amplitude spectrum was confirmed (Figure 5). Based on the results of comparing these data, it can be concluded that secular variations in the magnetic field are basis of processes that determine the variability of storm activity and climate in the north-west Atlantic.

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