Changes in solar activity based on radiocarbon data and climate variations in the interval 8000 – 1000 BC

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Abstract. This work examines the change in the activity of the Sun based on the reconstruction of the heliospheric modulation potential in the time interval 8000 - 1000 BC. Reconstructions of this potential were obtained using radiocarbon data, taking into account the influence of changes in the Earth's climate. A comparison is made of the variations in the activity of the Sun with the global surface temperature. It is shown that variations in global temperature during this period could be the result of changes in solar activity. So high solar activity could lead to recorded temperature maximums around 7000 and 5300 BC. The drop in temperature in the range 3000-1000BC could be the result of low solar activity.

1. Introduction
Studying the causes of changes in the Earth's climate on long time scales is of great interest. It is known that the Earth periodically experienced global cooling and warming, which is evidenced by the change in the content of carbon dioxide CO₂ in the Earth's atmosphere (Figure 1a) [1]. The period of the last warm interval in which we live, and which began about 12 thousand years ago, is called the Holocene. The maximum values of CO₂ concentration in the past were reached during warm periods, like the Holocene, and the minimum - during periods of maximum glaciation. It is obvious that the cause of such climate changes in the past is natural. Such reasons can be of both terrestrial and cosmic origin. Until the beginning of the 20th century AD, the CO₂ concentration did not exceed 300 ppm. In this work, we will consider the possibility of a change in the Earth's climate in the Holocene under the influence of variations in solar activity. Could variations in solar activity lead to observed variations in climate in the Holocene? In the article, we will consider the time interval 8000-1000 BC, i.e. after the end of the last glaciation. Changes in the global surface temperature, according to [2-4], in this interval are shown in Figure 1b. According to [1], about 18 thousand years ago, a rapid increase in the concentration of CO₂ in the Earth's atmosphere began, accompanied by an increase in temperature [2-4], which stopped at about 7000 BC. According to [1], the CO₂ concentration by this time was ≈260 ppm, and by the beginning of our era it reached ≈ 277 ppm. Figure 1b shows the change in the global temperature on Earth in the time interval 8000-1000 BC, which at about 7000, 5300 and 3300 BC reached maximum values, and after ≈ 3100 BC it sharply decreases. Could such temperature fluctuations be the result of variations in solar activity? And could such an influence of the Sun be reflected in the radiocarbon data?
2. Heliospheric modulation potential, solar activity and global temperature variations in the interval 8000-1000 BC

It is well known that the data on the content of the cosmogenic isotope $^{14}$C in the tree rings make it possible to reconstruct the production rate of this isotope in the Earth's atmosphere under the action of cosmic rays in the past. This makes it possible to study the history of solar activity using data from the $^{14}$C isotope in natural archives. For this, we will use a model that describes the exchange of carbon between natural reservoirs: atmosphere, biosphere, humus and ocean. It should also be borne in mind that variations in the terrestrial climate can affect the redistribution of carbon between these reservoirs. In the scientific literature, when reconstructing solar activity from radiocarbon data in the Holocene interval, as a rule, changes in the carbon exchange system were not taken into account. However, it was shown in [5] that climate change during the Little Ice Age affects the results of reconstructions of solar activity, which indicates the need to take into account the exchange of carbon in reservoirs when calculating the rate of production of the $^{14}$C isotope in the atmosphere. In [6, 7], a model was constructed that describes the change in the radiocarbon exchange system during climate change after the last global glaciation, which makes it possible to reconstruct the production rate of $^{14}$C [8] and the heliospheric modulation potential (HMP) [9] in the 17000-5000 BC time interval. As we know, this time interval is characterized by the end of the last ice age and the transition to the Holocene - a rather warm period that lasts to the present time. During the transition from the Ice Age to the Holocene, as it is known, there was an increase in the global temperature [2-4] and the concentration of carbon dioxide in the Earth's atmosphere [10]. Consideration of the influence of these factors of global temperature change on the rate of radiocarbon transition from the upper layer of the ocean to the atmosphere and from the atmosphere into the biosphere made it possible to reconstruct the rate of production of the $^{14}$C isotope in the Earth's atmosphere [8] and HMP [9]. For this, the linear temperature dependence of the rate of radiocarbon transition from the upper layer of the ocean to the atmosphere was used:

$$\lambda_{mOa} = (1 + k_1 \cdot \Delta T) \lambda_{mOa}^0,$$

where $\Delta T$ are global temperature anomalies [2-4]. The value of the coefficient $k_1$ is in the range (0.04-0.05) $^\circ$C$^{-1}$ K [6]. 17000 BC was selected as the starting time $t_1$. For the rate of transition of radiocarbon from the atmosphere to the biosphere, a more complex dependence was used [7]:

Figure 1. (a) - Changes in CO$_2$ concentration in the past [1] from 1950 AD, (b) - Global temperature anomalies [2-4].
where \( t_2 \) is the point in time from which the rate of transition of \(^{14}\text{C}\) from the atmosphere to the biosphere begins to change, and this change is characterized by the coefficient \( k_2 \), and is associated with a change in vegetation. In the calculations, it was assumed that \( t_2 = 8300 \text{ BC} \), \( t_3 = 5000 \text{ BC} \). In this case, the value of \( \lambda_{ab}^1 \) was taken 15\% less than the value for the middle of the 20th century AD given in [11] (see also [5]). The \( k_2 \) value can be \( \approx 0.01 - 0.02 \text{ K}^{-1} \). The calculations were carried out according to the 5-reservoir model of the radiocarbon exchange system.

As noted above, in [6-9], consideration was limited to the interval of 5000 BC. However, in the Middle Holocene, climatic changes also took place, the most global of which was accompanied by the transformation of the Sahara into a desert. Such climatic changes could not but affect the exchange of carbon between the atmosphere and the biosphere. Let's consider this issue in more detail. For this, we will assume that from time \( t_2 \) to time \( t_3 \) the rate of transition from the atmosphere to the biosphere \( \lambda_{ab}(t) \) changes according to (2), and from time \( t_3 \) the dependence \( \lambda_{ab}(t) \) becomes linear until the time \( t_4 \), at which \( \lambda_{ab} \) takes modern meaning and does not change anymore. We will carry out the calculations according to [9] with the same other values of the parameters of the five-reservoir model using the radiocarbon data of Intcal13 [12].

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\begin{align*}
\lambda_{ab} &= \lambda_{ab}^1 n(p u(t_1 < t < t_2) \\
\lambda_{ab} &= \lambda_{ab}^1 (1 + k_2(T(t) - T(t_1)) \sqrt{t - t_2}) n(p u(t_2 < t < t_3))
\end{align*}
\]

\[(2)\]

Figure 2a shows the results of calculating the change in the total content of the \(^{14}\text{C}\) isotope in the atmosphere, biosphere, humus and ocean. Figure 2b shows the change in the Earth's magnetic dipole moment according to [13]. From a comparison of these figures, it can be concluded that a decrease in the total content of \(^{14}\text{C}\) at time intervals of 10000 - 7000 BC and 4000-1000 BC may be associated with an increase in the Earth's magnetic field, which prevents the penetration of charged GCR particles into the Earth's atmosphere. The activity of the Sun also affects the production rate of \(^{14}\text{C}\) in the atmosphere and the content of this isotope in natural reservoirs.

Figure 3a,b shows the results of calculations of the production rate \( Q \) of the \(^{14}\text{C}\) isotope in the Earth's atmosphere for the times \( t_3 = 5000 \text{ BC} \) and \( t_4 = 3200 \text{ BC} \) and the reconstruction of the heliospheric modulation potential \( \phi(t) \) (HMP). It is well known that variations in HMP reflect variations in solar activity (SA). An increase in SA leads to a decrease in the intensity of GCR
penetrating into the interior of the solar system into the Earth's atmosphere and to an increase in φ (t). Thus, HMP reconstructions allow us to study the activity of the Sun in the past. The need to move from considering the production rate of $^{14}$C to considering HMP is due to the fact that the rate of $^{14}$C production in the atmosphere under the action of HMP is influenced by the time-varying magnetic field of the Earth. While HMP describes the modulation of the GCR in interplanetary space, i.e. outside the Earth's magnetosphere. The calculations of φ (t) were carried out using the values of the magnetic dipole moment given in [13] (Figure 2b) and using the method described in [14, 15].

The results of calculations show that at $t_4=3200$ BC the value of φ (t) decreases sharply after 3150 BC and this reconstruction describes the decline in solar activity from 3200 BC to 1000 BC. At the same time the global surface temperature decreases (Figure 1b). Note that the increased temperature intervals of about 7000 and 5000 BC corresponded to an increased value of φ(t) (Figure 3b). The decline of φ(t) (and the activity of the Sun) between 7000 and 5000 BC corresponds to the decline of GMP.

Figure 3c, d shows the results of calculations of the production rate of $^{14}$C at $t_4=1500$ BC. In this case, the value of φ (t) is kept at a high level in the range of about 5000-1700 BC and does not correspond to a decrease in the global temperature of about 3000 BC. However, high values of φ(t) around 7000 and 5000 BC also correspond to an increased global temperature.
3. Conclusion
The paper considers a possible connection between variations in the global surface temperature of the Earth in the time interval 8000-1000 BC with variations in solar activity. As an indicator of solar activity, we used the values of the heliospheric modulation potential, reconstructed on the basis of the radiocarbon data of IntCal13 [12] for various values of the rate of $^{14}$C transition from the atmosphere to the biosphere. The possibility of linking variations in global temperature with the activity of the Sun is shown. The decrease in global temperature in the time interval 3000-1000 BC could be caused by low solar activity. The observed temperature maximums around 7000 and 5300 BC could be caused by high solar activity.

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