Radiocarbon data from the Most Ancient Dryas to the Younger Dryas: cosmic rays and climate

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Abstract In the present work we consider the abundance of radiocarbon ($\Delta^{14}$C) in the Earth’s atmosphere in 12000-8500 BC years. Some periods of sharp cold and warming are fixed in this time interval. The so-called Younger Dryas ($\approx 10700$–$9700$ BC) is one of the most well known examples of dramatic change of terrestrial climate. The Younger Dryas ($\approx 10700$–$9700$ BC) lasted for ca one thousand years and a transition from the Last Glaciation to the interglacial Holocene has happened about 12 thousand years ago. During the Younger Dryas the amount of $\Delta^{14}$C increased within $\approx 10800$–$10560$ BC by 3% and it decreased by 6 % over a period 10560–9680BC. The reconstructions of the radiocarbon production rate and the heliospheric modulation potential based on $^{14}$C and $^{18}$O data sets are presents. The periods of extreme levels of these parameters are determined.

1. Introduction
It is well known that the cosmogenic isotopes $^{14}$C are produced in the Earth's atmosphere by high energy particles of Galactic Cosmic Rays (GCR). The variations of solar activity (SA) lead to changes of the interplanetary magnetic field and as consequence to variations of GCR flux. Therefore the data on the radiocarbon abundance in annual tree rings and Earth’s atmosphere enable to study the intensity of GCR and the history of solar activity in the past. However some problems exist on this way. So the variations of terrestrial climate distort the information about changes of GCR intensity and about solar activity variations fixed in the radiocarbon data. In the present work we consider the abundance of radiocarbon ($\Delta^{14}$C) in the Earth’s atmosphere in 12000-8500 BC. Some periods of sharp cold and warming are fixed in this time interval. The first time interval is the so-called Most Ancient Dryas ($\approx 11850$—$11700$ BC), the next interval Ancient Dryas ($\approx 11600$—$11400$ BC) and Younger Dryas ($\approx 10700$–$9700$ BC) are the periods of sharp cold.

The so-called Younger Dryas is one of the most well known examples of the dramatic change of terrestrial climate. The Younger Dryas is clearly observed in different paleoclimatic records. A sudden cold period took place after a period of increased global temperature and melting of glaciers. The Younger Dryas ($\approx 10700$–$9700$ BC) lasted for ca one thousand years and a transition from the Last Glaciation to the interglacial Holocene has happened about 12 thousand years ago. During the Younger Dryas the amount of $\Delta^{14}$C decreased by 6 %. Is this decrease associated with changes in the intensity of GCR or is it related to climatic changes? To answer this question the variations of the absolute abundances of $^{14}$C isotope in the Earth’s atmosphere, biosphere, humus and ocean obtained on the basis of $\Delta^{14}$C and the concentration of CO$_2$ in the atmosphere were analyzed [1]. So the concentration of atmospheric $^{14}$C isotope during the Younger Dryas varies only by $\approx 2\%$ (see also [2]).
Thus, the major part of $\Delta^{14}C$ variations can be related to the variations of CO$_2$ in the Earth’s atmosphere after its redistribution between the atmosphere and the ocean due to changes of global temperature. The remaining part of $\Delta^{14}C$ variations in the atmosphere can be associated with alterations of the $^{14}C$ production rate due to the changes of SA and the geomagnetic field. The reconstructions of the radiocarbon production rate and the heliospheric modulation potential based on $^{14}C$ and $^{18}O$ data sets are presented in the present work.

2. The variations of $^{14}C$ isotope content in the Earth’s atmosphere and climatic change during 12000-8500 BC

Let us consider the radiocarbon and climatic data sets during the time interval 12000-8500 BC. The atmospheric radiocarbon abundances ($\Delta^{14}C$) according to IntCal09 [3] and IntCal13 [4] data sets are shown below in Figure 1a. It is known that the parameter $\Delta^{14}C$ describes the deviation of ratio of the isotope $^{14}C$ and $^{12}C$ contents ($R^{14}C/12C$) from standard value $1.176 \times 10^{-12}$ (see for example [2,5]). The reliable calibration curves IntCal09 [3] and IntCal13 [4] were created in 2009 and 2013 years for correct using by radiocarbon method. These data took into account the variations of ratio $^{14}C/^{12}C$ for various epochs and for many locations in the world.

We can see in Figure 1a the set of minima and maxima of the $\Delta^{14}C$ values. Also it is possible to select two time intervals. The values of $\Delta^{14}C$ weakly increase before 11560 BC and $\Delta^{14}C$ sharply decrease after 11560 BC. The values of $\Delta^{14}C$ reach the local minima during the Most Ancient Dryas and the Ancient Dryas, however the same differences between IntCal09 and IntCal13 data sets take place. The large changes of $\Delta^{14}C$ take place during the Younger Dryas (10800 - 10560 BC). The value of $\Delta^{14}C$ is increased by ~3% during 10810-10560 year BC and fast declined thereafter.

It is well known that the concentration of carbon in the Earth’s atmosphere can change as the result of climate change. The climatic changes can result in the carbon redistribution between the natural reservoirs (the atmosphere, biosphere, humus, mixed and deep ocean layers). The variations of cosmic ray (CR) intensity penetrating into the Earth’s atmosphere also affect on the radiocarbon abundance in the atmosphere.

The variations of carbon dioxide (CO$_2$) concentration in the terrestrial atmosphere are shown in Figure 1b. According to the paper [6] the increase of the CO$_2$ concentration took place during $\approx$ 16000-11700 BC. The next increase CO$_2$ concentration occurred during $\approx$ 10500-9100 BC. This increase was accompanied by the decrease of $\Delta^{14}C$ value (see Figure 1a). The increase of CO$_2$ concentration can be explained by redistribution between the ocean and the terrestrial atmosphere as a result of the global temperature growth (Figure 1c) [7, 8]. Here it is necessary to note that radiocarbon concentration tends to weak growth during the time interval 11700-9300BC [7, 8]. This tendency contradicts to time dependence of $\Delta^{14}C$ (t). This distinction can be explained if carbon dioxide depleted by $^{14}C$ isotope going into the atmosphere from deep layers of the ocean and thawing glaciers since middle 11 millenia BC.

Figure 1d shows the data about isotope $^{18}O$ content in glaciers of Greenland [10]. These data ($\delta^{18}O$) describe the temperature of ice at its formation. It is known the dependence between $\delta^{18}O$ and the temperature of ice formation can be described as $\delta^{18}O=\alpha T+\beta$, where $\alpha$ and $\beta$ are constants (see for example [11]). Therefore $\delta^{18}O$ data sets can be used as the temperature indicator in the past. So, the minimum of value $\delta^{18}O$ in 11690 BC coincides with the the Most Ancient Dryas. Also we can see the Younger Dryas epoch (10700-9700BC) in Figure 1d.

3. Radiocarbon production rate and geliospheric modulation potential.

Let us calculate the radiocarbon production rate (Q) based on $^{14}C$ data sets. As a first step we consider the variations of radiocarbon content in terrestrial atmosphere using next equation

$$^{14}C(t) = \frac{^{12}CO_2(t) \cdot R_{st} \cdot (1 + \Delta^{14}C(t)/100)}{100}$$

(1)

where $^{12}CO_2(t)$ is the content of $^{12}CO_2$ molecules in the atmosphere; the value of $\Delta^{14}C$ is expressed in percents.
It is known that the ratio of $^{12}$C atoms concentration to the concentration of all carbon isotopes is $x=0.989$. So we can calculate the time dependence of $^{12}$CO$_2(t)$ based on CO$_2$ concentration data set [6].

In order to calculate the radiocarbon rate production $Q(t)$ we used the five reservoirs model. This model describes the radiocarbon exchange between the atmosphere, biosphere, humus, mixed and deep ocean layers. The method of calculation is well known and described in papers [9,12,13]. According to [9,12,13] we used the following equation for the rate of radiocarbon transfer $mOa$ from the mixed ocean layers to the atmosphere:

$$\lambda_{mOa} = (1 + k_1 \cdot \Delta T)\lambda^0_{mOa}$$  \hspace{1cm} (2)

where $k_1$ is the temperature coefficient, $\Delta T$ is the temperature anomaly.

![Figure 1](image)

Figure 1. (a) - $\Delta^{14}$C according to [3,4]; (b) - the carbon dioxide concentration in the atmosphere according to [6]; (c) - the global temperature variations according to [6,7]; (d) - the isotope $^{18}$O anomaly in Grenland ice sheet [10].

The value of $k_1$ can reach the next value 0.04-0.05K$^{-1}$ for time interval 17000-5000BC [13]. Now we will calculate at $k_1=0.045K^{-1}$. Also we use the radiocarbon content in the atmosphere according to the equation (1). Figure 2a shows the radiocarbon production rate reconstructed on the base of IntCal13 data set.

Now we will consider the result of calculations of $Q(t)$ on the base of $\delta^{18}$O data sets. We used the following equation for $\lambda_{mOa}$:

$$\lambda_{mOa} = (1 + k_2 \cdot (\delta^{18}O - \delta_0^{18}O))\lambda^0_{mOa}$$  \hspace{1cm} (3)
where δ$_{18}^{O}$ is the average value during 1960-1980 years.

The Figure 2b shows the result of calculation for $k_2 = 0.007 \text{ permil}^{-1}$. So, it is possible to select the few time intervals of high intensity of CR coming in the terrestrial atmosphere. Such intervals are approximately 11765 (11780), 11100 (11120), 10700, 10425 (10420), 9245, 9150 BC, when the values of Q exceeded 2.5 at cm$^{-2}$s$^{-1}$. Some peaks can be a result of powerful solar flares or a result of GCR bursts. The solar activity changes also lead to variations of the radiocarbon production rate since they modulate the GCR intensity in the Heliosphere.

![Figure 2](image)

**Figure 2.** The reconstructions of radiocarbon production rate on the base of variations of the global temperature (a) and δ$_{18}^{O}$ data sets (b).

Now we consider the reconstruction of heliospheric modulation potential which describes the solar activity variations. The method of this reconstruction is described in [14,15]. In order to reconstruct this potential we used the geomagnetic dipole moment according to [16] (Figure 3a). The result of calculation is presented in Figure 3b. The reconstruction shows that the solar activity can reach the maxima close to 10940, 10200, 9560 BC and grand minima close to 9700, 9200-9000 BC. Very high solar activity years are 10940, 10200, 9565 BC. It is possible also that the time intervals close to 9700, 9200-9000 BC were the periods of grand minima of solar activity.

![Figure 3](image)

**Figure 3.** (a) - the geomagnetic dipole moment according to [16]; (b) – the heliospheric modulation potential.
4. Conclusion
The radiocarbon production rate and the geliospheric modulation potential were reconstructed during the time interval 12000-8500BC. The reconstruction took into account the climatic variations. The periods of extremely high radiocarbon production rate are located. These periods are 11765 (11780), 11100 (11120), 10700, 10425 (10420), 9245, 9150 BC. The periods of very high solar activity are 10940, 10200, 9565 BC. It is possible also that the time intervals close to 9700, 9200-9000 BC were the periods of grand minima of solar activity.

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