RECONSTRUCTION OF THE ATMOSPHERIC RADIOCARBON PRODUCTION RATE FROM THE END OF LAST GLACIATION BEFORE THE MID-HOLOCENE

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1. INTODUCTION

It is known that the cosmogenic isotope ^{14}C is generated in the Earth's atmosphere by high energy charged particles of galactic cosmic rays (GCR). Intensity of GCR in the vicinity of the Earth's orbit is not constant and varies due to changes in solar activity. Changes in geomagnetic field intensity influence the spectrum of GCR in the atmosphere.

The account of these processes makes its possible to use the concentration of ^{14}C the Earth's atmosphere for estimation of solar activity during the past epochs, when we have no records of direct observations of the Sun.

The most reliable data of ^{14}C content in dated samples cover the last few tens of thousands of years whereas the duration of currently available reconstructions of the radiocarbon production rate (the intensity of GCR) are limited by the Holocene – the epoch when climatic changes are typically considered as negligible in the frame of some plausible approximation.

In the present work we consider reconstruction of the ^{14}C production rate (Q) in the Earth's atmosphere during the time interval from the the last glacial termination (*ca.* 17 ka BC) and till the middle of the Holocene. We take into account the increase of CO_2 concentration in the Earth's atmosphere from the latest glaciation, the increase of the global temperature and the alteration of vegetation processes during the early Holocene. As a result, we obtained the reconstruction of the ^{14}C production rate in the atmosphere for the considered time interval.

2. CLIMATIC CHANGES AND RADICARBON

The variations of the carbon dioxide (CO_2) concentration in the Earth's atmosphere (Monnin et al., 2004) and the variations global temperature (Marcott and Shakun, 2015; Shakun et. al., 2012) for the time interval from 17000 BC to 5000 BC are shown in figure 1A,B. We can see from this figure carbon dioxide concentration in the Earth's atmosphere and global temperature were increased before the Holocene. It is necessary to note that before the Holocene there is the apparent decrease of temperature and CO_2 concentration during the time interval known as «Younger Dryas» (≈11000-10000 BC).

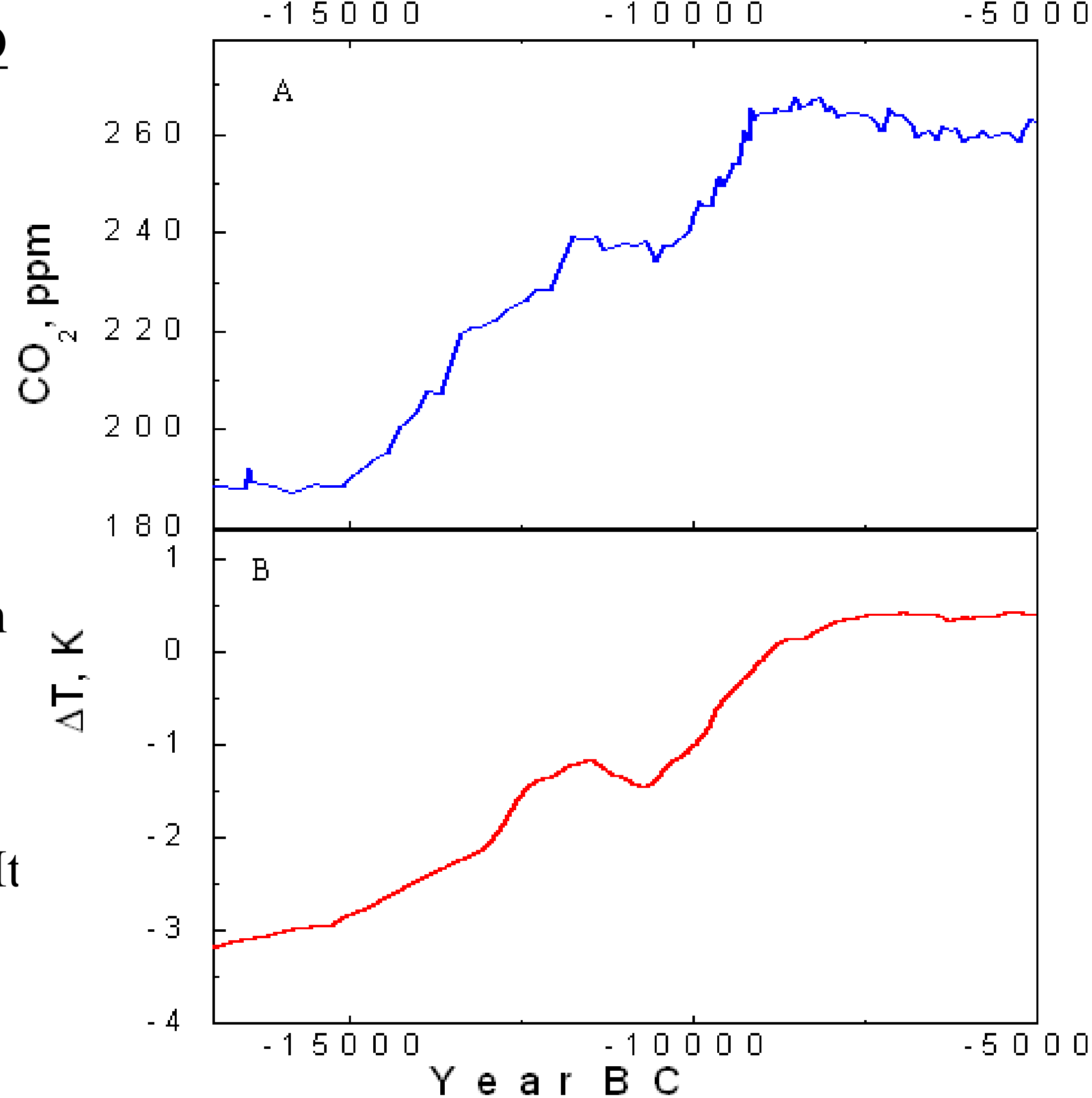

Figure 1. A - The variation of carbon dioxide concentration in the terrestrial atmosphere (Monnin et al., 2004) ; B – The variations of the global temperature according to (Marcott and Shakun, 2015; Shakun et. al., 2012)

As it was noted above the cosmogenic isotope ^{14}C is produced in the terrestrial atmosphere under the action of galactic cosmic rays (GCRs). The relative content (to ^{12}C isotope) of radiocarbon in the atmosphere ($\Delta^{14}C$) for this time interval is shown in figure 2A. Using values $\Delta^{14}C$ and carbon dioxide concentration we can calculate the change of the absolute ^{14}C content in the atmosphere ($N_a(t)$) (see for example Kuleshova et al., 2015) by means of the expression:

$$\frac{N_a(t)}{N_a(t_o)} = \frac{CO_2(t)}{CO_2(t_o)} \frac{(1+\Delta^{14}C(t)/100)}{(1+\Delta^{14}C(t_o)/100)} \qquad (1)$$

where t_0 is the initial moment of the time; $CO_2(t)$ is carbon dioxide concentration in the Earth's atmosphere; $\Delta^{14}C$ is expressed in percent.

The result of calculation is shown in figure 2C. It is possible to see that the absolute content of isotope ^{14}C (or $^{14}CO_2$) increases in terrestrial atmosphere before the Holocene (see also (Roth and Joos, 2013)). This increase is a result of the redistribution of the carbon dioxide between the ocean and atmosphere and, as a consequence, due to increase in temperature after the end of latest Glaciation.

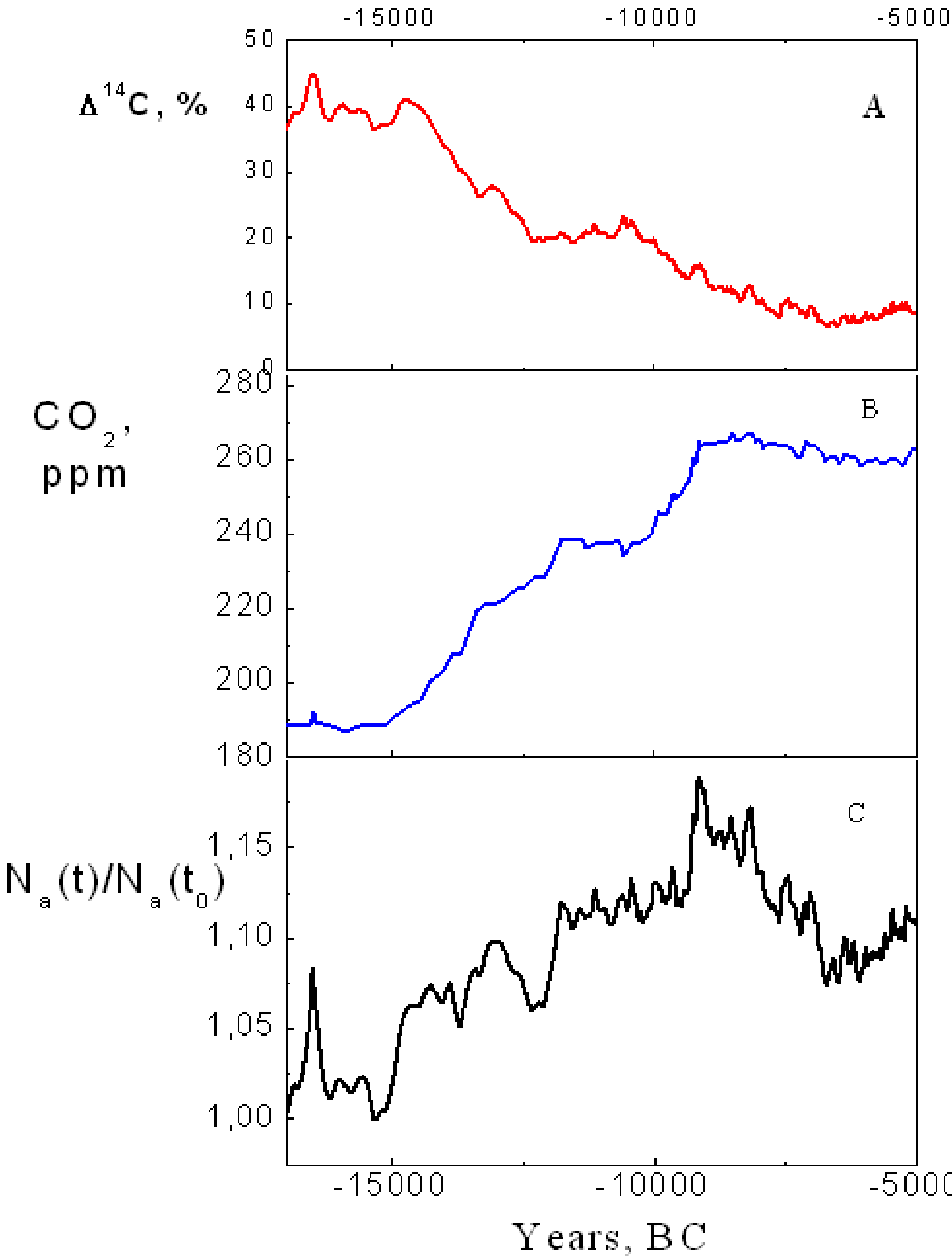

Figure 2. A- the variations of $\Delta^{14}C$ in the atmosphere according to (Reimer et al., 2009);

B - The variations of dioxide carbon concentration in the terrestrial atmosphere (Monnin et al., 2004);

C- The variation of absolute radiocarbon content in the atmosphere calculated according to equation (1) .

3. THE RECONSTRUCTION OF ATMOSPHERIC RADIOCARBON PRODUCTION RATE

In our previous work (Kudriavtsev et al., 2016a) we used the five-reservoir model (for example (Dorman, 1978)) for calculation radiocarbon exchange between natural reservoirs (atmosphere, biosphere, humus, upper (or mixed) and deep ocean layers):

$$\frac{dN_a}{dt} = Q(t) - (\lambda + \lambda_{ab} + \lambda_{amO})N_a + \lambda_{ba}N_b + \lambda_{ha}N_h + \lambda_{mOa}N_{mO} \quad (2)$$

$$\frac{dN_b}{dt} = \lambda_{ab}N_a - (\lambda + \lambda_{ba} + \lambda_{bh})N_b \quad (3)$$

$$\frac{dN_h}{dt} = \lambda_{bh}N_b - (\lambda + \lambda_{ha})N_h \quad (4)$$

$$\frac{dN_{mO}}{dt} = \lambda_{amO}N_a - (\lambda + \lambda_{mOa} + \lambda_{mOdO})N_{mO} + \lambda_{dOmO}N_{dO} \quad (5)$$

$$\frac{dN_{dO}}{dt} = \lambda_{mOdO}N_{mO} - (\lambda + \lambda_{dOmO})N_{dO} \quad (6)$$

where N_a, N_b, N_h, N_{mO}, N_{dO} are the contents of radiocarbon in the atmosphere, biosphere, humus, upper (or mixed) and deep ocean layers, respectivity; λ_{ab}, λ_{amO}, λ_{ba}, λ_{ha}, λ_{mOa}, λ_{bh}, λ_{mOdO}, λ_{dOmO} are the transition rates of the radiocarbon between the corresponding reservoirs; λ is the radiocarbon decay rate; Q(t) is radiocarbon production rate.

In present work we consider relative changes of Q(t), since the functions N_a, N_b, N_h, N_{mO}, N_{dO} and Q can be defined with accuracy determined by a constant multiplier (see Kudriavtsev et al., 2016 b), which, in turn can be determined using the initial conditions or value of Q in some time moment.

Based on Figure 1, we have assumed that the carbon system was almost in equilibrium at 17000 BP. Therefore, for the first calculation stage, we find the stationary (equilibrium) values for the ^{14}C isotope content in different reservoirs using the different value of temperature coefficient. After that we used these values as initial conditions in calculations of evolution of radiocarbon content in different reservoirs in the time.

In our paper (Kudriavtsev et al., 2016a) was shown that the redistribution of radiocarbon (noted above) is possible only if the transition rates of the radiocarbon from ocean into the atmosphere depends on temperature. We used the linear dependence

$$\lambda_{mOa}=(1+k_1 \cdot \Delta T)\ \lambda^0_{mOa,} \qquad (7)$$

where ΔT is a global temperature anomaly (from AD 1961-1990 mean) ; k - is the temperature coefficient.

The results of calculation of the total radiocarbon content in all reservoirs for various values of k are shown on Figure 3 (curves 2-4).

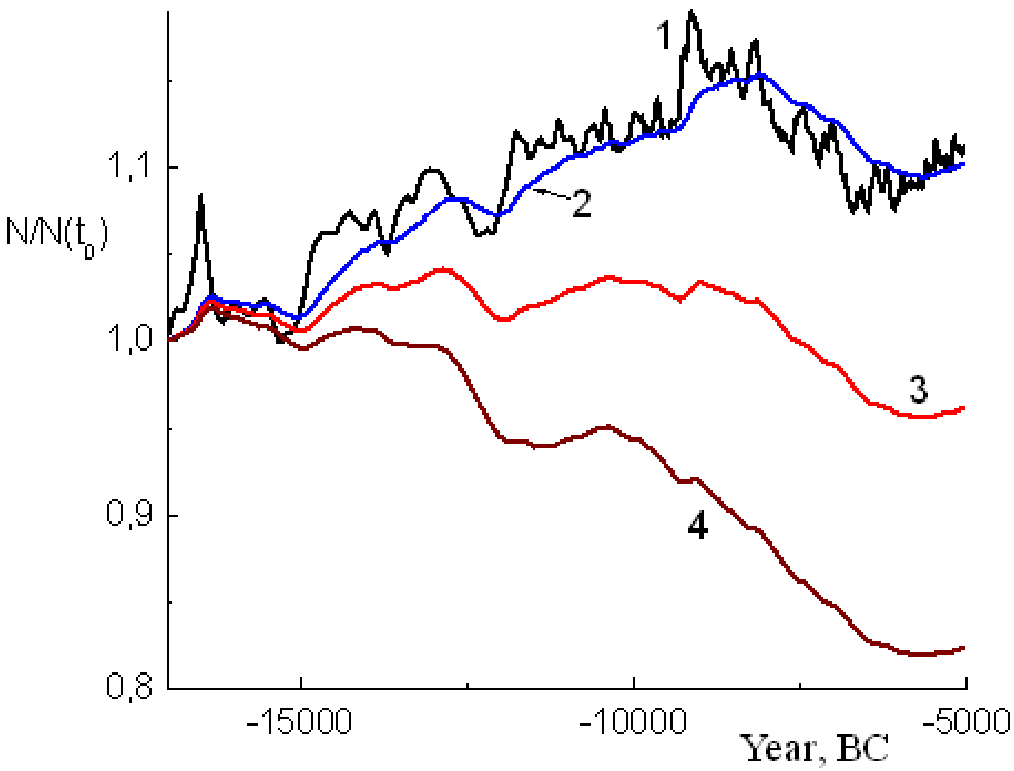

Figure 3. 1- The variation of the absolute radiocarbon content in the atmosphere calculated according to equation (1);

2,3,4 - The variation of the radiocarbon total content in all reservoirs (N_{Σ}) calculated using $k_1 = 0; 0.04; 0.08 K^{-1}$ accordingly. t_0 is 17000 year BC

We conclude from Figure 3 that the value of the temperature coefficient $k=0.04K^{-1}$ allows is to explain the redistribution of radiocarbon between the ocean and the atmosphere while the total content of radiocarbon in all reservoirs have a tendency to remain constant during the time interval 17000-9000 BC (see curve 3).

Decline of the curve 3 after 9000 BC could be a result of neglecting the change of radiocarbon transition rate from the atmosphere to the biosphere during the Early Holocene (Koudriavtsev and Dergachev, 2016b).

The possible time and temperature dependences of the ^{14}C transition rate between the atmosphere and biosphere λ_{ab} was presented in Koudriavtsev and Dergachev (2016). In this work λ_{ab} was modeled by expression

$$\lambda_{ab} = \lambda^0_{ab} = const \quad \text{when } t < t_2 \quad \text{and} \quad \lambda_{ab} = (1 + k_2(T(t) - T(t_0))\sqrt{t - t_2})\lambda^0_{ab} \quad \text{when } t \geq t_2$$

The value λ^0_{ab} was taken 15% less than in work (Kudriavtsev et al., 2016a); t_2=-8300 year.

The results of calculation of total radiocarbon content in all reservoirs are shown in Figure 4 using equations (7, 8) for λ_{mOa} and λ_{ab}....

Parameters of model:

λ^0_{ab}= 0,85/30 year^{-1}; λ_{amO}=1/6,84 year^{-1}; λ_{ba}=1/30,6 year^{-1}; λ^0_{mOA}=1/8,5 year^{-1}; λ_{ha}=1/101,2 year^{-1}; λ_{bh}=1/30,6 year^{-1}; λ_{mOdO}=1/3 year^{-1}; λ_{dOmO}=1/193 year^{-1}

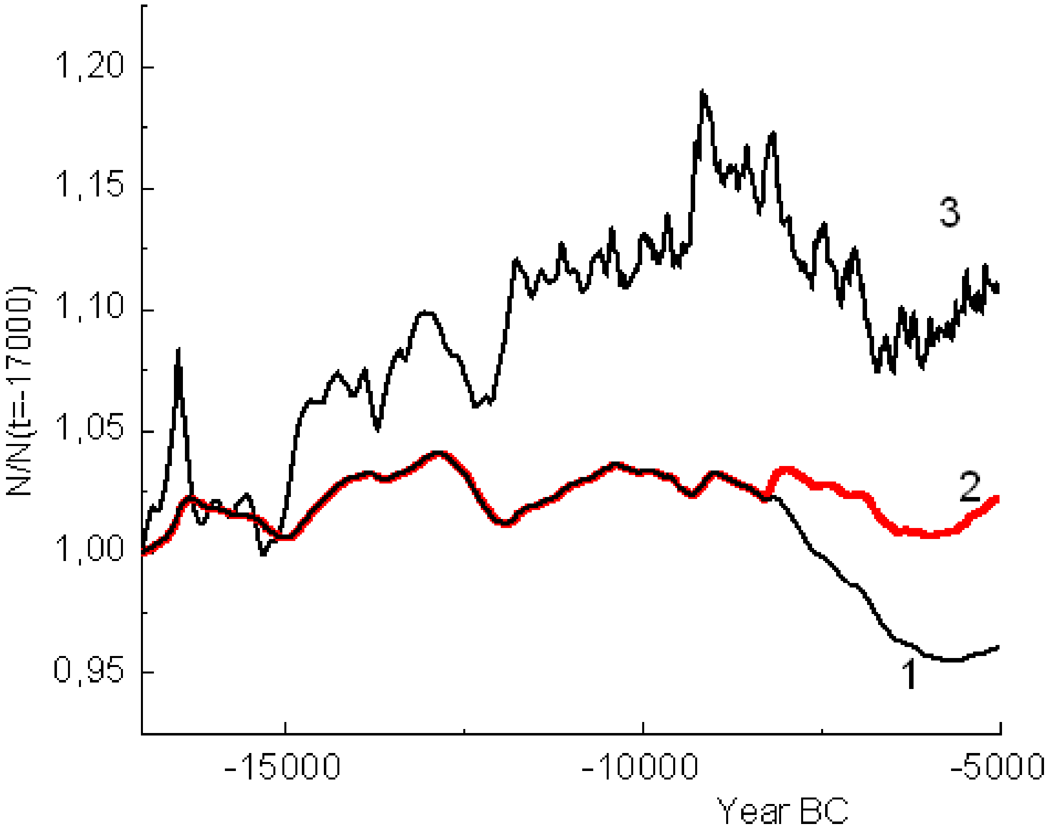

Figure 4.

1- The results of calculation of total radiocarbon content (N_Σ)in all reservoirs at $k_1=0.04$, $k_2=0$;

2- The results of calculation of total radiocarbon content (N_Σ) in all reservoirs at k_1=0.04, k_2=0.013;

3-Variations of the 14C isotope content in the atmosphere (N_a).

We conclude from Figure 4 that in case when $k_1 \approx 0.04$ and $k_2 \approx 0.013$ (when $t \geq t_{2\_}$) the total content of radiocarbon in all the reservoirs have a tendency to remain constant throughout the entire time interval 17000 BC – 5000 BC. Increase of radiocarbon transition rate from the atmosphere to the biosphere could be a result of increasing vegetation during this epoch, that is actually observed (see e.g. Monin and Shishkov, 1979).

The results of calculation of the radiocarbon production rate Q(t) are shown in Figure 5A. Some peaks (16490, 9150, 8200, 5465 BC) as well as minima (15310, 12350, 8360, 6715 BC) are also shown in this Figure. It should be noted particularly a minimum of the rate of ^{14}C production at 12350 BC. This minimum should correspond to the period of the high solar activity and, as a consequence, to the warm period of the Earth's climate, that is actually observed (Litt et al., 2007).

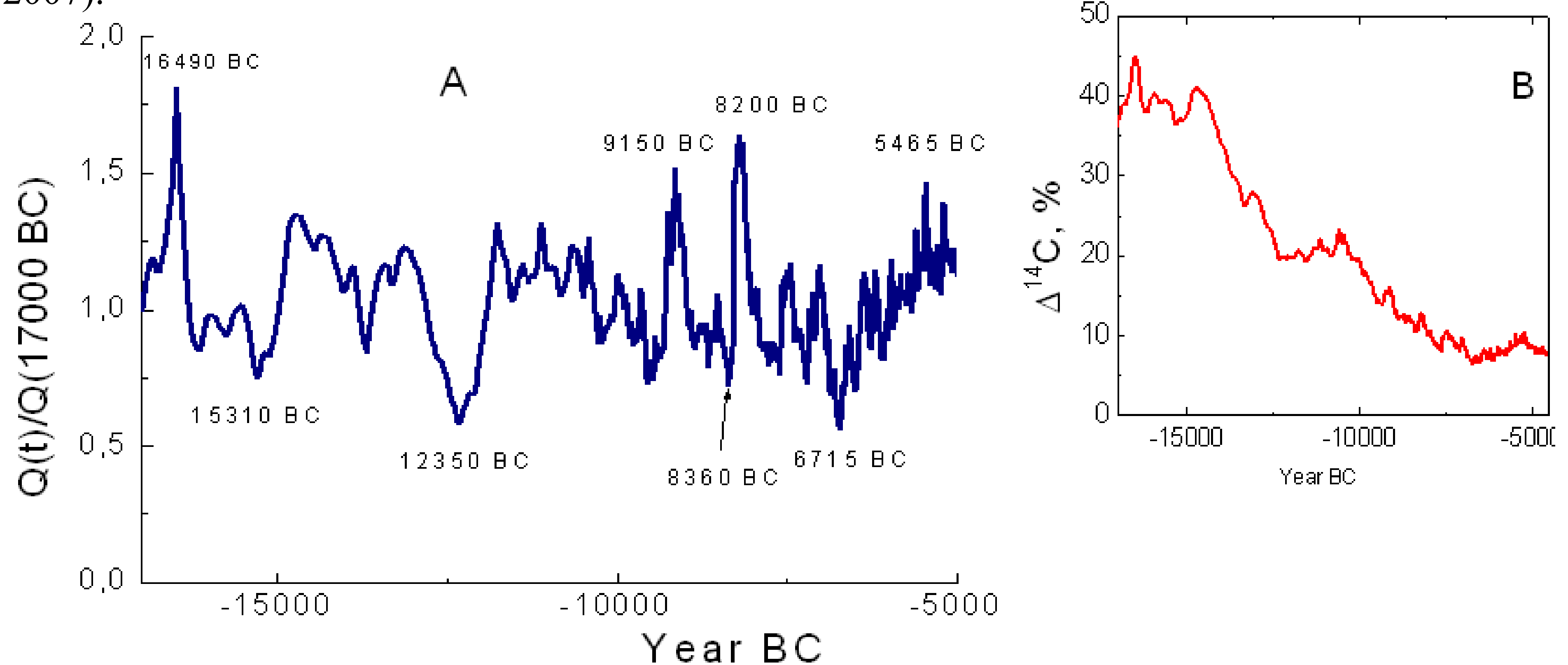

Figure 5. A- Radiocarbon production rate Q(t) calculated from $\Delta^{14}C$ using the variations of carbon dioxide and global temperature anomaly.
B- $\Delta^{14}C$ record after Reimer et al. (2009).

The initial $\Delta^{14}C$ data after Reimer et al. (2009) are shown in Figure 5B for comparison. Comparison of Figures 5A and 5B shows that use of climatic data makes it possible to reconstruct the rate of radiocarbon production in the terrestrial atmosphere over the time interval at which radiocarbon data are distorted by climatic changes.

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