RADIO-CARBON EVIDENCE OF THE SEASONAL GAS EXCHANGE OF CO₂ BETWEEN THE ATMOSPHERE AND THE OCEAN Alexey V. Byalko

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Abstract

In nuclear explosions in the atmosphere, neutrons reacted with air nitrogen formed radiocarbon ¹⁴C. As a result, in October 1965, when the international treaty banning nuclear testing in the atmosphere came into force, the content of radiocarbon in the atmosphere more than doubled comparing with the 1950 level. However, then measurements of its concentration showed an exponentially rapid decrease. In the atmosphere, radiocarbon and stable carbon isotopes are identical. A joint study of regular trends in the concentrations of ¹⁴C and CO₂ as well as their seasonal fluctuations provides unique information on gas exchange between the atmosphere and the ocean.

Since the time of Svante Arrhenius, it is known that the temperature of the Earth's surface increases with increasing atmospheric content of greenhouse gases (water vapor and carbon dioxide). Dependence of temperature on CO_2 concentration is called climatic sensitivity. It is difficult to calculate theoretically for the reason that the humidity of the atmosphere itself increases with temperature and depends on the state of cloudiness (water droplets and crystals do not contribute to the greenhouse effect). The best experimental estimate of climatic sensitivity was obtained while drilling Antarctic ice [1] but its applicability for modern climate conditions has not yet been proven. Therefore, we will not consider here the actual climate warming but we will clarify the relationship between the observed growth in the atmospheric concentration of carbon dioxide and the processes of its release during the combustion of fossil fuels, its absorption by the ocean (and terrestrial plants), and reverse release into the atmosphere.

Essential information in this analysis is observed by the series of measurements of the atmospheric concentration of radiocarbon ¹⁴C. It forms naturally as a result of the cosmic rays interaction with atmospheric N_2 and then decays with the half-live equals to 5830 years. These two processes provided in the past approximately constant concentration of ¹⁴C in the Earth's atmosphere. However, with the beginning of the nuclear tests this equilibrium has changed dramatically. Neutrons originated in nuclear explosions react with nitrogen of air forming a radiocarbon; its content in the atmosphere began to increase.

In 1958 academician A.D. Sakharov pointed to the negative biological consequences of the increase in the atmospheric radiocarbon concentration [2]. By

this time, it proved to be much higher than the natural radiocarbon background. The Sakharov's conclusion about the long-term exposure of radiocarbon to biota turned out to be erroneous; he did not take into account the role of gas exchange of the atmosphere with the ocean, the parameters of which were unknown in the 50's. However, his article played an important role in the conclusion of the International Treaty banning nuclear testing in the atmosphere; it came to force in October 1965. As can be seen from Fig.1, after the conclusion of this treaty, the concentration of radiocarbon averaged over seasonal fluctuations began to decline exponentially fast.



Fig.1. Change in atmospheric concentrations of radiocarbon and CO_2 relative to their 1950 levels. The radiocarbon measurements (black curve) are given in [3, 4]. The measurement data [5] of atmospheric CO_2 concentration (blue curve) is also normalized to the 1950 level. The oscillations of both experimental dependences occur with a period of 1 year, these are seasonal variations. The dashed black line on the curve ¹⁴C is an exponential with a characteristic time of 13.5 years. The dashed blue line of CO_2 is the smoothed annual average.

Averaged over the seasonal fluctuations in the radiocarbon concentration correspond to the following dependence: $1.026 + 0.781 \exp[-(t - 1965)/\tau]$. The characteristic time in the exponent of this expression is $\tau = 13.5$ years, which is much less than the half-life of ¹⁴C. Therefore, natural decay could not make a significant contribution to the decrease in its concentration. A logical explanation for this rapid fall is that atmospheric radiocarbon in the form of dioxide ¹⁴CO₂ was actively absorbed by ocean water (and to a lesser extent by land plants). Simultaneously, it was diluted with stable carbon isotopes due to the combustion of fossil fuels.

The influence of these processes on the trends of both dependences is considered in detail in the author's paper [6]. Equations that take into account the described processes are obtained. Analysis of observational data made it possible to quantify the flow of gases from the atmosphere to the ocean and back during the entire measurement period. In particular, in this work it is shown that before 1990 the absorption of radiocarbon by the ocean dominated, and then the ocean began to give it to the atmosphere. The phase dependences of both fluxes of carbon dioxide were also roughly estimated.

Here, the focus will be on seasonal variations in the concentrations of radiocarbon and carbon dioxide, their amplitudes and phases. First of all, we note that the amplitude of the seasonal oscillations of ¹⁴C and CO₂ relative to the concentrations themselves remains almost constant in time. To the accuracy of measurement errors, in both cases the relative magnitudes of seasonal fluctuations are from 0.10 to 0.14. The persistence of this relationship (its small violations are associated with the influence of the El Niño phenomenon) allows us to construct a general seasonal pattern of fluctuations.

The insolation and consequently all climatic dependencies have annual and semiannual periods. The basis for calculating the amplitudes and phases of CO₂ oscillations at different latitudes was provided by satellite data [7]. Their processing was carried out by calculating the average amplitudes and phases for latitudes in 10° increments, using a formula that takes into account annual and semiannual periods: : $a_1 \cos(2\pi t + \varphi_1) + a_2 \cos(4\pi t + \varphi_2)$. Subsequent smoothing made it possible to obtain the following picture of seasonal variations of carbon dioxide (Fig. 2).



Fig.2. Annual variations in the concentration of CO_2 (in parts per million) versus latitude according to smoothed data [7]. The maximum is reached in February, when the heating season in the Northern Hemisphere increases CO_2 emissions, and the minimum in August in the polar latitudes, when the dioxide is actively absorbed by the Arctic Ocean, which is freed from ice. Near the Antarctic, gas is absorbed almost evenly throughout the year.

This two-dimensional graph clearly demonstrates the relationship of CO_2 emissions with its emissions into the atmosphere during the burning of fossil fuels in those latitudes of the Northern Hemisphere where industry is most developed. There is also an obvious very intensive absorption of CO_2 gas in the polar latitudes and a partial reverse emission of it into the atmosphere at equatorial latitudes.

For the ¹⁴C curve shown in Fig. 1, the relative annual amplitude and phase were as follows: $a_1^{14} = 0.013 \pm 0.04$; $\varphi_1^{14} = 2.22 \pm 0.03$. The semiannual ¹⁴C amplitudes are negligible. The latitude of the Schauinsland point of radiocarbon measurements was 48° N. At this latitude, the annual amplitude and phase of the seasonal variations of carbon dioxide are equal to $a_1 = 0.014$; $\varphi_1 = 5.62$. It follows that the fluctuations in the radiocarbon concentrations are practically in anti-phase with the CO₂ oscillations: $\varphi_1 \approx \varphi_1^{14} + \pi$. This means that the effect of diluting atmospheric radiocarbon with industrial emissions from burning fossil fuels (that do not contain ¹⁴C) is the most significant factor determining in radiocarbon seasonal variations.

Conclusion: anthropogenic influence is manifested in both time dependences of the concentrations of radiocarbon and carbon dioxide, in their differently directed trends and in seasonal variations as well.

Literature

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