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The ~ 2400-year cycle in atmospheric radiocarbon concentration: bispectrum of ^{14}C data over the last 8000 years

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Abstract. We have carried out power spectrum, time-spectrum and bispectrum analyses of the long-term series of the radiocarbon concentrations deduced from measurements of the radiocarbon content in tree rings for the last 8000 years. Classical harmonic analysis of this time series shows a number of periods: 2400, 940, 710, 570, 500, 420, 360, 230, 210 and 190 years. A principle feature of the time series is the long period of ~ 2400 years, which is well known. The lines with periods of 710, 420 and 210 years are found to be the primary secular components of power spectrum. The complicated structure of the observed power spectrum is the result of ~ 2400-year modulation of primary secular components. The modulation induces the appearance of two side lines for every primary one, namely lines with periods of 940 and 570 years, of 500 and 360 years, and 230 and 190 years. The bispectral analysis shows that the parameters of carbon exchange system varied with the ~ 2400-year period during the last 8000 years. Variations of these parameters appear to be a climate effect on the rate of transfer of ^{14}C between the atmosphere and the the ocean.

Key words. Meteorology and atmospheric dynamics (climatology; ocean-atmosphere interaction; paleoclimatology)

1 Introduction

Radiocarbon, ^{14}C, is formed in the Earth's atmosphere as a result of cosmic ray neutron interactions with nitrogen nuclei: $^{14}N(n,p)^{14}C$. ^{14}C decays with a half life of 5730 years. Variations in the atmospheric concentration of ^{14}C are the result of changes in the Earth's dipole moment (Elsasser et al., 1956; O'Brien, 1979; Lal, 1988), strengthening or weakening of solar activity (Stuiver and Quay, 1980; Bard et al., 1997) and parameters of radiocarbon exchange system (Oeschger et al., 1975; Siegenthaler et al., 1980; Stocker and Wright, 1996; Goslar et al., 1999). Variability of the ^{14}C concentration is proved by experimental research, see (e.g. Damon et al., 1998; Kromer et al., 1998).

The longest cycle of ^{14}C concentration changes is attributed to the ~ 2400 year period (Houtermans, 1971). After the discovery of ~ 2400-year amplitude modulation for the ~ 210-year cycle (Sonett, 1984) the properties of the ~ 2400-year cycle were discussed by Damon and Linick (1986), Damon (1988), Damon et al. (1990).

In the publications of Damon and Sonett (1992) and Damon and Jirikowić (1992) the ~ 2400-year and ~ 210-year cycles are considered to be the fundamental ones, most of the other secular cycles discovered in radiocarbon data being harmonic components of the longest cycle. Sonett and Finney (1990) argue that, in the presence of nine prominent radiocarbon features, most are mutually dependent with perhaps only three independent lines. For more complete study of interdependence of the ~ 2400-year variations with other secular components we used bispectral analysis.

2 The primary properties of radiocarbon series

For the last 8000 years relative radiocarbon concentration ($\Delta^{14}C$) continually underwent small scale fluctuations with time, see (e.g. Vasiliev and Dergachev, 1998). This long-term change of $\Delta^{14}C$ of $\sim 10\%$ is explained by variability in the geomagnetic field (McElhinny and Senanyake, 1982; Bard, 1998). The fluctuations around the long-term trend of radiocarbon concentration show an amplitude of about 1.0%. The cyclic fluctuations with duration of tens of hundreds of years may be caused in the main by solar activity (Stuiver and Quay, 1980). To study the properties of these fluctuations in the radiocarbon series one needs to remove the long-term variation. In these studies we investigated the decadal data on radiocarbon concentration for the last 8000 years (Stuiver and Becker, 1993; Stuiver et al., 1998). Figure 1 shows the $\Delta^{14}C_D$ series which is the result of detrending of initial radiocarbon series. The strongest fluctuations occurred at 500, 2700, 5400 and 7200 years BP (before present). It

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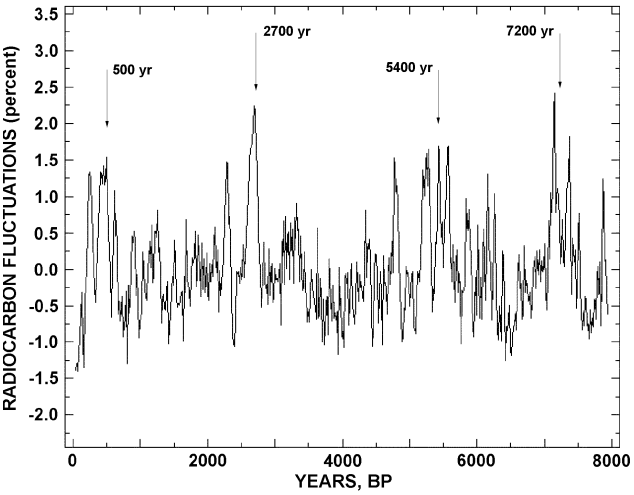

Fig. 1. Radiocarbon series $\Delta^{14}C_D$ in time after long-term detrending. The strongest fluctuations occurred at 500, 2700, 5400 and 7200 years BP (before present).

is remarkable that the first three periods correspond to the cold epochs revealed in dendroclimatic data (see Damon and Sonett, 1992, p. 378). Obviously these fluctuations of radiocarbon data need adequate analysis. Here we consider our results obtained by the method of multiple filtration (Dziewonski et al., 1969). This method is appropriate to get amplitude values as a function of two variables: a frequency and a time. This analysis allows us to conclude, that (i) the amplitudes of fluctuations vary in time (Fig. 2), (ii) the changes of amplitude are synchronous in the wide frequency band, (iii) the epochs of high amplitudes occur at 400, 2500, 5200 and 7200 years BP. These properties of radiocarbon series are consistent with the existence of long-period amplitude modulation, first discovered for the ~210-year variations (Sonett, 1984). Spectral analysis of the $\Delta^{14}C_D$ series is appropriate to estimate the mean period of modulation. In the power spectrum (see Fig. 3) the highest line is at ~2400-year period. The maximum values of long-period variations and epochs of high amplitude fluctuations coincide (Fig. 2), confirming the existence of ~2400-year amplitude modulation for a wide frequency band.

3 Bispectral analysis

The bispectrum is applied for analysis of non-linear processes and complex interaction in geophysical data (King, 1996). The bispectrum $B(\omega_x, \omega_y)$ is the two-dimensional Fourier transformation of the auto-covariance function $C(u, v)$:

$$B(\omega_x, \omega_y) = \int\int C(u, v)\, \exp\left(-2\pi i\, \omega_x u - 2\pi i\, \omega_y v\right) du\, dv, \tag{1}$$

where $C(u, v) = \langle f(t) f(t+u) f(t+v)\rangle_t$, ω_x and ω_y are frequencies, $\langle\rangle_t$ is averaging operator and $f(t)$ is an examined function. The definition (1) of the bispectrum is equivalent to

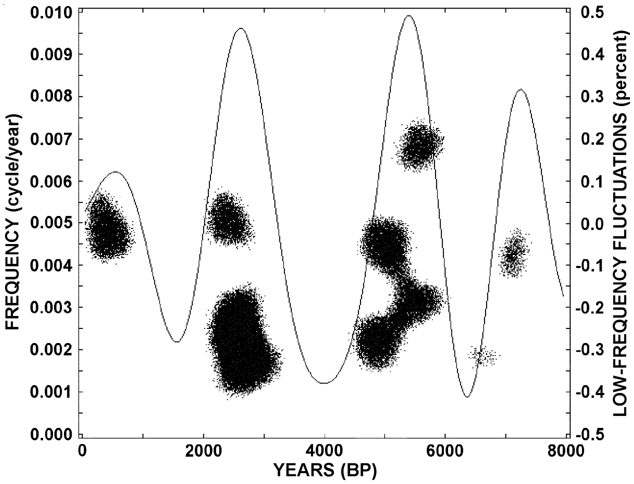

Fig. 2. The domains of high amplitude (dark areas) on the frequency-time plane found in the radiocarbon data by the multiple filtration method. The epochs of fluctuations with high amplitude are repeated each 2300–2500 years. The cyclic curve is the result of low frequency filtration with maximum frequency 0.00066 cycle/year.

$$B(\omega_x, \omega_y) = \left\langle A(\omega_x) A(\omega_y) A^*(\omega_x + \omega_y)\right\rangle_t, \tag{2}$$

where $A(\omega)$ are complex Fourier amplitudes and asterisk (*) indicates complex conjugation. Equation (2) indicates that the bispectrum value is zero if the phases of Fourier components are independent. In other cases, bispectrum values may be different from zero. The bispectrum is a function of two frequencies, ω_x and ω_y. Because of symmetry the bispectrum is determined uniquely on the plane (ω_x, ω_y) in the triangle with vertexes $(0, 0)$, $(\omega_{max}, \omega_{max})$ and $(-\omega_{max}, \omega_{max})$. Other bispectrum features are discussed by Kim and Powers (1979). A modulation with frequency $\tilde{\omega}$ is shown in the power spectrum by the presence of two side lines with frequencies $\omega - \tilde{\omega}$ and $\omega + \tilde{\omega}$, in addition to the primary line whose frequency is ω. If the modulation takes place, we observe peaks of $B(\omega_x, \omega_y)$ at some characteristic points of the plane (ω_x, ω_y), for example, at $(\pm\tilde{\omega}, \omega)$ and $(\mp\tilde{\omega}, \omega \pm \tilde{\omega})$. A more complete list of these points may be inferred using symmetry relations

$$B(\omega_x, \omega_y) = B(-\omega_x - \omega_y, \omega_y), \tag{3}$$

$$B(\omega_x, \omega_y) = B(\omega_y, \omega_x), \tag{4}$$

$$B(\omega_x, \omega_y) = B^*(-\omega_y, -\omega_x). \tag{5}$$

Figure 4 shows our results for the bispectral analysis of radiocarbon series $\Delta^{14}C_D$ and displays the upper side of the (ω_x, ω_y)-plane. The lower side is omitted because that is a symmetric continuation of the upper side according to the relations (4) and (5). The peaks are marked by dark spots. The left side $(\omega_x < 0)$ and right side $(\omega_x > 0)$ of bispectrum have axes of symmetry S1 and S2, respectively. There

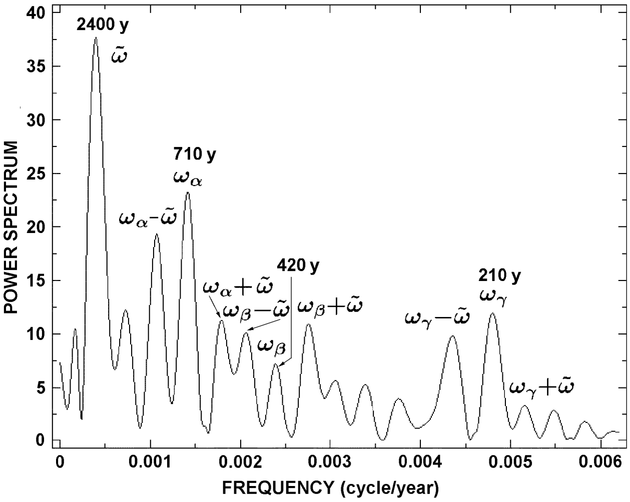

Fig. 3. The power spectrum of radiocarbon series $\Delta^{14}C_D$. The horizontal axis is the frequency, the vertical axis is the normalized power spectral density. A number denotes the period (years) of primary spectral components. A Greek symbol shows the frequency of primary and side lines (see Table 1).

are no peaks on axis S1 because the initial radiocarbon series is detrended. The presence of peaks on the axis S2 due to first harmonics of some lines. Most of the peaks lie on vertical lines 1A and 2A, horizontal lines 3A and 4A and inclined lines 1B and 4B. The abscissae of vertical lines 1A and 2A correspond to the $\sim$2400-year period. The peaks on other lines correspond to symmetry relations (3), (4) and (5). The peaks on all these lines indicate slow alteration of amplitudes of primary harmonic components defining the time shape of $\Delta^{14}C_D$ variations. The period of this slow alteration is $\sim$2400 years.

We focus our attention on peaks located on the lines 1A and 2A. The primary spectral lines would give peaks both on the 1A and 2A. It is just the case for the ω_α and ω_β frequencies. For the ω_α frequency we have the peaks $(-\tilde{\omega}, \omega_\alpha)$ and $(-\tilde{\omega}, \omega_\alpha + \tilde{\omega})$ on the line 1A, $(\tilde{\omega}, \omega_\alpha)$ and $(\tilde{\omega}, \omega_\alpha - \tilde{\omega})$ on the line 2A. The configuration of peaks for the primary frequencies ω_β and ω_γ is similar. The presence of a few spots was not marked due to the weakness of line with frequency $\omega_\gamma + \tilde{\omega}$ (see Fig. 3).

This classification of spectral lines, realized on the base of the bispectral analysis, reduces the number of independent lines to four only; namely, the modulation line and three primary lines: the α, the β, the γ. The remaining lines are due to the amplitude modulation. The results of the analysis are shown in Table 1. The existence and the location of these peaks suggests that the $\sim$2400-year amplitude modulation of ^{14}C fluctuations is real.

4 The nature of $\sim$2400-year modulation

The amplitude modulation of the $\sim$210-year radiocarbon fluctuations was discussed previously (Sonett, 1984). We should keep in mind three causes of this modulation: solar activity, climate alteration and change of the Earth's magnetic field. Hood and Jirikowić (1990) considered solar activity as the cause of the $\sim$2400-year cycle. The periodical Heliocentric motion induced by a perturbation action of the giant planets was demonstrated by Charvátová (2000). It was shown that the $\sim$2400-year periodicity in the Heliocentric motion is real as was earlier recognized $\sim$180-year motion. Charvátová (2000) suggests to a possible relation of the $\sim$2400-year period be a similar one discovered in radiocarbon series.

Table 1. The results of the bispectral analysis of radiocarbon series. Harmonic periods are shown in years

Period	2400	940	710	570	500
Status	$\tilde{\omega}$	$\omega_\alpha-\tilde{\omega}$	ω_α	$\omega_\alpha+\tilde{\omega}$	$\omega_\beta-\tilde{\omega}$
Period	420	360	230	210	190
Status	ω_β	$\omega_\beta+\tilde{\omega}$	$\omega_\gamma-\tilde{\omega}$	ω_γ	$\omega_\gamma+\tilde{\omega}$

O'Brien (1979) and Elsasser et al. (1956) discussed the principles of action of the geomagnetic field on the production rate of radiocarbon. As the number of ^{14}C nuclei formed in the Earth's atmosphere is proportional to $\mu(t)^{-0.52}$, where $\mu(t)$ is the Earth's magnetic dipole moment, it is possibile to explain the change of amplitude of the $\sim$210-year cycle by geofield forcing, see Damon and Linick (1986). Analysis of available palaeomagnetic and archaeomagnetic data for the last 10 000 years (Creer, 1988) shows that changes of the Earth's dipole field may not be causing the $\sim$2400-year variations in the radiocarbon concentrations of the atmosphere (Damon and Sonett, 1992) because the amplitude of the $\sim$2400-years geofield harmonics should be considerably higher (Sonett, 1984). The existence of a $\sim$2400-year cycle is proved in a number of studies of climatic data, (see e.g. Dansgaard et al., 1984; Pestiaux et al., 1988; Röthlisberger, 1986; Arabadzi, 1986; Levina and Orlova, 1993; O'Brien et al., 1995). This evidence of long-term change of climate allows us to assume that the variation of the ^{14}C concentration with $\sim$2400-year period has a climatic origin (Damon and Sonett, 1992). Time comparison of the epochs of high and low solar activity with climate alteration led to the conclusion that the cause of the $\sim$2400-year cycle, both in the ^{14}C concentration and in climate of the Earth, appears to be of a solar nature (Dergachev and Chistyakov, 1995).

The cause of the long-term variation of radiocarbon concentration may be due to a climatic influence on carbon transfer. The reasons for possible climatic forcing will be considered briefly. The mean temperature and wind velocity determines the exchange intensity of CO_2 between the atmosphere and the ocean. The amount of carbon stored in the ocean exceeds that available in the atmosphere by $\sim$100 times (Damon et al., 1978). Therefore, the residence time in the ocean considerably exceeds that in the atmo-

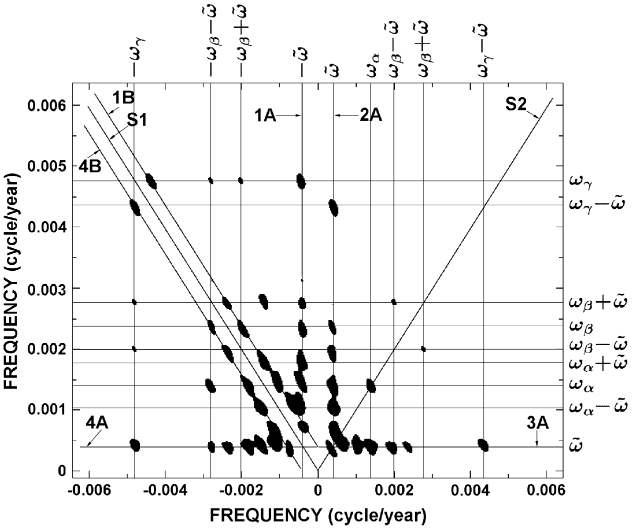

Fig. 4. The modulus of bispectrum for the radiocarbon series $\Delta^{14}C_D$. Dark spots denote spectrum peaks. The lines S1 and S2 are the symmetry axes of the left side ($\omega_x < 0$) and the right side ($\omega_x > 0$), respectively. The abscissae of vertical lines 1A and 2A correspond to the ~ 2400-year period.

sphere and the relative concentration of radioactive carbon in the ocean is lower. As a consequence, an increase of carbon exchange rate would result in a decrease of ^{14}C content in the atmosphere. This inference is supported qualitatively by a simple dissipative model of concentration change:

$$dN/dt = -\lambda N + Q(t), \tag{6}$$

where N is the ^{14}C concentration, λ is exchange parameter, $Q(t)$ is amount of ^{14}C generated in the atmosphere. For $Q(t) = Q_0 \sin \Omega t$ the solution of Eq. (6) is

$$N = Q_0 \sin(\Omega t - \varphi)/\sqrt{\Omega^2 + \lambda^2}, \tag{7}$$

where φ is a phase shift of time dependence of radiocarbon concentration relative to the production rate. According to Eq. (7), in the case $\Omega \ll \lambda$ that is most appropriate for this analysis, the amplitude of the concentration change is inverse to the exchange parameter. Therefore, the periodic alteration of parameters determining the rate of carbon exchange between the atmosphere and the ocean would cause corresponding changes of the ^{14}C concentration in the atmosphere.

5 Palaeoclimatology data

There are many data confirming the cyclical nature of the Earth's climate. The study of the $\delta^{18}O$ concentration in ice core (Dansgaard et al., 1984) showed a ~ 2500-year climatic cycle to exist. A ~ 2400-year quasiperiod was observed in the $\delta^{18}O$ concentration of deep see core with high sedimentation rates (Pestiaux et al., 1988). Similar periodic behaviour has been found in GRIP2 and GISP ice cores over the last 12 000 years. Glaciological time series indicate that the Holocene was punctuated by a series of ~ 2500-year events (O'Brien et al., 1995). The Middle Europe oak dendroclimatology demonstrates that the Little Ice Age (1500–1800 yr. AD), the Hallstattzeit cold epoch (750–400 yr. BC) and the earlier cold epoch (3200–2800 yr. BC) are separated by 2200–2500 years (see Damon and Sonett, 1992, p. 378). The time positions of these epochs are correlated with the periods of large $\Delta^{14}C_D$ fluctuations (Fig. 2). Detailed palynological and radiocarbon investigations of southern West Siberia, Levina and Orlova (1993), show that over Holocene the warmest periods occurred during 6300–5200 BP and 2300-1300 BP. The periods of 5200–4300 BP, 3200–2300 BP and 1300–200 BP were cool. A study of temperature of the Atlantic ocean for past epochs (Arabadzi, 1986) resulted in the conclusion that temperature minima occurred about 400, 2800 and 5100 BP. Therefore, we suggest that the climatic long-period modulation of radiocarbon fluctuations in the Earth's atmosphere is quite probable.

6 Fine details of the bispectrum

Some details of bispectrum were shown not to be a result of climatic effects. The bispectrum shows the first harmonics of primary line α with frequency $2\omega_\alpha$. Its presence appears as peaks $(\omega_\alpha, \omega_\alpha)$ and $(-\omega_\alpha, 2\omega_\alpha)$. The splitting of these harmonics by the basic modulation frequency $\tilde{\omega}$ (period – 2400 years) appears as the peak $(-\tilde{\omega}, 2\omega_\alpha+\tilde{\omega})$. The other remarkable feature is the peak at $(\omega_\beta - \tilde{\omega}, \omega_\beta + \tilde{\omega})$ resulting in splitting of the primary line β. This splitting occurs because of the coherence of harmonic components with frequencies ω_β and $2\omega_\beta$. The analysis of the left-hand part of bispectrum (Fig. 4) shows that oscillations with frequencies $-\omega_\beta-\tilde{\omega}$ and ω_γ ($-\omega_\beta+\tilde{\omega}$ and ω_γ) are coherent. This means the multiplicity of frequencies ω_γ and ω_β and the equality $\omega_\gamma=2\omega_\beta$. The ratio of β and γ amplitudes (Fig. 3) demonstrates that frequency ω_γ cannot be considered as a harmonic of frequency ω_β. Most probably it is a weak modulation of ~ 210-year variations that becomes apparent as the alternation of cycles of low and high amplitude. It should be noted that the multiplicity of β and γ frequencies were discussed earlier by Stuiver and Braziunas (1989).

7 Conclusions

Power spectrum, time-spectrum and bispectrum analyses were carried out on radiocarbon concentration data from the Earth's atmosphere over the last 8000 years, as observed in tree-rings. It was shown that the amplitude of radiocarbon fluctuations varied periodically. The quasiperiod of this change is about 2400 years. A bispectrum analysis of data demonstrates the existence of amplitude modulation. The period of main modulation is ~ 2400 years. Our bispectrum study results in the classification of lines of the power spectrum. Except for the modulation component, three primary lines were identified, α, β and γ with the periods 710, 420 and 210 years, respectively. The α component was shown to have first harmonics. The frequency of the primary component γ is twice that of the β component. The multiplicity of β and γ frequencies results in alternation of cycles with high and low amplitudes of $\sim$210-year periodicity. This amplitude modulation is considered to be the result of a climatic effect on the rate of radiocarbon transfer between the atmosphere and the ocean.

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