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SHORT-TERM VARIATIONS IN RADIOCARBON CONCENTRATION WITH THE 11-YEAR SOLAR CYCLE

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ABSTRACT. Previous investigations on short-term ^{14}C variations in tree rings are compared with ^{14}C measurements in wine samples. The comparison is made for 4 solar cycles (1903-1944) with the same method of statistical evaluation of measured results. The average amplitude of $\Delta^{14}C$ variations as observed by various authors in tree-ring samples is ca 2 ± 1 ‰; however, wine samples show an average amplitude of 4.3 ± 1.6 ‰. The anticorrelation dependence of $\Delta^{14}C$ on Wolf sunspot numbers was observed with a time shift between W maxima and $\Delta^{14}C$ minima of 3-5 yr for different solar cycles.

INTRODUCTION

Stuiver (1961) was first to point out an inverse correlation between ^{14}C concentration in tree rings and sunspot numbers. He found a ^{14}C cycle with a period of ca 100 years. More recently, Lin *et al* (1975) and Kocharov, Dergachev, and Gordeichik (1975) reported ^{14}C variations in tree-rings with a period of 80-90 years. The well-known Suess wiggles (de Jong, Mook, and Becker, 1979; Suess, 1980) have a characteristic time scale of ca 200 years. The amplitude of these ^{14}C variations is from 1 to 2%. It is believed that this effect is due to a modulation of galactic cosmic rays by solar wind (Stuiver and Quay, 1980; 1981).

The most prominent cycle in the solar activity observed till now is the 11-year solar cycle. Thus, it seems reasonable to investigate if the 11-year solar cycle has a similar influence on ^{14}C production as the 80-year solar cycle.

Calculations of ^{14}C production rate performed by Lingenfelter and Ramaty (1970) for the 19th solar cycle has shown that a global average ^{14}C production rate during solar minimum (1953), which corresponds to the maximum cosmic ray flux, was 2.4×10^4 ^{14}C atoms.m^{-2}.s^{-1}, while during solar maximum (1957) it decreased to 1.9×10^4 ^{14}C atoms.m^{-2}.s^{-1}. This points to variations in the ^{14}C production rate during the 19th solar cycle of ca 25%. Similar calculations (Povinec, 1977) performed for the 20th solar cycle showed that ^{14}C production rate during solar minimum (1965) was 2.6×10^4 ^{14}C atoms.m^{-2}.s^{-1} and for solar maximum (1968), 2.1×10^4 ^{14}C atoms.m^{-2}.s^{-1}. This was confirmed by calculation of ^{14}C production rate based on measurements of neutron fluxes in the atmosphere by the Deep River neutron monitor (Korff and Mendell, 1980).

However, short-term ^{14}C variations are difficult to observe because a change in the ^{14}C production rate may not give a measurable change in atmospheric ^{14}C concentration. This is because atmospheric carbon dioxide which is labeled with cosmogenic ^{14}C is in equilibrium with a large oceanic reservoir of CO_2, acting as a buffer against changes of atmospheric ^{14}C concentrations.

Houtermans (1966) showed that the amplitude of a ^{14}C variation with a period of 10 years is attenuated by a factor of ca 100, while ^{14}C variations with a period of the order of 100 years show an attenuation only by a factor of ca 10. More recent calculations by Siegenthaler, Heimann, and Oeschger (1980) who used the more sophisticated box-diffusion model (Oeschger et al, 1975) yielded an attenuation factor of 90.

Taking into account calculations of ^{14}C production rates based on the measured cosmic ray data for the 19th and 20th solar cycles and their approximation for previous solar cycles, as well as recent calculations on exchange rates between carbon reservoirs, a variation in the ^{14}C activity during an 11-year solar cycle may be expected to have an average amplitude of ca 1 ‰ to 2 ‰.

Experimental results on ^{14}C variations with the 11-year solar cycle have been scarce. The first ^{14}C results were reported for annual tree-ring samples ca 1910, in connection with the effect of the Tunguska meteor on the ^{14}C concentration of the atmosphere (Covan, Atluri, and Libby, 1965). Venkatavaradan (1965) compared these data with sunspot record; however, a definite conclusion was not obtained as only 2 to 3 ^{14}C values per solar cycle were available. Suess (1965) measured ^{14}C concentrations in single annual tree rings for the period 1860-1888 but did not observe short-term ^{14}C variations. Lerman (1970) analyzed tree-ring results of Lerman, Mook, and Vogel (1967) from 1894 to 1917. These results indicated some periodicity in ^{14}C concentration during the 11-year solar cycle with an amplitude of ca 2 ‰ and a phase shift of 4 years. Baxter and Farmer (1973) and Baxter, Farmer, and Walton (1973) reported an average amplitude of ca 10 ‰ in tree rings for the period 1829-1865. On the other hand, Damon, Long, and Wallick (1973a,b) reported ^{14}C tree-ring data which show only ca 1.5 °/oo amplitude variations with the 11-year solar cycle for the period 1940-1954. For the interval 1900-1916, Lavrukhina et al (1973) obtained for the average amplitude a value of ca 10 °/oo, but the same authors (Alekseev, Lavrukhina, and Milnikova, 1975) reported the average amplitude of 3 °/oo for 1810-1900. Povinec (1977) reported a 3 °/oo amplitude oscillation over the 11-year solar cycle for the interval 1932-1952. Very precise ^{14}C tree-ring measurements reported more recently (Tans, de Jong, and Mook, 1979; Stuiver and Quay, 1980; 1981; Stuiver, 1982) show only minor short-term ^{14}C variations.

All the ^{14}C measurements mentioned above were made on tree-ring samples. However, Baxter and Walton (1971) measured ^{14}C in samples of whiskies, wines, and plant seeds from the period 1890-1950, observing fluctuations with an average amplitude of ca 15 °/oo. On the other hand, Burchuladze et al (1980) found 4.3 ± 1.1 °/oo average amplitudes of ^{14}C variations in Georgian wine samples from the period 1909-1952.

This short review shows that different groups obtained contradictory results, even for the same solar cycle. A comparison of results obtained by Stuiver (1978) and Baxter, Farmer, and Walton (1973) suggests that the larger ^{14}C fluctuations found by the latter group may be due to a lower precision of their ^{14}C measurements. Generally, larger amplitudes observed with wine samples are poorly understood. One purpose of this paper is to compare ^{14}C results obtained by various authors for the same solar cycles and to perform a similar statistical evaluation of obtained results. A direct comparison of ^{14}C data from different groups was not possible before, as different methods of statistical analysis were used for the evaluation of ^{14}C variations.

RESULTS AND DISCUSSION

Spectral analysis, correlation analysis, and harmonic analysis of $\Delta^{14}C$ values were performed together with similar analyses of sunspot numbers. The most precise tree-ring ^{14}C data (Stuiver and Quay, 1981) and wine ^{14}C data (Burchuladze et al, 1980) covering 3 and 4 solar cycles (1903-1944), respectively, were used for the analyses. We excluded the 18th solar cycle (1944-1954), as $\Delta^{14}C$ values for this cycle have been disturbed by nuclear bomb effects. Figure 1 shows the results of spectral analysis, ie, the autocorrelation functions r(U) of stationary time rows $\Delta^{14}C(t)$ and the Wolf sunspot numbers, W(t). It can be seen that for both types of samples the autocorrelation functions have a quasiperiodical behavior with the

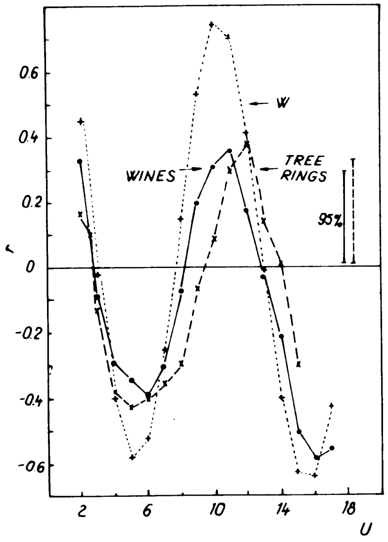

Fig 1. Autocorrelation functions r(U) of stationary time rows $\Delta^{14}C(t)$ (wine and tree-ring samples) and W(t) for argument values $U_{wines} = 11 \pm 1$ yr, $U_{trees} = 12 \pm 1$ yr and $U_W = 10 \pm 1$ yr.

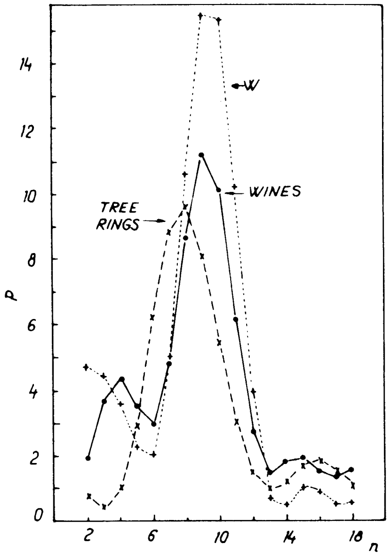

Fig 2. Spectrum estimation of stationary time rows $\Delta^{14}C(t)$ and W(t).

11-year period at the 95% confidence interval. The spectrum estimation of $\Delta^{14}C(t)$ and W(t) rows is shown in figure 2. The basic power of the spectra is concentrated at the period, 11 years. The existence of anticorrelation between the sunspot function and ^{14}C function has been confirmed by correlation analysis. Correlation coefficients have been obtained of more than - 0.6.

The results of the harmonic analysis are given in table 1. Harmonic analysis enables the determination of the amplitude and the phase of $\Delta^{14}C$ variations for different solar cycles, as well as the time shift between W and $\Delta^{14}C$. The amplitude of $\Delta^{14}C$ variations in wines ranged from (4.0 ± 0.8)‰ to (4.5 ± 0.9)‰ and from (1.5 ± 0.5)‰ to (2.1 ± 0.5)‰ for tree-ring samples for different solar cycles. The amplitude varies from cycle to cycle, but its dependence on sunspot numbers for the investigated solar cycles is within the error of analysis. The average amplitude for wines is (4.3 ± 1.6) ‰ and (1.9 ± 0.8)‰ for tree-ring samples.

Table 2 lists the results of the spectral analysis, the

TABLE 1. Amplitude of $\Delta^{14}C$ variations (in ‰) calculated for different solar cycles from wine samples (Burchuladze et al, 1980) and tree-ring samples (Stuiver and Quay, 1981) using harmonic analysis

Samples	14th solar cycle 1903-1913	15th solar cycle 1913-1923	16th solar cycle 1923-1933	17th solar cycle 1933-1944
Wines	4.0 ± 0.8	4.3 ± 0.8	4.5 ± 0.9	4.3 ± 0.8
Tree Rings		1.5 ± 0.5	2.1 ± 0.5	2.0 ± 0.5

TABLE 2. Comparison of data on $\Delta^{14}C$ variations with the 11-yr solar cycle as obtained by different groups

Reference	Samples	Investigated time interval	Periodicity (yr)	Average time shift (yr)	Average $\Delta^{14}C$ amplitude (‰)
Baxter & Walton (1971)	Whiskies	1925-1954	11±1	4	7.2±4.9
Damon, Long & Wallick (1973a)	Tree rings	1940-1954	10±1	4	2.1±1.0
Povinec	Tree rings	1932-1952	10±1	3	3.1±1.2
Burchuladze et al (1980)	Wines	1909-1952	11±1	4	4.3±1.6
Stuiver and Quay (1981)	Tree rings	1916-1954	12±1	4	1.9±0.8

correlation analysis, and the harmonic analysis of annual $\Delta^{14}C$ data reported by different groups. It can be seen that results obtained with tree rings are comparable, although only 1 to 2 solar cycles have been investigated. Tree-ring data of Tans, de Jong, and Mook (1979) were not used for comparison as the ^{14}C measurements were not performed on an annual basis. Results of Baxter and Walton (1971) on whiskies, wines, and seeds showed an average $\Delta^{14}C$ amplitude larger than by factor 2 in comparison with results on wines of Burchuladze et al (1980). All compared results showed the basic power of the spectra concentrated at the period ca 11 years. The calculated average time shifts between W maxima and $\Delta^{14}C$ minima for the different solar cycles are ca 4 years, indicating an anticorrelation dependence of $\Delta^{14}C$ on W.

A comparison of previous studies on short-term ^{14}C variations with the 11-year solar cycle revealed discrepancies that may be partly due to insufficient precision of ^{14}C measurements. This can also be seen from table 2, where calculated average $\Delta^{14}C$ amplitudes are well within 2 sigma. However, we can not entirely exclude the possibility of differences caused by sample location, such as local variations of stratospheric input and the time lag between input and growth season.

In conclusion, we want to stress that although our study demonstrated the existence of the 11-year ^{14}C variations at least for 4 solar cycles (1903-1944), more high-precision ^{14}C measurements in annually-dated samples are needed for a better understanding of short-term ^{14}C variations.

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