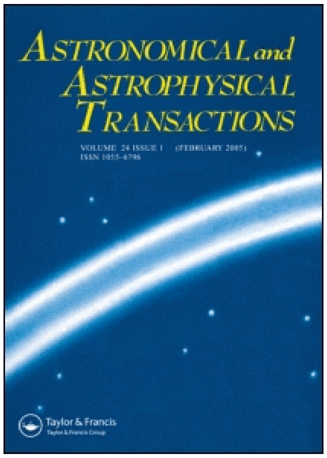

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HISTORY AND FORECAST OF SOLAR ACTIVITY

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From a new reconstruction of the radiocarbon production rate in the atmosphere we obtain a long history of maximum Wolf sunspot numbers. Based on this reconstruction as well as on the history of other indicators of solar activity (^{10}Be, aurora borealis), we derive a long-period trend which together with the results of spectral analysis of maximum Wolf numbers series (1506–1993) form a basis for prediction of solar activity up to 2100. The resulting trigonometric trend points to an essential decrease in solar activity in the coming decades.

KEY WORDS Maximum Wolf sunspot numbers, indicators of solar activity, radiocarbon production rate, forecast

1 INTRODUCTION

Despite the fact that the full study of the impact of solar activity on the climate of the Earth has not been completed yet, there is no doubt of the presence of a stable statistical relationship between some characteristics of solar activity and climatic factors. Among these characteristics the most important are the length of quasi 11-year Schwabe cycle and the Wolf sunspot numbers in the years of maxima of solar activity (Reid, 1991, Friis–Christensen and Lassen, 1991). In the present paper an attempt is made to reconstruct the history of sunspot maxima and build their forecast on the basis of historical, glaciological and dendrochronological data.

Figure 1 shows the annual mean Wolf sunspot numbers from 1500 until 1993, where values for the period 1610–1993 were obtained as a combination of data from Eddy (1976), Waldmeier (1961) and from Solar Geophysical Data (1994). Values for 1500–1609 were reconstructed by Schove (1983) from observations on aurora borealis. In the picture the maxima $R_{\max}(x)$ of Wolf numbers are connected with solid lines.

We proceed from assumption that the behaviour of the series $\{R_{\max}(x)\}$, where x is the number of a Schwabe cycle, can be satisfactorily described by a linear

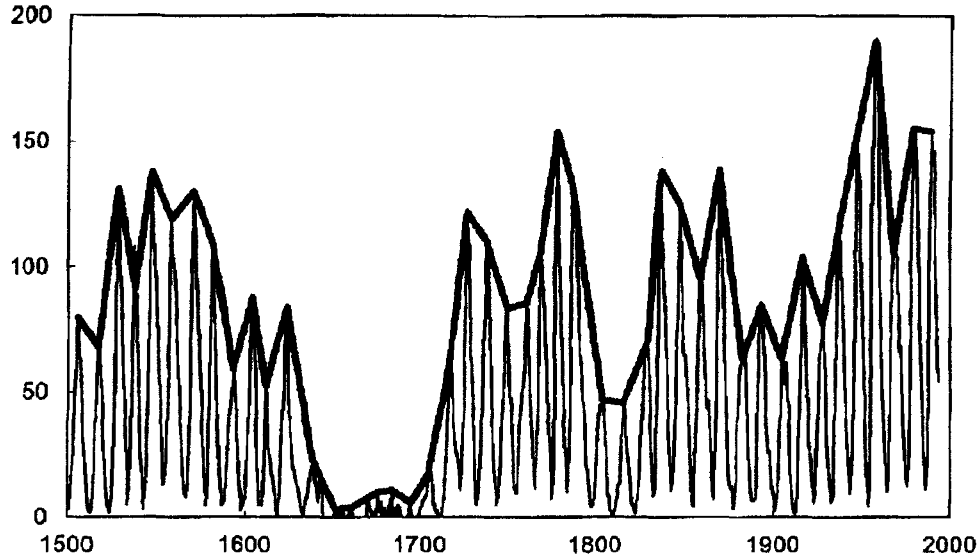

Figure 1 Annual Wolf numbers for 1500–1993.

regression model

$$R_{\max}(x) = \sum_{i=1}^{n} R_i(x) + C + \varepsilon(x), \tag{1}$$

where $R_i(x) = A_i \cos 2\pi x/T_i + B_i \sin 2\pi x/T_i$, C is a constant, and $\{\varepsilon(x)\}$ are independent random variables with a zero mean and finite variance.

It can be seen from Figure 1 that the values of $R_{\max}(x)$ for $x = -22, -21, \ldots, 22$ have a significant increasing trend. This fact leads to the hypothesis that the data contain harmonics with periods exceeding the length of the time interval of reliable data. Here it is assumed that the reliable data are those from 1749. So the problem of detecting periodic components in the series splits into two parts. First we shall look for a long-period trend based on supplementary information. Second we shall investigate the behaviour of $\{R_{\max}(x)\}$ with the long-period trend eliminated.

2 INDICATORS OF SOLAR ACTIVITY

The magnetic fields induced by the solar wind in the space near the Earth deflect a part of cosmic rays producing radioactive isotopes by interaction of neutrons with atmospheric nitrogen. Hence the measurements of amounts of isotopes such as ^{14}C and ^{10}Be can provide a record of changes in solar activity.

Constantly produced by cosmic ray flux, radiocarbon is being oxidized to $^{14}CO_2$ and rapidly mixed with atmospheric CO_2 thus participating in the carbon exchange between the atmosphere, ocean, biomass and litter. Being absorbed together with

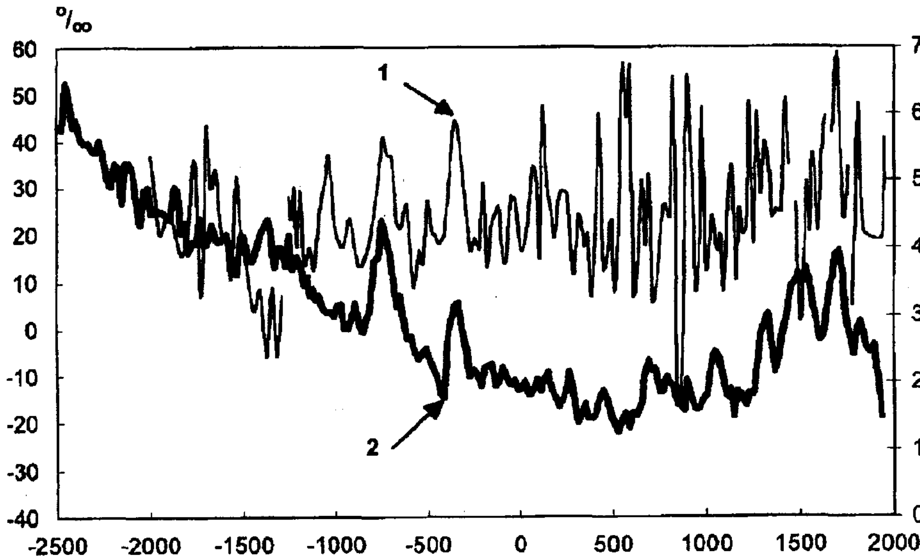

Figure 2 ^{10}Be concentrations for 2000 BC – 1950 AD (1) and Δ^{14}C for 2500 BC – 1940 AD (2).

other carbon isotopes by living organisms and plants, it is contained in them in about the same proportion to the total amount of carbon as in the atmosphere. The data on ^{14}C used below were obtained by calculating the radiocarbon age and ^{14}C-activity in tree rings. The results are presented as Δ^{14}C, which represents the normalized ^{14}C-activity at its formation, expressed as a deviation in parts per thousand from the oxalic acid standard activity (Stuiver and Polach, 1977). For our study we have chosen mixed high precision data of Seattle and Belfast labs (Stuiver and Pearson, 1986; Pearson and Stuiver, 1986) for the period 2500 BC – 1880 AD with 20-year sampling step (Figure 2). It should be emphasized that below we use data on ^{14}C until 1880 AD only because they were not perturbed by Suess-effect, i. e. the effect of reducing the $^{14}CO_2$ proportion in the atmosphere due to an increased consumption of fossil fuel not containing ^{14}C.

Unfortunately, the other available indicators of geophysical environment strongly depend on regional fluctuations. The geochemical pathways of ^{14}C and ^{10}Be are very different. As beryllium does not form gaseous compounds in the atmosphere, it is rapidly removed from it, so the changes in ^{10}Be production are directly reflected in the concentrations of ^{10}Be in geological reservoirs (polar ice, lake sediments etc.). However owing to a short lifetime in the atmosphere (1–2 years) the concentration of ^{10}Be depends much on the local parameters such as precipitation and other meteorological conditions. Here we chose a 3000-year record of ^{10}Be concentration in the ice core from the station Dome C in Antarctica (Stephenson and Wolfendale, 1988) expressed in terms of the number of atoms per 1 gram of water (Figure 2).

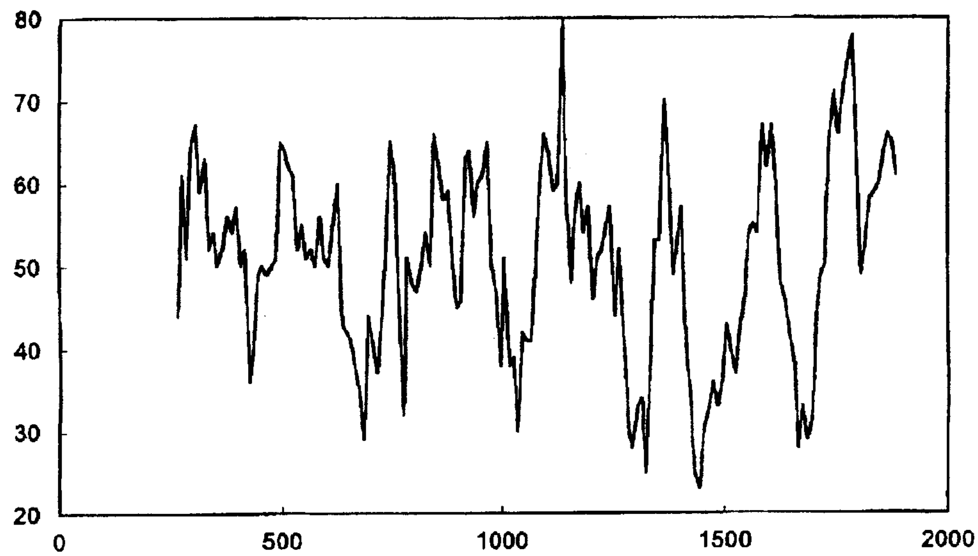

Figure 3 The intensity of aurora borealis for 300–1880.

The changes of solar activity are also reflected in changes of the frequency of aurora borealis in the middle latitudes of Europe and Asia. Figure 3 shows the data for 300–1880 obtained by Schove (1983) from Chinese and European historical records.

We believe that the data on $\Delta^{14}C$ are the most reliable owing to a high accuracy of measurements, however they do not directly reflect changes of solar activity. The values of $\Delta^{14}C$ are proportional to changes of the $^{14}C/^{12}C$-ratio in the atmosphere. The radiocarbon is permanently redistributed between the main large carbon reservoirs – the atmosphere, ocean and biosphere, therefore short-period variations in the ^{14}C production correspond to essentially damped variations of the $^{14}C/^{12}C$-ratio, and long-period variations in the ^{14}C production are reflected by this ratio with a possible delay. In the following section data on the ^{14}C production rate are reconstructed from a $\Delta^{14}C$ record, and in Section 4 we attempt to reconstruct maxima of the Wolf numbers for 0–1520 AD.

3 RECONSTRUCTION OF RADIOCARBON PRODUCTION RATE FROM $\Delta^{14}C$ DATA

For last several millennia the extra long-period trend in the $\Delta^{14}C$ data is related to changes of the geomagnetic field intensity and can be approximated by a sine wave function with the period of $\sim$ 10.8 thousand years (Stephenson and Wolfendale, 1988):

$$\Delta^{14}C(t) = 36.6 - 48.8 \sin\left(\frac{2\pi}{10780}t + 1.29\right) \tag{2}$$

This trend was subtracted from the data on $\Delta^{14}C$, and the residual signal was used for calculation of radiocarbon production rates.

Stuiver and Quay (1980) convincingly demonstrated that the variations in solar activity and the quantity of radiocarbon produced in the atmosphere are coherent. They also presented a reconstruction of Wolf numbers for the present millenium obtained on the basis of this coherence. The radiocarbon production rates for this period were calculated using the box-diffusion model (Oeshger *et al.*, 1975) which describes the processes of CO_2 and ^{14}C exchange between the atmosphere, ocean and biosphere. Then the linear regression estimate of Wolf numbers averages for each Schwabe cycle was obtained on the basis of the data on sunspot numbers and radiocarbon production rates for 1720–1860. It was shown that the value of the scale factor calculated by the above methods can be essentially changed if the other time interval is used.

To reconstruct the radiocarbon production rates for 2500 BC – 1880 AD, we use the outcrop-diffusion model of Siegentaler (1983), which is an advanced version of the model of Oeshger *et al.* (1975), equipped with some new conceptions about the intensity of a biospheric CO_2 source. In order to find radiocarbon production rates it is necessary to solve an equation inverse to the equation of atmospheric carbon balance. We solve the inverse equation under the condition that deviations of CO_2 and ^{14}C concentrations from their steady states are small. Calculation of the derivaties of relative changes of CO_2 atmospheric concentration and of radiocarbon relative concentration from experimental data depends on a method of data smoothing and, therefore, it is rather a subjective operation. That is why we use the equation of atmospheric balance of CO_2, taking into account industrial and biospheric sources of carbon dioxide. Here the emission of biospheric source was obtained with the model of biospheric box (Klimenko *et al.*, 1993), and the emission from the industrial source from 1750 AD was taken from Snytin *et al.* (1994). The estimation of the derivative of radiocarbon relative concentration and data interpolation were implemented on the basis of nonparametric estimation methods for longitudinal data (see e.g. Müller, 1988).

4 RECONSTRUCTION OF SOLAR MAXIMA FROM RADIOCARBON DATA

In Figure 4 two versions of deviations of the ^{14}C production rates from their mean over the period of 0–1880, obtained from the outcrop-diffusion model with constant and varying CO_2 concentrations, are shown together with equidistant series $\tilde{R}_{max}$, which is an interpolation of R_{max} with 20-year sampling period. It can be seen that taking into account of a growth of the atmospheric CO_2 concentration after 1800 has led to the better correlation between modelling results and data on Wolf numbers.

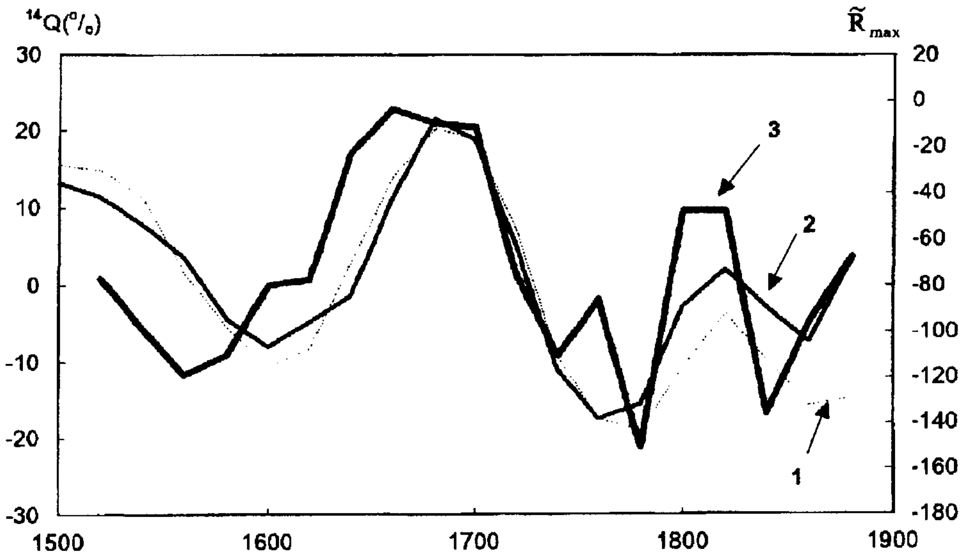

Figure 4 Deviations of the ^{14}C production rates from their mean over 1–1880 obtained with constant (1) and varying (2) CO_2 concentrations and equidistant $\tilde{R}_{max}$ (3).

At the following stage we estimate coefficients in the linear regression model

$$\tilde{R}_{max}(t) = \alpha \cdot Q(t) + \beta + \varepsilon(t), \quad t = 1660, 1680, \ldots, 1880, \tag{3}$$

where $Q(t)$ denotes deviation of the ^{14}C production rate from its 1880-year mean, calculated under a constant or varying CO_2 concentration, $\varepsilon(t)$ are independent zero mean random values with finite variance. In Table 1 least squares estimates (LS) of parameters α and β are given together with estimates obtained by the instrumental variable method (IVM) (see e.g. Kendall and Stuart, 1967). Here we use data on aurora borealis and ^{10}Be as instrumental variables. As was expected, the absolute values of IVM estimates of the scale factor α are larger than those of the LS method,

Table 1. Estimates of the coefficients in regression of R_{max} by ^{14}C production rates

Method		*Varying CO_2 concentration*		*Constant CO_2 concentration*	
LS	α	−3.2		−2.6	
	β	71.7		61.6	
	Instrumental variable	^{10}*Be*	*Aurora borealis*	^{10}*Be*	*Aurora borealis*
IVM	α	−4.5	−3.6	−3.6	−3.1
	β	73.5	73.2	61.7	63.2

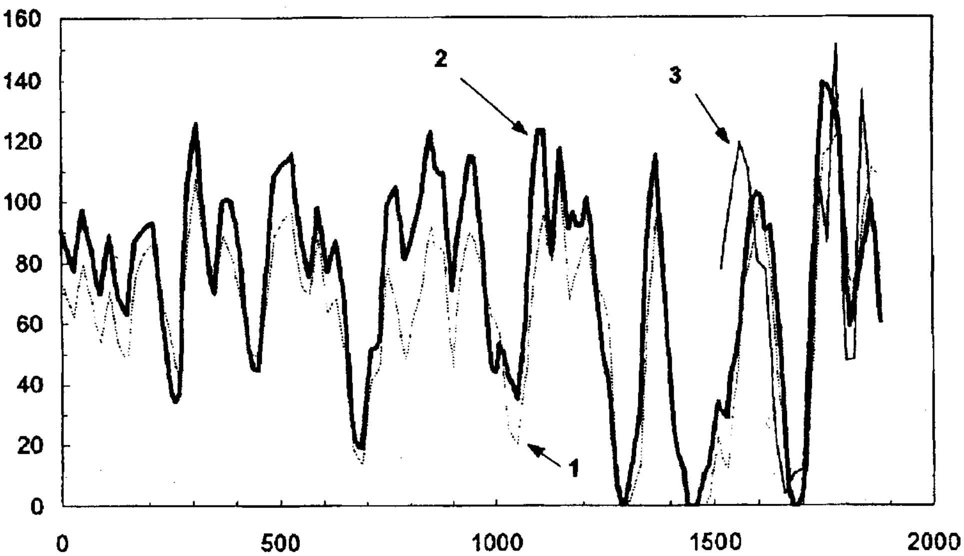

Figure 5 Reconstructions of $\tilde{R}_{max}$ obtained for constant (1) and varying (2) CO_2 concentrations with aurora borealis taken as an instrumental variable and $\tilde{R}_{max}$ for 1520–1980 (3).

but the results seem to be rather close. Figure 5 shows IVM reconstructions of $\tilde{R}_{max}$ both for constant and varying CO_2 concentrations with aurora borealis as an instrumental variable. We chose this series as it correlates well with radiocarbon series and does not contain gaps on the considered time interval.

For the reason mentioned in the beginning of this section we chose the reconstruction of the Wolf maximum numbers obtained from equation (3) with IVM estimates of coefficients and a varying CO_2 concentration. This reconstruction denoted below as $\hat{R}_{max}$ consists of two parts: backward extrapolation of equation (3) for A.D. 1–1520 and $\tilde{R}_{max}$ series for 1520–1980.

5 LONG-PERIOD TREND FOR RECONSTRUCTION OF MAXIMUM WOLF NUMBERS AND PERIODIC FLUCTUATIONS IN MODERN SOLAR DATA

The spectra of radiocarbon series were repeatedly investigated by different methods. Here we apply the maximum entropy method (MEM) (see e.g. Andersen, 1974) for a nonparametric estimation of the spectral density of our reconstruction of the radiocarbon production rates for the interval A.D. 1–1880. Figure 6 shows the obtained estimate, where the method dimension is equal to 40, together with the spectra of $\hat{R}_{max}$ calculated with the same method dimension for the interval A.D. 1–1980. It can be seen that the spectral structures of these two series are similar.

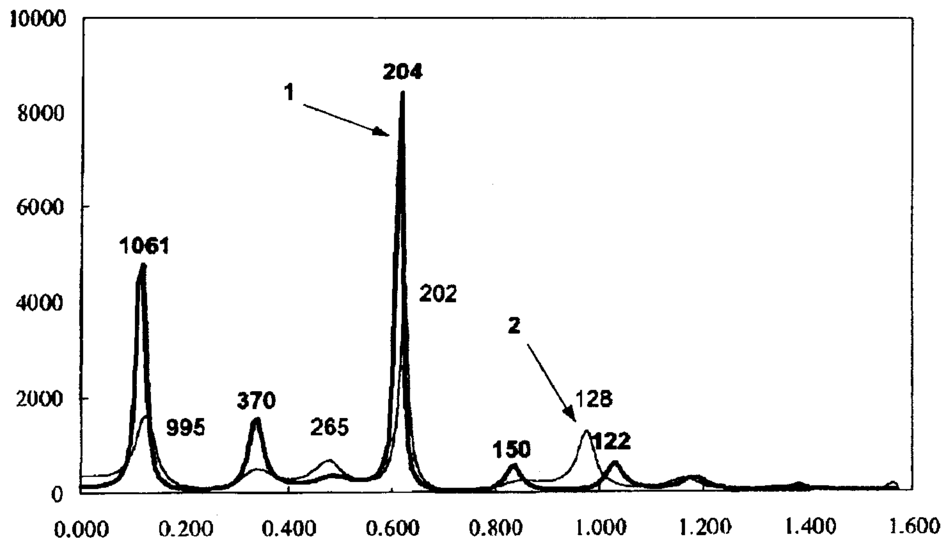

Figure 6 MEM spectral density estimates of $\hat{R}_{\max}$ (1) and radiocarbon series (2) for A.D. 1–1980 and A.D. 1–1880 respectively.

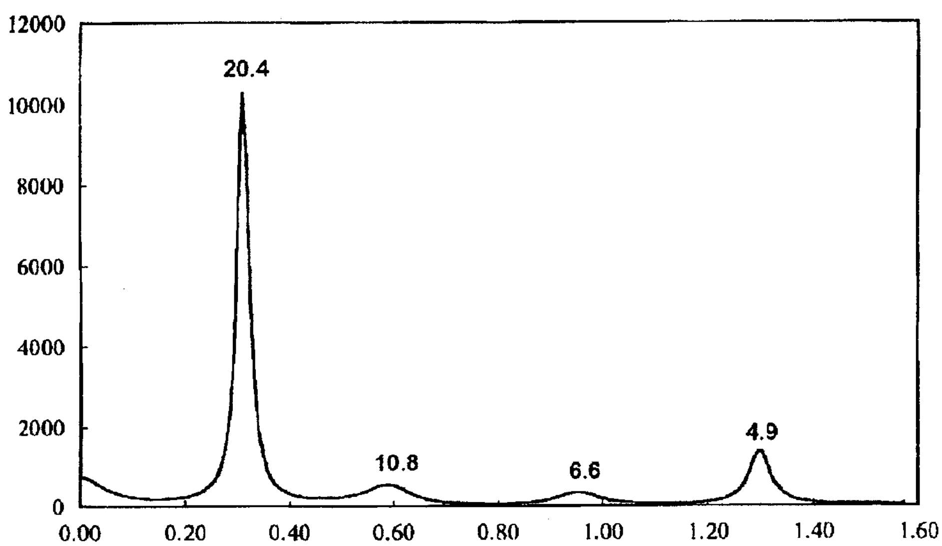

Figure 7 MEM spectral density estimates of $R_{\max}$ series for 1500–1993.

The long-period trend for $\hat{R}_{\max}(t)$, $t = 0, 1, 2, \ldots, 2100$, is constructed as a sum of harmonics with periods of 1061 and 370 years (that corresponds to 96.7 and 33.7 Schwabe cycles) and a constant term. The values of coefficients are found by the LS method. Then we subtract this long-period trend from $R_{\max}(x), x = -22, -21, \ldots, 22$, where x is a number of Schwabe cycle.

Table 2. Main characteristics of R_{max} trend

Periods in years	*Periods in cycles*	A_i	B_i	*Amplitudes*
1061	96.6	3.6	14.5	14.9
370	33.7	−14.5	0.7	14.6
210	19.1	7.6	33.3	40.9
119	10.8	13.9	-6.7	15.4
72	6.6	−12.1	2.5	12.3
54	4.9	−5.3	−16.8	17.6

Next we investigate a high frequency part of the R_{max} spectrum. In Figure 7 MEM estimates of the spectral density of $R_{max}(x)$, $x = -22, -21, \ldots, 22$, without long-period trend are shown, here the method dimension is equal to 20. It is easy to observe the maxima of spectral density in the periods of 20.4 (225 years) and 4.9 (53 years), and it is also possible to detect the maxima, corresponding to the periods of 10.8 (118 years) and 6.6 (72 years).

The stability of 200-year periodicity in the Sun activity is confirmed by minima regularly occuring in odd centuries: the minima of Oort (1010–1050), Wolf (1280–1340), Spörer (1420–1530), Maunder (1645–1715), Dalton (1790–1830) (see Figure 5). However the length of this period for R_{max} has appeared a little bit greater than for the series presented in Figure 5.

Proceeding from the afore going, the trigonometric trend for $R_{max}(x)$ is constructed as a superposition of a long-period component and harmonics with the periods of 19.1, 10.8, 6.6 and 4.9 Schwabe cycles. The main characteristics of this trend are presented in Table 2. Coefficients A_i and B_i, $i = 1, \ldots, 5$ of equation (1) are given in recalculation to the standard numbering of cycles, at which the zero cycle corresponds to 1750.

It is known that the length of Schwabe cycle is linked to solar activity in such a manner that short cycles correspond to a high activity and vice versa. The form of a cycle depends on the value R_{max} and

$$\log R_{max}(x) = 2.73 - 0.18T(x), \tag{4}$$

where $T(x)$ is the time of rise of an index from the minimum to the maximum for the cycle with number x (see Schove, 1983). In order to date the predicted values of $R_{max}(x)$ the results of the forecast of minima dates for Wolf numbers (Fyodorov *et al.*, 1995) were used starting from a 23-rd cycle:

$$D_{max}(x) = D_{min}(x) + (2.73 - \log R_{max}(x))/0.18 \tag{5}$$

Here $D_{max}(x)$ is the date of the maximum and $D_{min}(x)$ is the date of the minimum for the cycle with number x.

The resulting trigonometric trend for R_{max} and its long-period component are presented in Figure 8 up to 2100. It follows from the appearance of these curves that an extremely high level of solar activity in the second half of the present century is

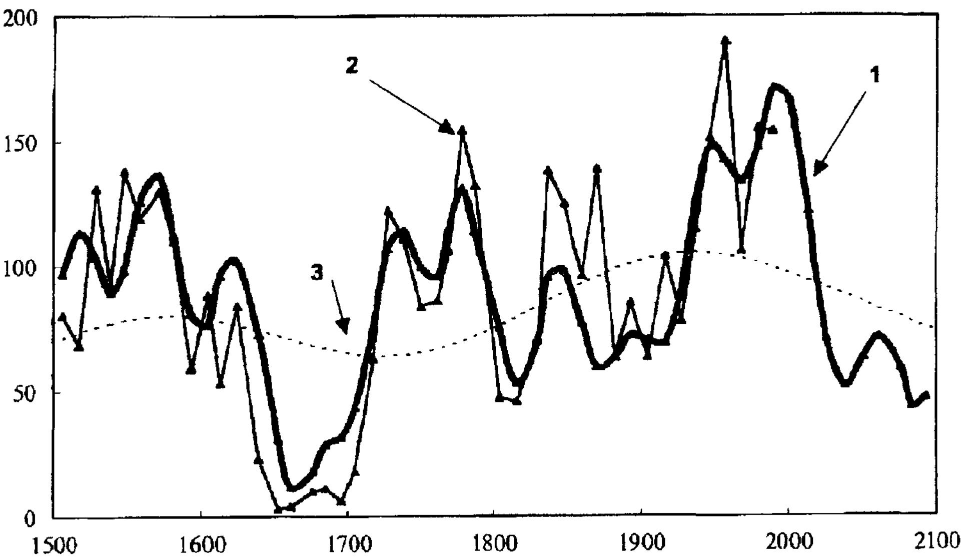

Figure 8 Trigonometric trend (1) for R_{max} (2) and its long-periodic component (3).

caused by a superposition of the 200-year harmonic and long-period components. The behaviour of the trigonometric trend also points to a reduction of solar activity starting from 2000. It will involve the decrease in the solar constant by several tenths of a percent resulting in a substantial change of the mean global temperature.

6 CONCLUDING REMARKS

1. The research performed shows the necessity of consideration of changes in the CO_2 concentration caused by the impact of human activity on the biosphere, while calculating the radiocarbon production rates. The calculated series of the radiocarbon production rate correlates well with the series of maximum Wolf numbers and serves as a basis for the reconstruction of solar activity in the past and for revealing tendencies of solar activity within the range of several centuries.

2. Of course, the long-period trend need not be actually of a trigonometric form but the trigonometric approximation proves to be an effective and convenient tool for describing the behaviour of series under consideration.

3. The question can arise why we have not use Gnevyshev–Ol's rule while predicting the maximum Wolf numbers. We shall remind that, according to Vitinskij (1963), by Gnevyshev–Ol's rule the following statements are meant:

(i) the series of Wolf numbers falls in the sequence of approximately 22-year cycles, each of these cycles corresponds to a pair of even and odd Schwabe cycles (according to Zurich numbering, the dependence between maximum values of

Wolf numbers within these 22-year cycles is higher than the dependence between 22-year cycles);

(ii) as a rule the maximum value of an odd Schwabe cycle is greater than the maximum value of the preceding even Schwabe cycle;

(iii) there exists a linear relationship

$$R_{\max}(2x+1) = \alpha R_{\max}(2x) + \beta + \varepsilon_x, \tag{6}$$

where $x = -11, -10, ..., 10$, $\{\varepsilon\}$ are independent random errors; the estimates of α and β from sample $R_{\max}(0), \ldots, R_{\max}(18)$ without pair $\{R_{\max}(4), R_{\max}(5)\}$, which is an obvious exception, are equal to 0.94 and 32.4 respectively.

Indeed the LS estimates of the parameters in (6) from sample $R_{\max}(0), \ldots, R_{\max}(21)$ without pair $\{R_{\max}(4), R_{\max}(5)\}$ are $\hat{\alpha} = 0.94$, $\hat{\beta} = 34.8$. However the estimate of variance of $\{\varepsilon_x\}$ is equal to 478.5, so part (iii) of Gnevyshev–Ol's rule is of little interest for practical forecast of Wolf numbers.

Consider a sequence $\{\Delta_x, x = -11, -10, \ldots, 10\}$ of differences between the values of the maximum Wolf numbers within each pair of Schwabe cycles. If we prove the hypothesis that the frequencies of the event $\{\Delta_x > 0\}$ for subsequencies $\{\Delta_x, x < 0\}$ and $\{\Delta_x, x \geq 0\}$ are equal, it will bear witness to the validity of statement (ii). Under assumption that these differences are independent random values, it can be shown by the standard statistical procedures that the hypothesis of the equality of frequencies is true with probability 0.04. The fact that the values of Δ_x for $x < 0$ contain errors has little effect on the value obtained if the variance of errors is substantially less than the variance of $\{\Delta_x\}$. The proximity of the scale α to 1 suggests that $\{\Delta_x\}$ are independent of $R_{\max}(2x)$. This supposition is verified by the results of F and t-test both for the entire sample and for $\{\Delta_x, x \geq 0\}$ with or without pair $\{R_{\max}(4), R_{\max}(5)\}$. Moreover it can be observed that the sample can be divided into two clusters of equal size, and nonparametric density estimates for each cluster are close to the normal densities. Parameter estimates for these normal densities are respectively (–13.1, 148.0) and (37.1, 80.5), where the first number in the pair is a sample mean and the second one is a sample variance. It is easy to show that probability of being in the second cluster (this event corresponds to statement (ii)) depends on the cycle number x and is growing as x increases.

Proceeding from the foregoing facts we come to the conclusion that parts (ii) and (iii) of the considered rule are valid only for a relatively short time interval adjacent to the present one. Thus we see a little reason for using these statements to forecast the behaviour of $R_{\max}$ for a comparatively long time interval.

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