The supercenturial solar minima and their preceding phenomena

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Abstract. The main aim of this study is to find different observational characteristics of sunspot cycles, which could be used as precursors of forthcoming supercenturial solar minima. A data set of indirect records for solar activity (so called Schove's series) between 214 BC - AD 2000 has been analyzed. Two potential precursors of the further behaviour of the solar activity have been pointed out - the violation of Gnevyshev-Ohl's rule in even-odd numbered pairs of Schwabe-Wolf's cycles and the increasing of the cycles duration. A third method for prediction, based on two-factor regression model has been applied too. In this method the magnitudes of both even-odd sunspot cycles are used as predictors. On the base of the actual data for the current pair of the Zurich cycles No.22 and 23 a prediction for a relatively weak sunspot cycle No. 24 with expected maximum about AD 2012/13 and Wolf's index $W_{max} \approx 90$ was made. A prediction of forthcoming supercenturial solar minimum in the period AD 2030-2080, like the Dalton minimum in AD 1795-1830, is given also. Some climatic effects may be expected in the period of the supercenturial solar minimum. As a result a "global cooling" climatic effect in the range of 0.4-0.7 °C could be expected.
Key words: solar activity, Schove's series

Свръхвековите слънчеви минимуми и предхождащите ги явления

Борис П. Комитов

Главната цел на това изследване е намирането на различни наблюдателни характеристики на слънчевите цикли, които биха могли да се използват като прединдикатори на настъпващи свръхвекови слънчеви минимуми. Анализирана е съвкупността от индиректни данни за слънчевата активност, известна като "ред на Шове" за периода 214 г. пр.н.е. - 2000 г. н.е. Установено е, че потенциални предвестници на бъдещото поведение на слънчевата активност са нарушението на правилото на Гневишев-Ол в "четно-нечетните" двойки цикли на Швабе-Волф и увеличаването на продължител-ността на циклите. Приложен е и трети метод за прогноза, базиран на двуфакторен регресионен модел. При този метод като фактори (предиктори) се използват мощностите на четния и нечетния петнообразувателни цикли. На базата на актуалните данни за текущата двойка цюрихски цикли с номера 22 и 23 е направена прогноза за относително слаб слънчев цикъл No 24, с очакван максимум около 2012/13 г. и околомаксимумно Волфово число ≈90. Направена е също и прогноза за настъпващ свръхвекови слънчев минимум в периода 2030-2080 г, подобен на Далтоновия минимум (1795-1830г). В периода на свръхвековия слънчев минимум могат да се проявят ефекти върху климата. Би могъл да се очаква климатичен ефект на "глобално застудяване" в диапазона 0.4 -0.7°C.

1 Introduction

The cyclic behaviour is the main feature of the solar activity processes. This fact has been established for the first time in the middle of 19th century on the base of Schwabe's observations, which is generalized in the works of R.Wolf (Wolf, 1862-1893). According to Wolf's results the main sunspot activity cycle has a mean duration of 11.04 years. Later it has been found by different authors that a quasi-11-year variability is visible in many other solar activity processes too (electromagnetic flux, corpuscular radiation, flares activity, coronal processes, solar wind parameters etc.). At the beginning of the 20th century a cycle with duration of two Schwabe-Wolf's cycles (i.e 20-22 years) has been detected in the changes of the sunspots group polarity, as well as in the behaviour of the total solar magnetic field.

Very soon after the discovery of the quasi-11-year of the sunspot oscillations it has been detected that the cycle duration and amplitude vary significantly from cycle to cycle. The typical durations of single Schwabe-Wolf's cycle lays in time period 9-13 years.

The amplitude variations of the quasi 11-year sunspot cycles are even much more expressive. On the base of instrumental sunspot observations after AD 1749 a quasi-cyclic 80-90 years amplitude variations of Schwabe-Wolf's cycles have been established by Gleissberg (Gleissberg, 1944). He has detected two well expressed periods of relatively weak Schwabe-Wolf's cycles at the beginning of 19th and 20th centuries, respectively, appearing as quasicenturial sunspot activity minima.

However much more earlier, still at the end of 19th century G. Spoerer and E. Maunder (Maunder, 1893) present evidences for extremlly low sunspot activity levels during two relatively long periods: 1420-1550 and 1645-1715. Now the first one is labeled as "Spoerer minimum", while the second one is known as "Maunder minimum".

Few decades later D. J. Schove (Schove, 1955), on the base of very large number of historical data (messages for observed auroras, simple eye visible sunspots, tree rings width data, etc.), build a series of Schwabe-Wolf's sunspot cycles macroparameters (calendar years of sunspot minima and maxima, sunspot cycle magnitude), which are labeled later as "Schove's series". These series begin at AD 296 and contain information for 155 Schwabe-Wolf's cycles close to AD 2000 (Zurich cycle No. 23 maximum).

According to Schove's initial analysis of this data set, there is a series of continuous deep solar minimum epochs with weak 11-year sunspot cycles, which are on the middle time distance of ≈180 years each other (Fig.1). As it is point out in Section 3, the Spoerer and Maunder minima are the best expressed phenomena of this type between ≈200 BC and AD 2000. The last similar event, the "Dalton minimum", has been occurred between AD 1795 and 1830.

In our earlier study on the base of time series analysis it has been shown that these deep solar minima are caused by powerful quasi 204 year cycle, which exists in Schove's series (Komitov, 1997). After AD 1000 other similar phenomena are the so called minima of Oort and Wolf in 11th and 13th-14th centuries respectively (Fig.1).

Earlier a quasi-bicenturial 200-210 year solar cycle in ^{14}C tree rings and ^{10}Be continental ice densities data series has been established too (Stuiver & Quay, 1980; Damon & Sonett, 1991; Dergachev & Chistyakov, 1991; Bier et al, 1997 etc.). The downward phases and minima of the last one are in a very good coincidence with afore-said periods of very weak 11-year sunspot cycles amplitudes in Schove's series.

All recently mentioned phenomena are labeled as "supercenturial solar minima" (SCSM). They have been occurred during the downward and near minimum phase of the quasi-bicenturial 200-210 year cycle usually by superposition of minima of other long term solar oscillations with durations of range of 80-100 years or longer.

The SCSM forecasting is a problem of high importance, because according to the paleoclimatic data they are in very good coincidence with temporal global Earth climate cooling effects with a mean value of ≈ 0.8 °C (Damon & Sonett, 1991). In this course it is interesting to search for some observational phenomena, which could be pre-indicators of forthcoming supercenturial solar minima.

Gnevyshev-Ohl's (G-O) rule (Gnevyshev & Ohl, 1948) is known as ordering of relative lower Zurich even numbered Schwabe-Wolf's cycles with higher odd numbered one. In our previous work (Komitov & Bonev, 2001) it has been shown that the violations of the G-O rule are preceding phenomena of forthcoming SCSM. This conclusion has been derived on the base of Schove's series continuous part for the last 1700 years. In the above mentioned paper the present G-O rule violation for Zurich pair cycles 22-23 is discussed as a pre-indicator of a new supecenturial solar minimum, which will occur in the middle part of 21st century.

Independent evidences in this course are given on the base of time series models extrapolations (Komitov & Kaftan, 2003) and statistics of SCSM events frequency during Holocene (the last ≈11000 years) on the base of ^{14}C data series (Solanki et al, 2004).

The main aim of the present study is a more detailed analysis of two phenomena, which are possible pre-indicators of SCSM events. Schove's series data for the last ≈2200 years (214 BC - AD 2006) are used.

The G-O rule violations are considered as first pre-indicator. In our first study (Komitov & Bonev, 2001) it has been shown that G-O rule violations are more than 90% probable events, if the even numbered cycle magnitude exceed a "critical level" of W_{max}>125. (W_{max} is the near maximal mean annual Wolf's spot number). In the present work a more detailed analysis of G-O rule violation conditions has been provided. A hypothesis that the "critical level" depends on the supermillenial solar activity dynamics has been tested.

Schwabe-Wolf's cycle length variations are considered as second possible pre-indicator of forthcoming supercenturial solar minimum. On the base of instrumental Zurich and Group sunspot numbers series it could be concluded that the forthcoming centurial or supercenturial minima lead to an increasing Schwabe-Wolf's cycles length. However this statement is based only on two such events during the epoch of instrumental observations: the supercenturial Dalton minimum (1795-1830) and the quasi-centurial Gleissberg minimum (1898-1923). Consequently, a more general study of the problem for a much longer period is needed.

2 Data and methods

As it has been already pointed out in Section 1, Schove's series is the oldest large time scale solar activity data set, based on historical records. Its main advantage over the other similar series, including "cosmogenic" isothopes too, is that it contains directly information about Schwabe-Wolf's cycles. The last version of Schove's series has been published in 1983 (Schove, 1983) and it is used in present analysis.

The full data period is about 2600 years. It could be separated into six parts:

(a) - before 214 BC; there are data only for single sunspot cycles;

(b) - between 214 BC and AD 196; this part contains full information for 38 Schwabe-Wolf's cycles;

(c) - between AD 196-296; this period contains data for minima and maxima of 7 sunspot cycles, without magnitude data;

(d) - AD 296-1749; this part contains full information for 131 sunspot cycles;

(e) - AD 1749-1954; this part is based on instrumental data of the Zurich series. The Zurich cycles No. 0-18 are included there, too. It has been used for calibration of all Schove's series;

(f) - after AD 1954; this period does not contain original part of Schove's series. It has been added by author of the present study and contains the calendar years of minima and maxima of Zurich cycles No. 19-23, based on instrumental data

In our previous works (Komitov, 1997; Komitov & Bonev, 2001) the continuous part of Schove's series from AD 296 to 1996 has been used. In the present study Schove's series is extended by adding parts (b) and (c). Totally, in parts (b) - (f) 201 sunspot cycles are included. The initial data proceeding is the same as in the aforesaid papers.

The cycle magnitude before AD 1749 is pre-calculated in W_{max} by using of calibration scale, which is given by J. D. Schove. The mean values of W_{max} has been accepted for each of the corresponding magnitude levels.

As it is already noted, there are not magnitude data during AD 196-296 (part (c)) and by consideration of continuity a value $W_{max} = 0$ is accepted. This fact is taken into account in our analysis of magnitude data.

After AD 1749 the real smoothed values of near maximal annual Wolf's number are used as W_{max}.

Schwabe-Wolf's cycle length is determined as a time interval between calendar years of two adjacent minima. The uncertainty of the last ones is essentially higher for the earlier parts of Schove's series. However, it could be shown that by specific features of

Schove's data proceeding algorithm, concerning the number of Schwabe-Wolf's cycles per century, this effect of calendar years uncertainty is strongly minimized.

The mean duration of Schwabe -Wolf's cycles (11.04 years) is a "natural " time step of Schove's series. It is labeled further in the text as "Sc"(sunspot cycle).

The sunspot cycle numbers according to our work from 1997 (Komitov, 1997) are used, where "1" is the number of cycle started in AD 296 and "155" is the number of the present Zurich cycle No. 23. By this way the even numbered sunspot cycles in Zurich series are even numbered in Schove's series, too. Negative numbers have been assigned to sunspot cycles before AD 284 and the number of cycle started in AD 284 is "0".

The analysis is based mainly on the T-R periodogram procedure (see below). The last one has been described already in few previous works (Komitov, 1986, 1997; Benson et al.,2003 etc.).

The idea of method is to approximate the studied original time series $F(t)$. We minimize a function of simple periodic type $\varphi(t)$, i.e:

$$\varphi(t) = A_0 + A\cos\left(\frac{2\pi t}{T}\right) + B\cos\left(\frac{2\pi t}{T}\right) \quad (1)$$

where $t = 0, 1, 2\ldots$ are the corresponding moments in time step units (the time series step) and A_0, A and B are the free parameters. Here A_0 is the mean value of $F(t)$ obtained on the base of all time series terms and T is the period, which varies in range $[T_0, T_{max}]$ by step of $\mathit{\Delta}T$. By this way a series of p minimized functions $\varphi(t)$ is obtained, where $p = (T_{max} - T_0)/\mathit{\Delta}T$. The minimal possible value of T_0 is equal to 2 steps of the time series.

For each one of the derived functions $\varphi(t)$ the correlation coefficient R with respect to the time series $F(t)$ is calculated. The local maxima of R are indicated for a possible existence of cycles by durations equal to corresponding periods T. The statistical significance of these cycles is estimated on the base of ratio R/σ_R, where $\sigma_R = (1-R^2)/\sqrt{N}$ is the standard error of R and N is the length (number of terms) of time series. A cycle is taken as a real for more than 95% probability if $R/\sigma_R > 1.96$.

On the base of Monte-Carlo modeling of time series we derived an essentially stronger criterion. It is satisfied if $R/\sigma_R > 454/N^2 + 3.46$, where for long series ($N \to \infty$) R/σ_R tends to 3.46. The last criterion is needed because there are many cases of cyclic oscillations in pseudo random number series for which R/σ_R is between the both critical levels. In these cases the cycle reality could be estimated on a base of the additional expert criteria.

Since Rdepends on T, the function $R(T)$ obtained with the help of the afore-said procedure is labeled as "T-R correllogram" (Komitov, 1997).

In the T-R periodogram procedure the total magnitude of all oscillatons in a period interval $[T_1, T_2]$ may be labeled quantitatively by means of the "integral power index" S:

$$S = \int_{T_1}^{T_2} a(T)dT \quad (2)$$

Here

$$a(T) = \sqrt{A(T)^2 + B(T)^2} \quad (3)$$

is the amplitude of corresponding minimized periodic function φ and $A(T)$ and $B(T)$ are determined by a least squares procedure. For numerical calculating of S it could be taken $\mathit{\Delta}T$ instead of dT.

Above-mentioned procedure could obtain the mean parameters of the cycles which exist in the time series. However, the last ones could be significantly changed in separated parts of the time series. For searching for evolution of the cycles so called "Moving Window T-R Periodogram Procedure" (MWTRPP) is used (Bonev et al., 2004). In this procedure a part of the time series with length P (the size of the "moving window"), where $P < N$ is defined. By author's opinion it is recommended that $P/N < 1/3$.

In the beginning of the procedure the "moving window" contains the first P items of the time series $F(t)$ and T-R procedure is applied on them. After this the "moving window " is shifted on a step ΔT of one or more integer data items and the T-R procedure is repeated.. By this method a series of T-R correllograms could be obtained, where as columns in two-dimensional maps (Y-coordinate corresponds to t values), are presented, while the rows are corresponding to central or starting moments of "moving window" epochs. Except R values maps of R/σ_R, $a(T)$ could be obtain, as well as coefficients $A(T)$ or $B(T)$, too.

Discriminant analysis for studying the conditions of the G-O rule violations has been used.

3 The results and analysis

3.1 The quasi-bicenturial cycle and its evolution

Figure 1 shows the average magnitude values $W_{max}[5]$ of Schwabe-Wolf's cycles (Sc) in the time interval 214 BC - AD 2000, smoothed through averaging of the data for 5 neighbour Sc. The empty band marks the missing magnitude data during the 3rd century.

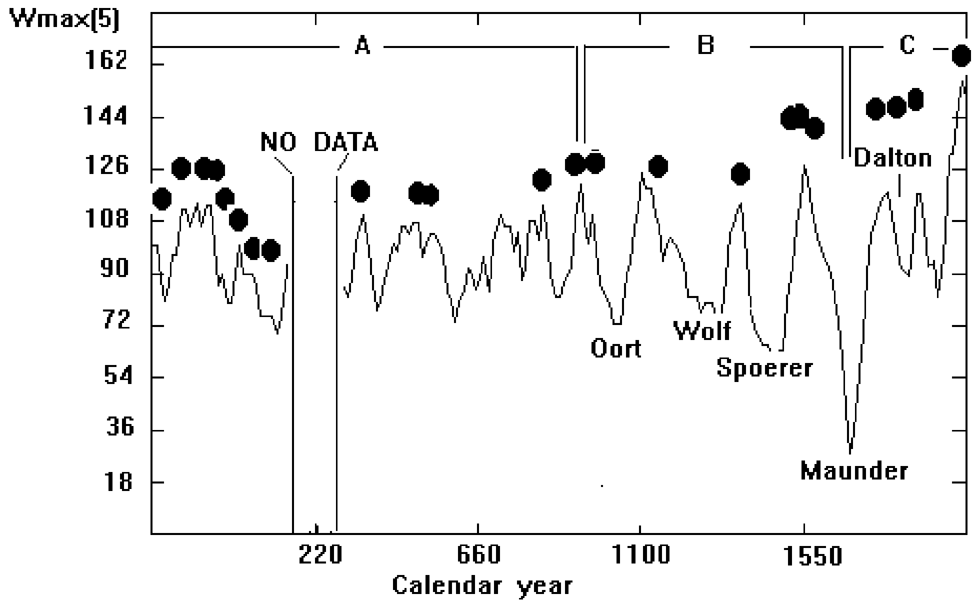

Fig. 1. Magnitudes of the 11-year sunspot cycles (Sc) in the time interval 214 BC - AD 2000, smoothed by averaging of 5 neighbour Sc. The supercenturial minima of Oort, Wolf, Spoerer, Maunder and Dalton are noted. The violations of the Gnevyshev-Ohl's rule are marked by dots.

Schove's series could be separated into three parts:

A/ During the first ≈1200 years the solar activity is on relatively high levels, but the amplitude variations of Schwabe -Wolf's cycles are generally smaller than these ones after AD 1000.

B/ After the 10th century a well expressed supercenturial downward tendency has begun. Its main feature is the series of the supercenturial minima of Oort, Wolf, Spoerer and Maunder (in 11th, 13-14th, 15th and 17th centuries. As it is shown the last one is the deepest in the whole studied period.

C/ After the Maunder minimum (in the beginning of 18th century) a rapid upward supercenturial tendency has started. The last one has temporary terminated in 19th century (in the supercenturial Dalton (AD 1795-1930) and centurial Gleissberg (1898-1923) minima).

Figure 1 shows also that the second part of the 20th century is characterized by the highest mean solar activity in the last ≈1700 years, or most probably ≈2200 years. It is caused by the fact that between AD 1944 and 1996 there are four Schwabe-Wolf's cycles with magnitudes $W_{max} > 150$ (the cycles with Zurich numbers 18, 19, 21 and 22). It could be mentioned that there is only another cycle in Schove's series with $W_{max} > 160$. This is the cycle with sunspots maximum in AD 1372 (because of the smoothing the data this maximum is not visible in Fig.1).

This dynamics of Schove's series reflects the supermillenial 2200-2500 year cycle structure. As it has been already pointed out (Komitov & Kaftan, 2003) the relative high level of the solar activity before AD 1000 represents the near-maximal, quiet phase of the previous bimillenial oscillation (part 'A' on Fig. 1). The period between AD 1000 and 1700 (part 'B') is the final downward phase of the last one, while after 17th century the initial active phase of a new 2200-2500 year cycle has started (part 'C').

As it is already proved on the base of ^{14}C tree rings data series (Damon & Sonett, 1991; Komitov, 1999; Bonev et al., 2004) the amplitude of quasi-bicenturial cycle is modulated by 2200-2500 year cycle. According to afore-said studies the amplitudes of 200-210 year oscillations during the near maximal phase of quasi-bimillenial cycle are small. The last ones are increasing in 2200-2500 year cycle downward phases, reaching maximum simultaneously with the Maunder-type minima. This effect is well visible in Fig. 1. The supercenturial minima before AD 1000 (part 'A') are in generally not so deep as these in the phase 'B' and first of all like the Spoerer and Maunder minima.

This visual impression about the long term changes of the solar activity has been tested on the base of MWTRPP method. A "moving window" with duration of 30 Sc (≈330 years) and window shifting step of 1 Sc are used. By this way 201-30=171 moving window epochs are calculated. The chosen parameters for the T-R correlogram procedure are: T_0=2 Sc, ΔT=0.25 Sc and P=150. Five matrixes, every one with 171 rows and 150 columns for values of R, R/σ_R, amplitude a and coefficients A and B coefficients (see formulas in Section 2) have been calculated. A gray-scaled map of the obtained R/σ_R values is shown on Fig.2.

The duration of the typical quasi-bicenturial cycle, derived by different authors on the base of different data sets, is 19±3 Sc, i.e. 210±35 years. Figure 2 shows that before AD 1000 the last such cycle is very weakly expressed and only in short separated epochs. The quasi-bicenturial oscillation is visible relatively better near AD 550-600, where the corresponding R/σ_R is between 3.5 and 5 for $T \approx$230 years. However during the epoch AD 700-1000 the quasy-bicenturial cycle is almost absent in Schove's series. But there are also two weak "traces" at $T \approx$18-19 Sc ($R/\sigma_R \approx 2.5$) in moving window epochs, which calendar centers are in 9th century. By missing sunspots cycles magnitude data the situation in 3rd century could not be correctly taken into account. However there are some possibilities for estimation the behaviour of the solar activity during the 3rd century on the base of sunspot cycle duration data (Section 3.3).

As it is well shown in Fig.2 the epoch of 11th-12th centuries is very interesting with the long-term solar activity variations. This is the stage when a powerful quasi-bicenturial cycle formed almost immediately after maximum of the 2200-2500 year cycle. Its amplitude and statistical significance are rapidly increased during the next few centuries, reaching maximum in 17th century, i.e. the Maunder minimum, when corresponding R/σ_R is 10 to 12. During 11th - 17th the quasi-bicenturial cycle dominates totally over all other solar oscillarions in range of 2-40 Sc (22-450 years).

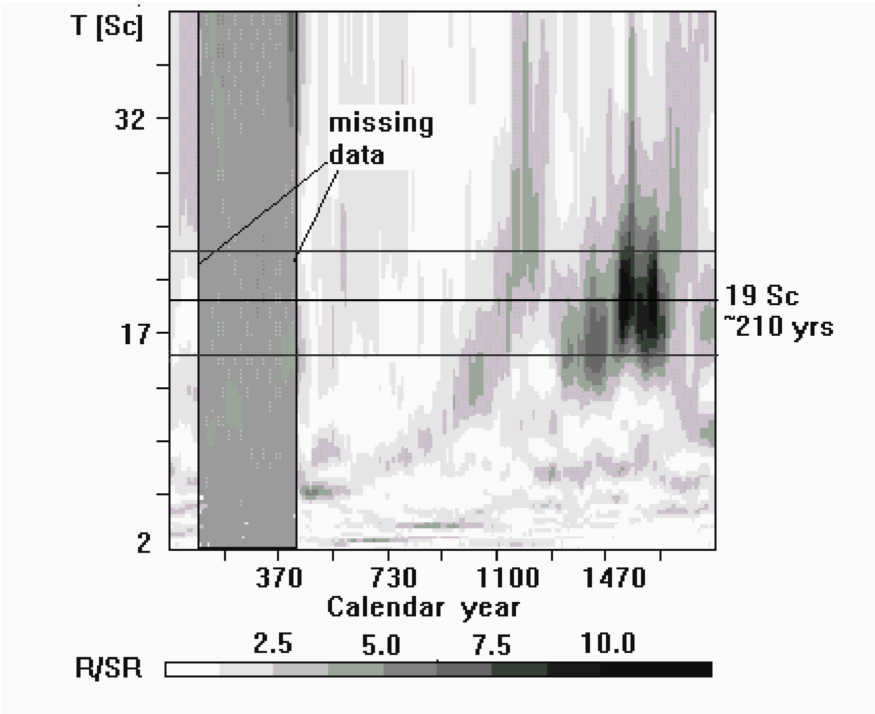

Fig. 2. The values of R/σ_R. The typical "bands" of quasi-bicenturial cycle is marked withy horizontal lines. The affected by missing magnitude data zone in 3rd century is presented as a continuous gray colored band.

After AD 1700 the quasi-bicenturial cycle has been essentially decreased, but remain significant (R/σ_R = 4-5) close to the present epoch.

The quasi-bicenturial cycle dynamics is presented in Fig. 3 by integral power index S too. The boundaries of T_1=16 Sc and T_2=22 Sc, respectively, has been used. The same moving window by duration of 30 Sc has been used.

The maximum in gray band between AD 50-350 is non-real. It is caused by using of W_{max}=0 during AD 196-296, where there are not magnitude data. However the weak local maximum at AD 600 is clearly shown. It could be also estimated that the power index S in the last studied moving window epoch (AD 1670-2000) is about 65-70% of its near maximal value during the moving window epoch with calendar center at the Maunder minimum.

Consequently, on the base of Fig.2 and Fig.3 it could be concluded, that the quasi-bicenturial cycle has an important role in the present epoch, too.

3.2 Gnevishev-Ohl's rule and supercenturial solar activity dynamics

In Fig. 4 the results, concerning the G-O rule for 96 pairs even-odd numbered Schwabe-Wolf's cycles, are shown. By the missing magnitude data only the sunspot cycles from 3rd century has been excluded there. On the X-axis the mean calendar moments of corresponding pairs T_m are placed. They correspond to the minima of odd numbered Schwabe-Wolf's cycles. On the Y-axis the magnitudes of even numbered cycles (labeled as W_1) are placed. The cases when the G-O rule is valid are signed as empty cycles, while the violations are marked by dots.

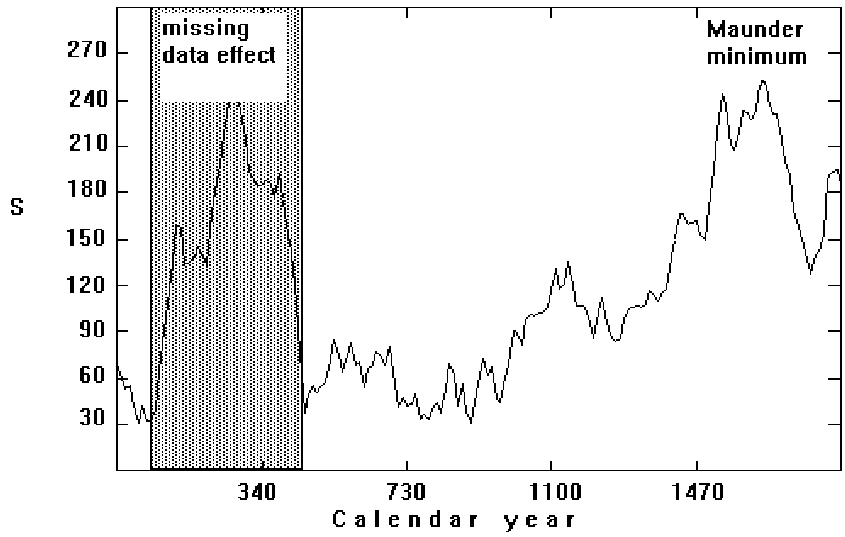

Fig. 3. The integral power index "S" of the quasi-bicenturial cycle in Schove's series (214 BC - AD 2000).

This choice of the both parameters (T_m and W_1) has been made on the base of discriminant analysis procedure. It was found by proceeding of the last one that these factors are most important for the validation or violation of the G-O rule.

By using of a large number discriminant functions it has been found that the best separation in two zones of dominating violations in first one and validations in second one occurs when a function of the following type is used:

$$Y(T_m, W_1) = aT_m^3 + bT_m^2 + cW_1^2 \qquad (4)$$

The corresponding Snedecor-Fisher's F-parameter is equal to 41.47, while the critical 99% level of the last one is 6.9. Comparing with our preliminary results for the G-O rule in Schove's series (Komitov, 1997; Komitov & Bonev, 2001) this level (or approach) is essentially better and more precise.

As it is clearly shown in Fig. 4, in the upper area (over the discriminant curve) the violations are dominated (18 violations vs. 8 validations), while in lower one the validations are $\approx$ 80% from the all cases. Our previous result that the area over $W_1 > 125$ is a zone of almost total presence of the G-O rule violations is confirmed again there.

However, there are significant changes of the boundary level between both zones relating to W_1. It is relatively very close to the end of 2nd century and than it is going down until $\approx$ AD 1000, remaining constant during next $\approx$ 100 years. After that a well expressed upward tendency is observed. The 11th century one approximately corresponds to the begin of the decreasing phase of the previous 2200-2500 year solar cycle (part 'B' in Fig. 1). The present boundary W_1 level is the highest for the last $\approx$ 2200 years.

It is interesting to note that for all used discriminant functions, where the obtained value is $F > 30$, a boundary W_1 level minimum near AD 1000-1100 is pronounced.

On the base of presented results it could be concluded that there is some indication for influence of quasi-bimillenial 2200-2500 year solar cycle on the 'critical' W_1 level for the G-O rule violations. The last one is slowly decreasing from high levels to minimum during the 'quiet' to near maximal phase of the afore-said cycle and increased after its main maximum, through the bimillenial (Maunder-type) minimum and initial active phase of the next cycle. However this conclusion is derived on the base only of the last two millennia. On this stage it is difficult to generalize the last one for longer time scale.

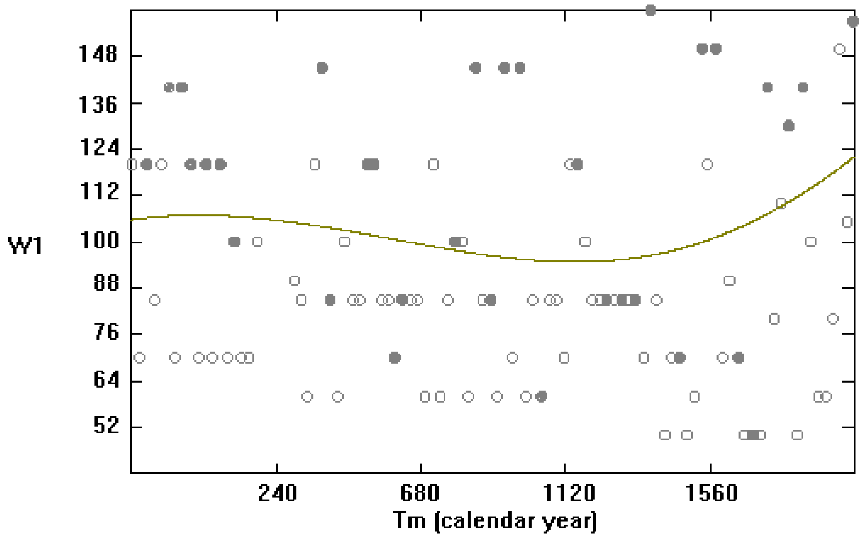

Fig. 4. Gnevyshev-Ohl's rule in Schove's series.

As it is already established on the base of the previous analysis of Schove's series (Komitov & Bonev, 2001) almost all G-O rile violations have been occurred at the beginning or during the downward phases of supercenturial solar minima. The adding of earlier part (b) in present analysis helps us to generalize this conclusion (Fig.1). Consequently, it could to suggest the events of the G-O rule violations as potential pre indicators of forthcoming supercenturial solar minima. This is an important and actual conclusion, while for the present pair even-odd numbered Zurich sunspot cycles 22nd and 23rd the G-O rule violation is already a fact. By this one it is very probably that a new supercenturial solar minimum will be formed during the next few decades. Additional arguments will be given in Section 4.

3.3 The sunspot cycle length variations and the supercenturial solar minima

Unlike the sunspot cycle magnitudes the cycle length data are continuous during the all studied period of 2200 years. The smoothed by five points Schwabe-Wolf's cycles lengths values L are presented in Fig.5.

As it is shown there is a clear tendency for larger L values during the supercenturial solar minima, as well as shorter ones in the epochs of high solar activity. However, the dynamics of sunspot cycle length is much more complicate. There are also many other local extremums of L, which have, as it is shown in Fig.5, a quasi-cyclic behaviour. By this reason a precise time series analysis is necessary.

The T-R correllogram of L values data series is shown in Fig.6. There are two correlation coefficient R peaks exceeding the second "critical" level $R/\sigma_R \approx 3.5$. They correspond to cycles of 7 and 18.5 Sc, i.e. ≈78 and 205 years. All other detected cycles at 3, 4, 5 , 6, 9 and 12 Sc are with less significance ($2 < R/\sigma_R < 3.5$). As it is shown there are not cycles longer than quasi-bicenturial one.

Generally there is an anticorrelation between L and W_{max}. However, it is statistically significant only between smoothing data of the both parameters. When the smoothing

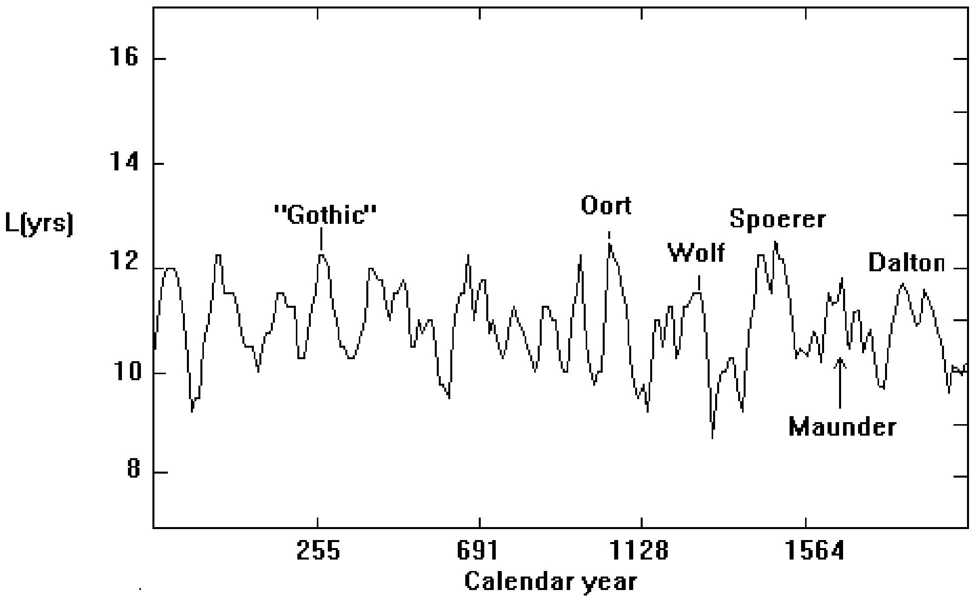

Fig. 5. Schwabe-Wolf's cycle length variations in Schove's series

procedure is applied over 5 points (Schwabe-Wolf's cycles) the correlation coefficient is R =-0.41 ($|R/\sigma_R|$=6.31), but without smoothing it is only R=-0.11 ($|R/\sigma_R|$=1.43). If the smoothing procedure is applied over 10 points $|R|$ it is even slightly decreased (R=-0.38). Consequently, the reverse relationship between L and W_{max} is better expressed when the smoothing is over few sunspot cycles. These results have been found by analysis of Schove's series data after AD 296, when the missing data effect for the 3rd century is ignored.

On the base of all presented results in this Section it could to conclude, that the increasing of the sunspot cycle length L is a potential indicator of forthcoming relatively long and week sunspot cycles, including an epoch of supercenturial solar minimum too. However, a more precise forecast needs some additional condition - for example whether the G-O rule is valid or not.

In the light of the obtained relationship it is interesting to analyzed the local maximum of L during the 3rd century (Fig. 5). As it has been already pointed out a few times, the magnitude data for this epoch are missing. The above mentioned maximum of smoothing L values is an evidence that most probably the solar activity during 3rd century was predominantly low. It well corresponds to a supercenturial minimum, very similar to these in 5th and 6-7th centuries.

An additional evidence for supercenturial solar minimum in 3rd century is the local peak in ^{14}C tree rings data series for this epoch (Stuiver et al, 1998). The corresponding solar minumum is labeled in Fig. 5 as "Gothic" in association with the massive gothic invasion in Roman empire during the middle of 3rd century.

It could to assume that the effect of the missing magnitude data is caused by combination of supercenturial solar minimum plus disadvantaged social and political situation in Roman empire and China during the 3rd century.

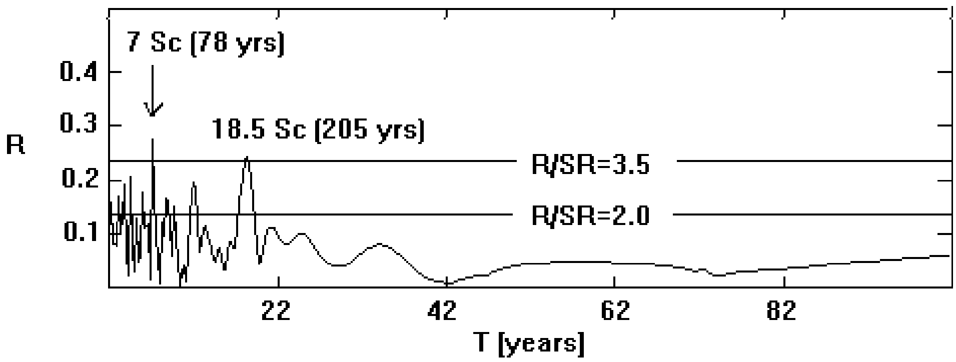

Fig. 6. The T-R correllogram of the sunspot cycle length in Schove's series ($T_0 = 2$ Sc, $\Delta T = 0.25$ Sc, $p = 400$)

3.4 The magnitudes of the sunspot cycles in "even-odd" numbered pairs: Regression models

As it is shown from the results in Sections 3.2 and 3.3, the G-O rule violations and sunspot cycle length L increasing could be used as a possible precursors of forthcoming supercenturial solar minima. However, as it is already shown for L and will be demonstrated for the G-O rule violations too in Section 4, they are not very strong indicators for the beginning of the afore-said events.

Another, more precise prediction could be obtain on the base of regression models, describing relationships between the magnitude of the even-numbered sunspot cycle in "even-odd" pair $W_{max}(2n)$, odd-numbered one $W_{max}(2n+1)$ and the next even-numbered cycle $W_{max}(2n+2)$ (n=0,1,2...). Using all parts of Schove's series with full set of data, i.e the parts 'b','d','e' and 'f" (see Section 2), two best regression models has been derived. They describe the relationships between $W_{max}(2n), W_{max}(2n+1)$ and $\Delta W(2n, 2n+2) = W_{max}(2n) - W_{max}(2n+2)$.

The first one is a simple linear regression, where only $W_{max}(2n)$ is taken as a factor. It is expressed as:

$$\Delta W_{max}(2n, 2n+2) = 98.5 - 1.06 W_{max}(2n) \tag{5}$$

The corresponding correllation coefficient is R=-0.71. Snedecor-Fisher's parameter is F=2.04, while the "critical" 99% value is 1.59. The value of F is determined as the "total" to "residual" variances ratio.

Using the model (5) and taken $W_{max}(2n)$=157 for Zurich cycle No. 22, it could be found that $\Delta W(2n, 2n+2) = -68 \pm 27$ and finally $W_{max}(2n+2) = 89pm29$ for the magnitude of the cycle No 24.

The second relationship is of two-factor type:

$$\Delta W(2n, 2n+2) = 69 - 1.16 W_{max}(2n) + 0.4 W_{max}(2n+1) \tag{6}$$

where $W_{max}(2n+1)$ is the magnitude of odd numbered cycle in the "even-odd" sunspots cycles pair. The multiplied correlation coefficient is R=0.78 and F =2.45.

Using the model formula (4),$W_{max}(2n) = 157$ and $W_{max}(2n+1)$, for the cycle No. 23 it could obtain $W_{max}(2n+2) = 92 \pm 27$ for the next No.24.

The regression relationship (6) is of two-factor type, however it needs to note, that the even numbered sunspot cycle magnitude remain a main factor for $\Delta(W(2n, 2n+2)$ changes, which yield about 75% of the total factor variance.

4 Discussion

The problem of the long term solar activity variations is of high importance for the solar-terrestrial relationships. This statement is even more valid if it is taken into account the very stable coincidences between the supercenturial solar minima and global cooling events in the range of 0.5- 1°C, which could be tracked during the last two millennia by paleoclimatic and historical data (Borisenkov., 1988; Damon & Sonett, 1991; Dergachev & Chistyakov, 1991; Hong et al, 2000; Abdussamatov, 2004; Raspopov et al, 2005). The extremal case is the deepest solar Maunder minimum and corresponding to "Little ice epoch".

In a recent work of Lockwood & Frolich (2007) the solar forcing over the climate for the last 30 years is denied. However, by author's opinion in these studies some very important details are missing in the analysis. This problem is outside the field of present study and will be an object of our future paper. That is why it could be only mark here, that the most probably a new supercenturial solar minimum will cause a very serious effect over the climate changes in 21st century.

It has been demonstrated already in the models of Komitov & Kaftan (2003) that the downward phases and minima of quasi-bicenturial cycle are a main factor for supercenturial solar minima. According to this study the next quasi-bicenturial solar cycle minimum will occur near to AD 2060-2070. In the afore-said models a few other solar oscillations in the range of 90-1000 years are taken into account, too. The extrapolations of Schove's and Group sunspot number series show a fast decreasing of the mean solar activity at the beginning of 21st century (2000-2025). In each of the models the deepest phase is near to AD 2060-2070. In all models the depth is similar as to the Dalton minimum.

In all above mentioned models the mean values of the cycle amplitude and duration has been used. However, as in Section 3.1, as well as and in some other studies, concerning ^{14}C tree rings data, (Damon & Sonett, 1991; Komitov, 1999; Bonev et al., 2004; Komitov et al., 2004), the last cycle parameters could be seriously varied in large time scales. Especially the solar quasi - bicenturial cycle amplitude is modulated by quasi-bimillenial (2200-2500 years) cycle. The amplitude is the weakest during the near-maximal phases of 2200-2500 oscillations and the strongest during the minima of last one (the Maunder-type events).

It needs to note that the studied here time interval contains practically all full phases of one 2200-2500 year solar oscillation: the quiet "plateau" phase (200 BC - AD 350), the "secondary" minimum (according to Komitov & Kaftan, 2003) (AD 350 - 700), the near maximal phase (AD 700 - 1000), the main downward phase + "Maunder-type" minimum (AD 1000 - 1700) and the initial active phase (AD 1700 - AD 2000/2050).

As it is shown in Fig.2 and Fig.3 the increasing of the 200-210 year cycle magnitude during downward phase of quasi-bimillenial cycle (i.e. after $\approx$ AD 1000) is very well visible in Schove's series, too. There is also a weaker local maximum of calculated S values near to AD 600 (Fig.3), which corresponds to the deepest phase of the quasi-bimillenial cycle "secondary" minimum. Consequently, there is a confirmation on the previous results, based on 14C tree rings data that the increasing of 200-210 year oscillations corresponds to downward tendency in the supercenturial solar activity dynamics.

On the other hand the quasi-bicenturial cycle amplitude remain relatively high after the Maunder minimum. The R/σ_R value near to period of T=210 years is $\approx$5 (Fig. 2), while the corresponding value of integral power index S is 70-75% of its maximal value during Maunder minimum (Fig.3). By this reason one could conclude that the 200-210 year cycle plays an important role in present epoch too and it must be accounted in the solar dynamics forecast for the 21st century.

Except the aforesaid models there are some other studies on which base predictions for the supercenturial solar minimum during the present century have been made too (Fyodorov et al.,1995; Komitov & Bonev, 2001; Shatten & Tobiska, 2003; Abdussamatov, 2004; Solanki et al., 2004). On the base of statistical analysis for supercenturial solar minima frequency in ^{14}C series during last $\approx$ 11000 years it has been concluded by Solanki et al. (2004) that the probability to start a new supercenturial solar minimum before AD 2050 is about 92% and over 99% before AD 2100.

As it has been already pointed out, Gnevyshev-Ohl's rule violations are potential precursors of the supercenturial minima. The statistics of these events during studied epoch (214 BC - AD 2000) show that there is very strong tendency between the magnitudes of even numbered sunspot cycles in the pairs with the G-O rule violations and the next even numbered ones. In 94 % of all cases for pairs with G-O rule violation the even numbered cycle is higher or approximately equal to the next even numbered cycle, i.e $W_{max}(2n) => W_{max}(2n + 2)$. Consequently, on the base of this consideration it is almost sure that the next Zurich sunspot cycle No.24 could not be more powerful than the cycle No. 22. This is not a strong evidence for starting of a new solar supercenturial minimum, but in any case it indicates that the Modern supercenturial maximum (AD 1945-1996/ 2000) is already going to its end.

An increasing of the sunspot cycle length is observed for the present 23rd cycle. Close to this moment (Aug. 2007) it is not ended yet, but it is already clear, that the Zurich cycle 23 will be longer than 11 years. The parameter L for the previous cycles No. 21 and 22 is about 10 years. This increasing is an additional potential, but not strong indicator for long downward solar activity tendency too.

The prediction on the base of the regression models (Section 3.4) is essentially more precise. A magnitude in the range of 90 puts the cycle No.24 between the cycles 16th and 20th. This is significant lower not only in comparison with the powerful even Zurich cycles No.18 and 22, but also in comparison with the present cycle No.23. By this reason it could be suggested with high probability that a new supercentural solar minimum will start simultaneously with the sunspot cycle No.24.

On the base of the presented results it could not be predicted how deep will be the afore-said minimum. The time series models and their extrapolations (Komitov & Kaftan, 2003) show a solar activity levels in the period AD 2030-2080 which are typical for the Dalton minimum.

A second G-O rule violation for the pair cycles 24-25 by author's opinion is possible. There are three cases of "double" G-O rule violations in Schove's series. All they have been occurred before AD 700 - one on the "plateau" before AD 300 and two - during the "secondary " minimum of the previous 2200-2500 year cycle. It is in relation with the expected quiet ("plateau") phase, beginning in the present quasi-bimillenial cycle and possible stopping the "critical" increasing of the levels of the even numbered sunspot cycles in the G-O rule. As it has been pointed out, the start of the "plateau"- phase could occur between AD 2000 and 2050.

5 Summary

The main results and conclusions of this paper may be summarized in the following directions:

1. The quasi-bicenturial cycle is the main long-term cycle in the solar activity dynamics, observed in Schove's series during the last $\approx$ 2200 years. Its duration is 200-210 years, but its main parameters - the integral power index S and length vary significantly in the historical time scale. There is an additional evidence that the quasi-bicenturial cycle is modulated by longer solar oscillation, which duration is 2200-2500 years.

2. The present amplitude of quasi-bicenturial 200-210 year cycle is about 75% of its maximal value during Maunder minimum (17th century). Consequently, it remains important during the modern epoch and it must be taken into account in the solar activity predictions for the 21st century.

3. Schwabe-Wolf ‘s cycle length L is modulated mainly by the quasi-centurial and bicenturial solar cycles. A tendency for longer sunspot cycle length during supercenturial solar minima has been detected. By this reason it could be suggested that the increasing of L as a potential precursor of the forthcoming supercenturial solar minimum. The high mean values of L during 3rd century is an evidence for a supercenturial minimum in this time.

4. Gnevyshev-Ohl’s (G-O) rule violations are precursors of forthcoming supercenturial solar minima too. There is an indication that the “critical level” of even numbered sunspot cycles magnitude for a G-O rule violation depends on phase of quasy 2200-2500 year solar cycle.

5. On the base of the magnitude data in Schove’s series a two-factor statistical regression model is derived. It has been found that the magnitude of even-numbered sunspot cycle depends on magnitudes of previous two ones (an “even-odd” pair).

6. On the base of the afore-said two-factor model a relatively small magnitude $W_{max} \approx 90$ for the Zurich sunspot cycle No.24 has been predicted. If it is taken into account also the G-O rule violation for the pair cycles No.22-23, as well as the observed prolongation of the cycle No. 23, it could be concluded that a new supercenturial solar minimum is coming soon.

7. The forthcoming supercenturial solar minimum could be a very good test for the validity of all basic climatic theories. By author’s opinion a “global cooling” effect in range of 0.4 °C from AD 2000 to AD 2030 or ≈0.7 °C to AD 2070. The last value will correspond approximately to the climatic situation during the first half of 19th century (Dalton minima).

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