The "Sun – climate" relationship.
I. The sunspots and the climate.

Boris Komitov
Institute of Astronomy, Bulgarian Academy of Sciences
Sofia 1784, Bulgaria
bkomitov@sz.inetg.bg

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Abstract. We investigate the problem about the reason for the significant sub-centurial (50-55 and 60-65 yr) and quasi-centurial (120-130 yr) climatic oscillations. The 50-55 and 60-65 yr cycles are clearly detectable in numerous global and regional climatic parameters, i.e. in the temperatures of the Northern Hemisphere and World Ocean surface, in the tree rings widths, in the atmosphere concentration of CO_2, etc. Searching for analogues of these cycles in the solar activity we study the connections between various types of solar, geophysical and climatic cycles. In this Paper I we analyze time series of residual variations of the Northern Hemisphere (AD 1610-1979) and World Ocean surface (AD 1856-1995) temperatures in respect to the corresponding regression models "sunspot activity – temperature". We use the Group Sunspot Number (GSN) as sunspot activity proxy and confirm the existence of well pronounced 50-55, 60-67 and ≈118 yr cycles in the solar activity and temperature variations. In Paper II we will show the existence of powerful 60-65 yr cycle in the middle latitudes auroras and sub-centurial variations in the concentration of the Greenland and Antarctic "cosmogenic" ^{10}Be. In Paper III we will summarize the evidences that the reason of these climatic oscillations are probably processes occurring in the solar corona. Unlike the overall solar activity and the total solar irradiance variations, the high level of these processes leads to a climate cooling, while their low levels correspond to climate warming.

Key words: Sun, solar-climatic relationship

Зависимостта "Слънце – климат".
I. Слънчевите петна и климатът.

Борис Комитов

Ние изследваме проблема с причината за значителните суб-векови (50-55 и 60-65 г) и квази-векови (120-130 г) климатични осцилации. Цикли с продължителности 50-55 и 60-65 г са ясно детектирани в множество глобални и регионални климатични параметри, напр. в температурите на северното полукълбо и повърхността на световния океан, в ширините на годишните пръстени на дърветата, в концентрацията на CO_2 в атмосферата и др. Търсейки аналози на тези цикли в слънчевата активност, ние изучаваме връзките между различните типове слънчеви, геофизични и климатични цикли. В тази Статия 1 ние правим анализ на времеви редове на остатъчни вариации на температурите в Северното полукълбо (AD 1610-1979) и Световния океан (AD 1856-1995) спрямо съответния регресионен модел "слънчева активност - температура". Като индекс на слънчевата активност ние използваме броя на групите слънчеви петна (GSN) и подтвърждаваме съществуването на добре изразени 50-55, 60-65 и 118 г цикли във вариациите на слънчевата активност и температурата. В Статия 2 ние ще покажем съществуването на мощни 60-65 г цикли на полярните сияния на средни ширини и суб-векови вариации на концентрацията на "космогенен" ^{10}Be в Гренландия и Антарктида. В Статия 3 ние ще обобщим свидетелставта, че причината за суб-вековите и квази-вековите климатични осцилации са вероятно процеси в слънчевата корона. Противно на цялостната слънчева активност и на вариациите на общото излъчване на Слънцето, високото ниво на тези процеси води до климатично захлаждане, докато техните ниски нива предизвикват климатично затопляне.

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1 Introduction

One of the most remarkable feature of the climate changes in the modern epoch (last 150-160 years) is the existence of significant quasi- and sub-centurial (predominantly 50-70 years) oscillations in the large part of global and regional time series of the climatic parameters. They are clearly visible and they have high statistical significance in Northern Hemisphere (Thompson, 1997) and World Ocean surface temperatures, in the atmospheric CO_2 concentration (Thompson, 1997), as well as in many regional direct or indirect climatic time series, including tree ring widths.

On other hand, there are many significant tracers of other sub-centurial cycles in regional climatic parameters. Some examples are the 52-54 yr cycle in summer rainfalls in South-East Europe (Komitov et al., 2006) and in tree ring widths in Central Bulgaria (Komitov et al., 2003), the 36-38 yr oscillation (so called Buchner cycle) in the hydrological regime of many rivers and seas, etc. However, it is necessary to point out that many of these cycles are expressed predominantly in the regional climatic indexes, while the 60-65 yr one is an important feature of the planetary or hemisphere temperature series. It is also important to note that the above-cited cycles are almost absent in the Southern Hemisphere (Thompson, 1997).

The temperature variations caused by cycles with sub-centurial duration (mainly 60-65 years) in the Northern Hemisphere and in the World Ocean surface fall into the range of 0.35 to 0.40 K. This is about 50-60% of the total climate warming effect for the period of AD 1850 to 1995. After AD 1850 there are two periods of significant temporary global cooling. The first one is approximately found between 1880-1910 and the second one is realized from AD 1940 to the middle of 1970. The warming epochs 1911-1940/42 and 1976-2005/2007(?) may be considered roughly as a resulting effect both of the general super-centurial warming tendency and the upward phases of the 60-65 yr cycle. Therefore, it is important to note that the "conventional" explanation of the last warming period (after 1975-1978) is some new factor, which is significant only in the modern epoch, but not in the past (de Jager and Usoskin, 2006; Lockwood and Frolich, 2007). The origin of this new factor is attached more or less to the human activity.

Usually, the explanation for one or other climatic cycle is done on the base of some cyclic extraterrestrial factor (orbital or rotational fluctuations of the Earth's motion, solar activity, etc). However, very significant astronomical or solar cycles with 60-65 or 50-54 yr duration are not known at this stage. That is why usually these sub-centurial variations of the terrestrial climatic system have been explained as inner auto-oscillations (Schleissinger, 1993).

The subjects in this Paper I are the long-term cycles in sunspot activity and climate time series with duration in the range of 30 to 150 years. In the next Paper II we will show the existence of a very powerful 60-65 yr cycle in the middle latitudes auroras and sub-centurail variations in "cosmogenic" ^{10}Be, discussing their possible solar origin. In Paper III evidences for that the sub-centurial 60-65 yr oscillations in ^{10}Be concentration, middle latitude auroras and climate oscillations are caused by processes in the Sun will be summarized.

The latter conclusion is valid for the 50-55 and 120-130 yr cycles, as well as for most of the other sub-centurial oscillations. Most probably, the reasons are processes that occur in the solar corona. This conclusion is very important due to the fact that the yield of the sub-centurial oscillations in the global and Northern Hemisphere surface air temperature changes in the modern epoch are large (0.35-0.40 K). The consequences for the theories of the climate changes and especially for the mechanism and magnitude of the "Sun-climate" relationship will be also discussed.

2 Data and methods

The mean annual temperatures of the Northern Hemisphere for the period AD 1610-1979 are taken from Moberg et al. (2005), while the mean annual temperatures of the World Ocean surface for the period 1856-1995 are taken from Parker et al. (1995). The mean annual sunspot indexes R_i (the international Wolf's number) and the Group Sunspot Number (GSN), i.e. the index R_h (Hoyt and Shatten, 1998) are published in the database of National Geophysical Data Center (NGDC):
$ftp://ftp.ngdc.noaa.gov/STP/SOLAR\_DATA$

Our analysis is mainly based on the T-R periodogram procedure that has been already described in a few other papers (Komitov, 1986, 1997, 2007, etc.). The idea of this method is to approximate the studied time series $F(t)$ with N data minimizing functions $f_i(t)$ of simple periodic type, i.e:

(1) $f_i(t) = A_O + Acos(2\pi t/T) + Bsin(2\pi t/T)$.

Here $t = 0, 1, 2...$ are the corresponding moments in time step units (the time series step). A_O is the mean value of $F(t)$ on the base of all time series data and T is the period, which is varying in the range $[T_0, T_{max}]$ with a step of ΔT. In this way a series of p minimized functions $f_i(t)$ will be obtained, where $p = (T_{max} - T_0)/\Delta T$. The minimal possible value of T_0 is equal to 2 steps of the time series which corresponds to linear frequency of 0.5.

For all obtained functions $f_i(t)$, the correlation coefficient R in respect to the time series $F(t)$ is calculated. The local maximums of R indicate possible cycles with duration equal to corresponding period T. Since R depends on T, the obtained function $R(T)$ may be labeled as "T-R correlogram" (see also Komitov, 1997).

The statistical significance of these cycles is checked on the base of the ratio $R/\sigma(R)$, where $\sigma(R) = (1 - R^2)/\sqrt{N})$ is the error of R. A cycle is taken as a real one with more than 95% probability if $R/\sigma(R)$ ¿ 1.96.

On the base of Monte-Carlo time series an essentially stronger criterion has been derived. It needs that $R/\sigma(R) > 454/N^2 + 3.46$. For the long series ($N \to \infty$), $R/\sigma(R)$ is approaching 3.46. The last criteria is needed by the fact that there are many cases of cyclic oscillations in pseudo random number series for which $R/\sigma(R)$ is between both critical levels. In these cases the cycle existence could be estimate on the base of additional expert criteria.

As a measurement of the total magnitude of all oscillations in the range of periods $[T_1, T_2]$ on the base of T-R periodogram procedure a quantity labeled as "integral power index" S is given as:

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

Here

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

is the amplitude of corresponding minimized periodic function $f_i(t)$. The constants $A(T)$ and $B(T)$ are determined by the mean least square procedure. For calculating S, it can be taken $dT = \Delta T$.

Using already mentioned procedure we can obtain the mean durations of cycles that exist in the time series. However, the cycles could be significantly changed in different parts of the time series. For discovering cycles evolution, the so called "Moving Window T-R Periodogram Procedure" (MWTRPP) (Bonev et al., 2004) is used. In this algorithm a part of time series with length P (the "moving window"), where $P < N$, is defined. The recommendation here is P/N ¡ 1/3.

In the beginning, the "moving window" contains the first P terms of the time series $F(t)$ and the standard T-R procedure is applied on them. After that the "moving window" is shifted by step dT (one or more integer time series step) and the T-R procedure is repeated, etc. The derived series of T-R correllograms could be presented as columns in a two-dimensional map. In this map the X-coordinates to the central or starting moments of the "moving window" epochs and the Y-coordinate corresponds to the period T. Maps of R/SR, $a(T)$, as well as $A(T)$ and $B(T)$ could be presented also in such a way.

3 Results and interpretations

3.1 Regression models "Sunspot activity - variation of the air and ocean temperatures"

The GSN mean annual indexes (R_h) of Hoyt and Shatten (1998) are the most representable sunspot activity data set for the last 400 years. It is based on about 480 000 individual sunspots observations, including the first ones provided by Galilei in AD 1610. From a physical point of view, it is better than the Zurich series (1749-2008) sunspot activity proxy. Unfortunately, it is not updated after AD 1995, but this is not essential for the aims of this study.

The Northern Hemisphere mean annual temperatures Θ of Moberg et al. (2005) between AD 1610 and 1979 has been used for the first task here.

We introduced the time series $\Delta\Theta$ of the differences between the annual temperature and the mean temperature in the time interval AD 1961-1979. Further, we smoothed both series (R_h) and $\Delta\Theta$ with sliding average under a window of 11 years. This smoothing aims: (i) to eliminate the short-time fluctuations including the 11-yr cycle and (ii) to allow better comparison with the results from the study of de Jager and Usoskin (2006) based on the same data. The smoothed time series are shown in Fig.1.

The regression model of the influence of the solar sunspot activity on the temperature variation has been then found as:

(4) $\Delta\Theta = 0.00727R_h - 0.654 \pm 0.0207.$

The correlation coefficient of the model (4) is r=+0.7797 and the corresponding ratio is $r/\sigma(r)$=37.74, where $\sigma(r)$ is the standard error of r.

The corresponding Snedekor-Fisher's F-parameter (the ratio between the total and the residual variance) is 2.54, i.e. the factor variance (by the R_h influence) is about $1.54/2.54 = 61\%$ of the total variance, while for the residual variance (the part of other factors and data errors) 39% remained. Consequently, the growth of the sunspot activity is the main factor of climate change since 17th century up to the second half of 20th century.

The best form of the relationship (4) is linear. The addition of nonlinear terms do not lead to better r or F.

The model (4) corresponds well to the general tendency of sunspot activity and total solar irradiance (TSI index) increasing during the last 300 years. The TSI dependence on the sunspot 11-yr Schwabe-Wolf's cycle is already established fact (Frolich et al., 1997; Pap et al., 2002). The TSI reconstruction has been given by Lean et al. (1995), Lean (2000, 2004) since AD 1610.

It is necessary to note that the relationship (4) could integrate not only the TSI variations effect, but the influence on the climate of different physical mechanisms, which depend on the sunspot activity. Such are the galactic cosmic rays variations and their effect over the aerosols formation rates in the Earth's lower atmosphere (Svensmark and Friis-Christensen, 1997; Yu, 2002).

The first study of these data (de Jager and Usoskin, 2006) contains the data between AD 1961 and 1965 and the derived regression model is almost the same as the one presented here (4). In the present study the data for the last 14 years of the Moberg series up to AD 1979, has been included to test how the recent data could affect the results for r and F. The result is a negligible increasing of r (in order of 0.001) and F for the extended series (up to 1979). Consequently, there is no evidence that during these 14 years of the temperature series a new factor (the human activity or something else) had forced essentially the Northern Hemisphere climate.

The World Ocean temperature series between AD 1856 and 1995 of Parker et al. (1995) has been used here for the second task. The original data series is shown in Fig.4. For the second task $\Delta\theta$ is the 11-yr soothing annual surface World Ocean temperature deviation in respect to the temperature for AD 1940. The regression model of type (4) has been found as

(5) $\Delta\theta = 0.081R_h - 0.612 \pm 0.0138.$

For this model we derived $r = +0.877$ and $F = 4.31$. The 11-yr residuals $\Delta_2\theta$ of the data from the model (5) are shown in Fig. 5.

The residual variance in (5) is about 1.5 times less than in (4). This result shows that the World Ocean temperature change is more sensitive indicator for the "Sun – climate" relationships than the data for the relatively "continental" Northern Hemisphere.

3.2 Analysis of the regression models deviations

The next step in the present study is to analyze the dynamics of the residual deviations from the models (4) and (5). The questions here are how are they distributed in individual epoch, are there trends or cycles, etc.

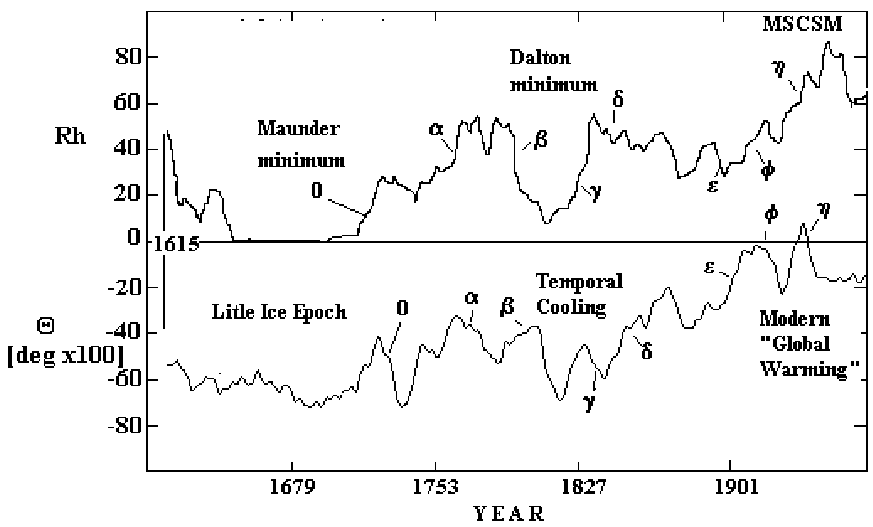

Fig. 1. The behavior of the 11-yr smoothed values of R_h and $\Delta\Theta$ for the Northern Hemisphere. The letters show the short periods of opposite changes in the curves.

Fig. 1 shows the behavior of the 11-yr smoothing values of R_h and $\Delta\Theta$ for the Northern Hemisphere temperatures. In accordance with the model (4) there is a good coincidence between the details in both time series: the general upward tendencies from 17th to the end of 20th century, the super-centurail Maunder and Dalton solar minimums, the Little Ice Epoch and the temporal climate cooling at the beginning of 19th century, the Modern super-centurial solar maximum (MSCSM) and the global warming period in 20th century.

However, more precise look points out that there are many divergences in shorter time intervals. There are a few epochs with mean duration of ≈ 30 years, where R_h and $\Delta\Theta$ are rather in anti-correlation than in correlation. Eight such epochs are labeled by symbols $0, \alpha, \beta ....$ in Fig.1. The total length of these "mirror" epochs for the "$R_h - \Delta\Theta$" model (4) is about 50% from the whole last period of 370 years. It also seems that there are some cyclic tendencies.

This assumption could be easily checked. The model (4) has been removed from the "primary" smoothing values series $\Delta\Theta$. The residual variations, denoted as $\Delta_2\Theta$ are shown in Fig.2.

The model (4) is presented by the "zero-line" in Fig.2. The mean calendar years of the largest fluctuations $\Delta_2\Theta$ are also shown. The largest negative deviations lie near to AD 1735, 1784, 1839 and 1956, while the largest positive ones lie near to AD 1805, 1876, 1911 and 1940. There are also a few not so spectacular extrema like these near to AD 1640, 1688, 1895 1920 (minimums) and AD 1660, 1715, 1764-65 (maximums). There are two interesting details in Fig.2. The first one is the essentially faster climate warming from AD 1840 up to 1911, relative to the model (4). The second one is that the dominating tendency of $\Delta_2\Theta$ for the 20th century, from AD 1911 to the end of 70's, is downward.

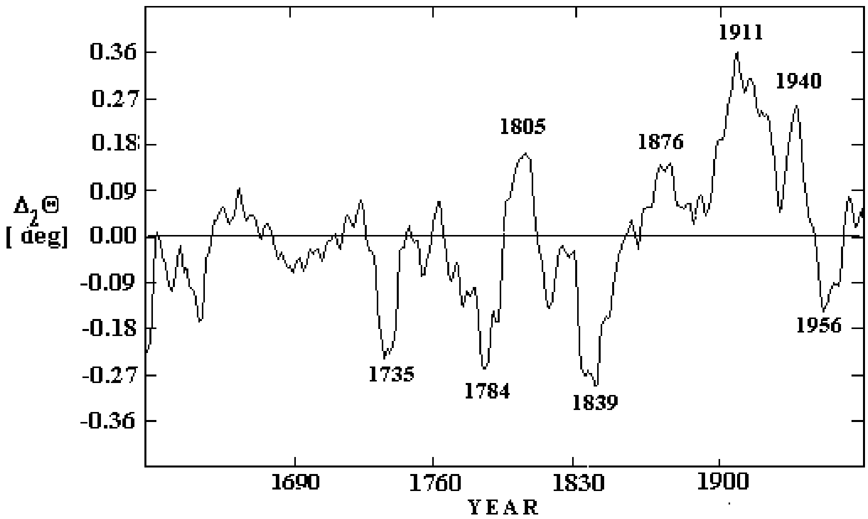

Fig. 2. The residuals $\Delta_2\Theta$ compared to the model (4) (AD 1610-1979)

The "residual" series $\Delta_2\Theta$ has been studied for statistically significant cycles existence by means of the T-R periodogram procedure. The results are shown in Fig.3. There are six quasi-periodic oscillations whose probability exceeds 99%. They have duration of 22, 28, 54, 67, 118 and 134 years, respectively. The most important ones are the cycles of 54 and 118 years.

The World Ocean temperature variations and their residuals of the model (5) are shown in Fig.4 and in Fig.5, respectively. The mean total amplitude of the last ones is about 0.25 K, i.e. essentially smaller than the same ones for the

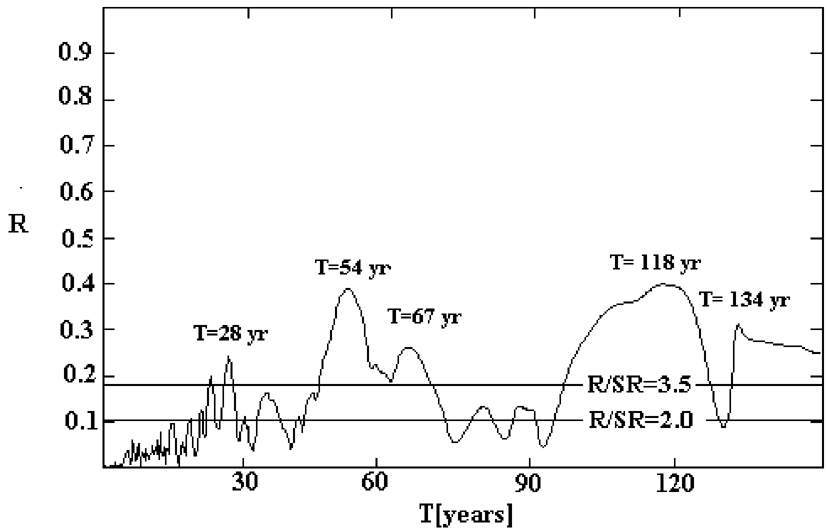

Fig. 3. The T-R spectra of the "residual" series $\Delta_2\Theta$ for the Northern Hemisphere.

Northern Hemisphere. A quasi-cyclic sub-centurial variation with duration of 50-60 years is well seen too. The negative fluctuations in respect to the model (5) are dominant before 1970th. Unlike the Moberg series, the upward tendency of the residual fluctuations is not so strong in the middle and the end of 19th century (Fig.2). The upward tendency could be follow since 1950th, but more significant positive excess over the model is hardly observed after AD 1980.

The general effect caused by all these features is that in the World Ocean temperatures residuals time series there is a secondary upward nonlinear trend of parabolic type: $\Delta_2\theta = ap^2+bp+c$ (p is the number of years after AD 1856). After removing of the last one, a final series with very well expressed sub-centurial oscillations has been obtained (Fig.6). The corresponding T-R spectra is shown in Fig.7.

As it can be seen in Fig.7, the main cycle has duration of 52 years followed by 63, 28 and 22-yr oscillations. This picture is very similar to the corresponding T-R spectra for the Moberg's series in a time interval less than 100 years, where a powerful 54-yr cycle, as well as 63, 28 and 22-yr cycles has been also detected.

It is interesting to compare these results, concerning the Parker's series, with earlier author's study of the same subject (Komitov, 2008). In the latter work the general upward temperature trend has been approximated by nonlinear (parabolic) function. The primary annual data has been used there without any smoothing procedure. The residual data series, after the trend removing, is shown in Fig.8 and the corresponding T-R spectra - in Fig.9. The main cycle is a "doublet" which components are with durations of 58 and

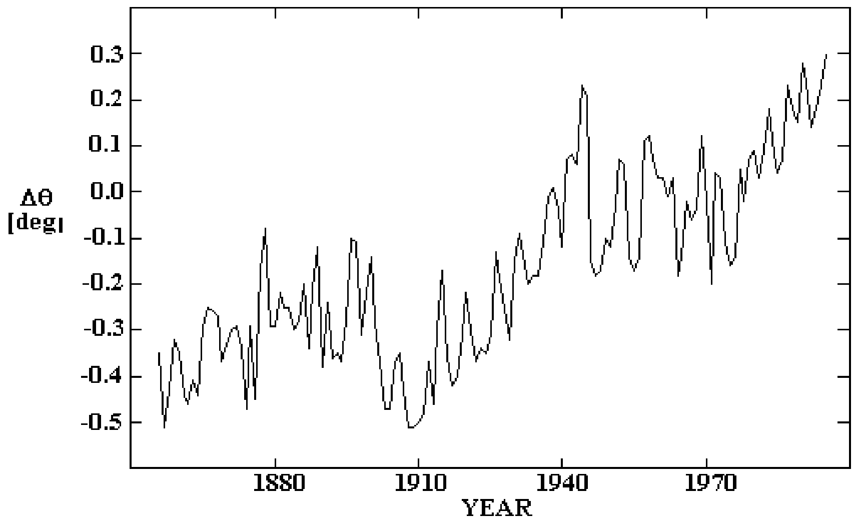

Fig. 4. The World Oceans surface temperature changes according to Parker et al. (1995) in the period AD 1856-1995. The original non-smoothing data series is shown.

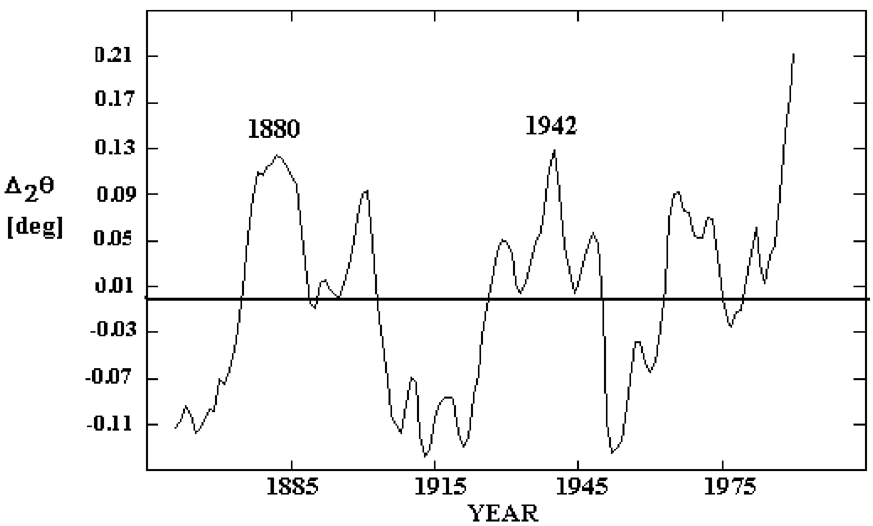

Fig. 5. The 11-year residuals $\Delta_2\theta$ of the data shown in Fig.4 compared to the model (5).

67 years, respectively. The second important cycle is the one with duration of 88 year.

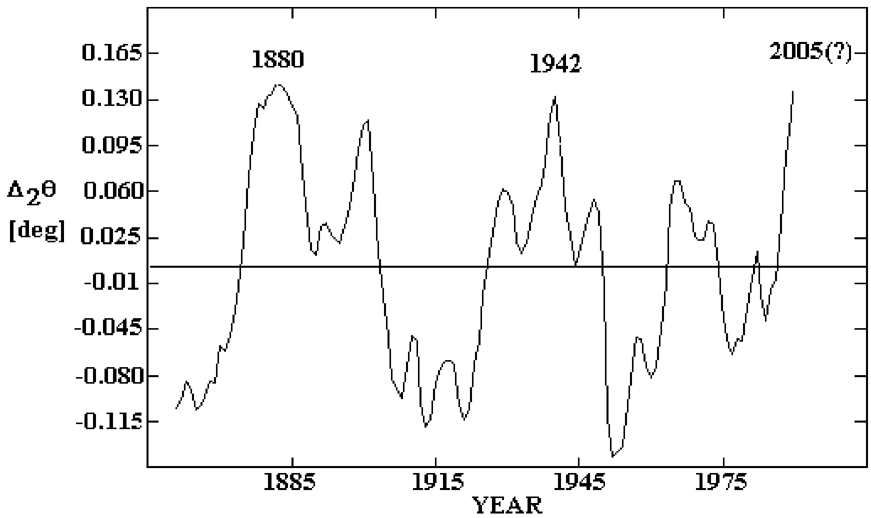

Fig. 6. The final residual time series of World Ocean 11-yr smoothed temperature changes. The local maximums near to AD 1880 and 1940-42 are well visible.

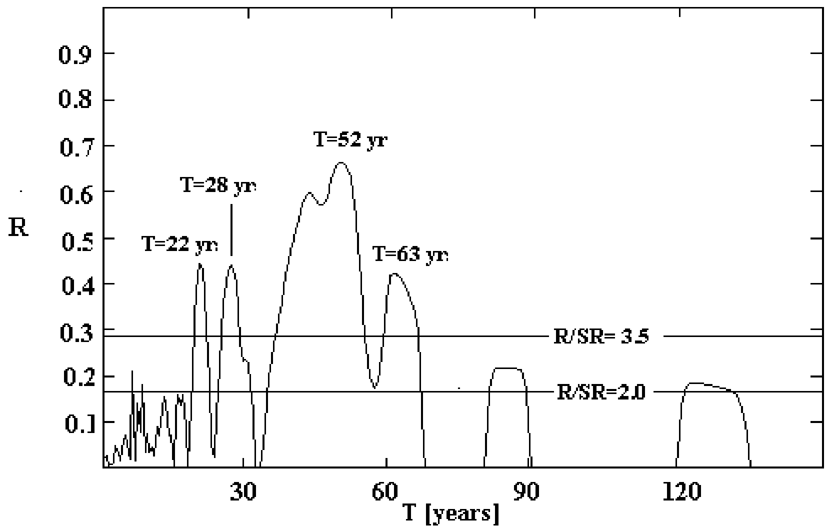

Fig. 7. The T-R spectra of the same series shown in Fig.6.

Discussion

In Section 3.2, some of the derived cyclic oscillations in both "residual" temperature time series have clear solar analogs. For example, the 22-yr cycle

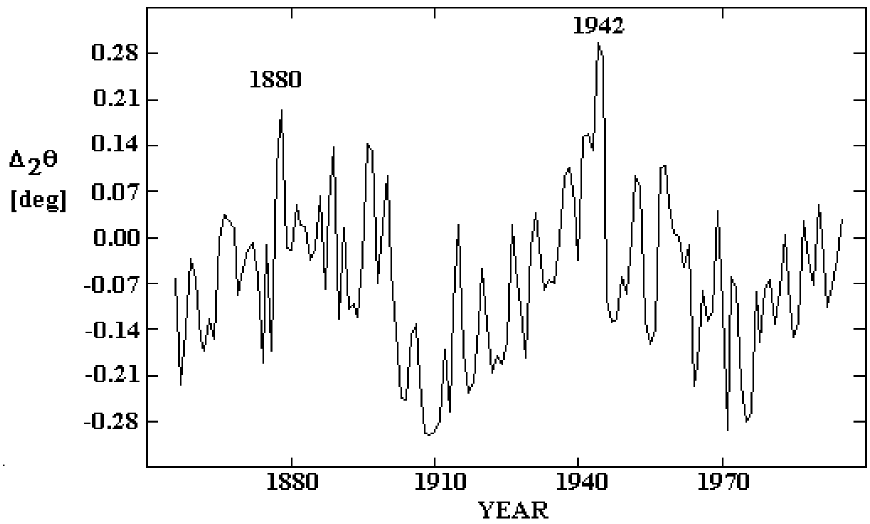

Fig. 8. The residual series of World Ocean non-smoothing temperature variations (Komitov, 2008).

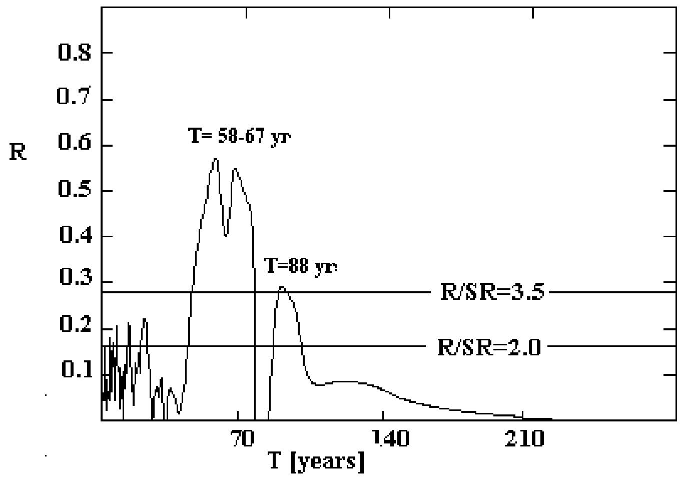

Fig. 9. The T-R spectra after removing of the trend on Fig.8 (Vomit, 2008).

(Fig .7) well corresponds to the Hale solar magnetic cycle, while the 88-yr one corresponds to the sunspot cycle with centurial duration (Vitinskii, 1973, 1976). However, the possible origin of the other quasi-periodic oscillations and especially the most important 50-55, 60-67, 120-130 yr ones seems not very clear yet. Are they a result of auto-oscillations of the Earth's climate or, in contrary, a result from some cosmic factor, for example - specific solar activity processes?

The answer of this question is very important for the correct understanding of the "Sun – climate" relationships. The amplitude of the sub-centurial oscillations that last three centuries belongs to the range of 0.3 to 0.4 K. As it has been already shown, this is the key for the explanation of the "mirror" epochs. If their solar origin become obvious, this will give another evidence for the dominant role of the Sun for the climate changes in the modern epoch.

The existence of solar oscillations with duration of 3,4 or 5 Schwabe-Wolf's sunspot cycles has been studied by many authors (Ahhuwalia, 1998; Javaravah et al., 2005; Du, 2006, etc.). The stability of these cycles and especially the tree cycle periodicity has been subjected under critical analysis by Kane (2008). In our previous work (Komitov and Kaftan, 2003) we have been detected weak, but statistically significant cycles by duration of 38-40, 54, 62 and 118 years in the Group Sunspot Number series. We have also obtained similar cycles in the Zurich series (durations of 53 and 64 years). The corresponding peaks in the T-R correlograms have statistical probability higher than 95%. There is also a weak trace near to 95% level of significance in Zurich series. However, all these cycles show relatively weak amplitude, much less than the Schwabe-Wolf's cycle. On other hand, it is not clear why the sub-centurial 50-55 and 60-67 yr oscillations remain in residual series after removing of the models "sunspot activity – temperature changes" from the primary data sets.

A possible course of explanation could be based on a situation when the sub-centurial climate oscillations are caused by phenomena, which are close connected not with the total sunspot activity, which is proxyed by parameters as R_h or R_i, but only with specific types of sunspots or sunspot groups. The sub-centurial oscillations are not well expressed in the overall sunspot indexes R_h and R_i, but they could be very strong for these specific active centers. The last ones should be primary sources of strong flares and coronal activity.

If the present assumption is correct, a good sub-centurial cyclic recurrence should be expressed in the geomagnetic and auroral activity. The 54 and 65-66 yr cyclic variations in auroral activity is firstly commented by Schove (1955). In the next Paper 2 the sub-centurial auroral activity variations and their influence on other geophysical parameters will be discussed in details.

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