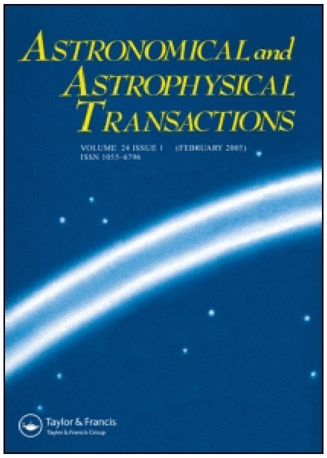

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The Wolf number and total solar irradiance variations during 21–23 solar cycles

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In this work, the numerical sequences of the total solar irradiance data and the corresponding values of the international sunspot index, both for the same time interval (about 25 years), are compared. The data are analysed by means of two methods: continuous wavelet transformation and Fourier spectrum decomposition. Special attention is given to short periods of approximately 27 days. It is shown that the 27 day periodicity, caused by rotation of the active regions, is demonstrated well in the Wolf number spectrum, while in the total solar irradiance spectrum a time interval of about 15–60 days is displayed. The peaks at about 1 year and the weaker quasibiennial peaks (2–2.5 years) are noticeable in both spectra.

Keywords: Sun; Wolf numbers; Total solar irradiance; Wavelet analysis.

1. Introduction

Many researchers have carried out a time sequence analysis of different solar activity indices using continuous wavelet transformation. For example in [1–3] (see also the references therein) it was shown that for the Wolf numbers it is possible to use continuum wavelet analysis successfully with the Morlet wavelet as the basic wavelet. The basic periods ranging from 11 to 100 years are well known. The results of the shorter-period search were presented, for example, in [4–6]. Many shorter periods are not too confidently fixed in these articles (probably some of these are the 11 year period harmonics). The existence of the 27 day periodicity in the Wolf number data has been noticed by many workers (see, for example, [5]). A search for periodicity in the total solar irradiance (TSI) data by means of wavelet analysis was carried out in [7]. The existence of the 27 day period was revealed in the daily values of the TSI data during the solar activity period.

2. Data

The TSI values have been taken from The World Radiation Center data (http://www.pmodwrc.ch/). They are duplicated by several solar satellite data and corrected to an identical

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scale. Linear data interpolation inside the missing interval was used in the case when data were missing. In the case when there were several data for a given day their values were averaged. As a result the daily sequence of TSI values were obtained. The international sunspot numbers R_i have been used for the sunspot daily data. They are published by the Solar Influences Data Analysis Center, Brussels (Regional Warning Center Belgium, World Data Center for the Sunspot Index, Royal Observatory of Belgium (http://sidc.oma.be/index.php3)). This international index is calibrated to suite the traditional Zurich sunspot numbers R_Z. Comparison was carried out for the short data files chosen from the general set of the Wolf numbers for a time period of about 25 years from I January 1979 to 10 June 2004. The limitation of this interval, naturally, is caused by the amount of available TSI measurements.

3. The algorithm

It is very useful to apply wavelet transformation to the time–frequency analysis of the data because the basic functions are determined not only by the frequency but also by the time (see the theory of wavelet analysis in [8]). The wavelet spectrum allows not only the certain period in a given time sequence to be revealed but also its time change to be analysed. A generalization of the wavelet theory for continuous transformations also exists. Formally the continuous wavelet transformation is defined as

$$W(a,\tau) = \frac{1}{a^{1/2}} \int_{-\infty}^{\infty} x(t)\psi^*\left(\frac{t-\tau}{a}\right) \mathrm{d}t,$$

where ψ represents the basic wavelet, the superscript asterisk means a complex connected value, a is a scaling parameter and τ is the shift parameter. Thus, the transformed signal $W(a,\tau)$ is a function of two variables: the time shift τ and the scale a. For each scale it is possible to introduce a characteristic frequency of the wavelet and from that, simultaneously, to obtain the distribution of energy depending on the shift, with respect to both the time and the frequency. The global wavelet spectrum is also used, *i.e.* the integral of the wavelet modules

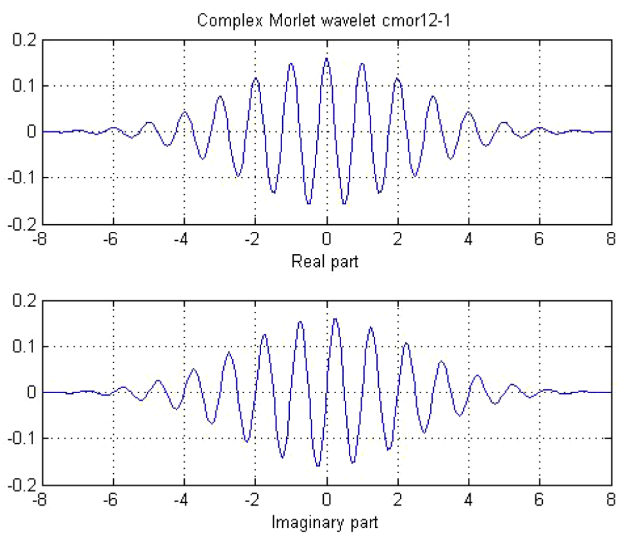

Figure 1. Complex Morlet wavelet ($F_\mathrm{b} = 12$; $F_\mathrm{c} = 1$).

for the given period calculated for all time values:

$$P_W(a) = \int |W(a, \tau)| \, d\tau.$$

In this work, continuous wavelet analysis is used. As a basic wavelet the complex Morlet wavelet $\psi(t, a)$ has been assumed. Some variants of the wavelet parameter choice have been investigated and as a result a pass band of 12 and a central frequency of 1 was assumed. The resulting Morlet wavelet having these characteristics is presented in figure 1.

4. Results

The short time sequence of the Wolf number data is compared with the TSI data for the same time interval, namely for the 25 years from 1979 to 2004.

Figure 2(a) presents the daily sunspot Wolf number values. In figures 2(b) and (c) are two continuous wavelet spectra illustrating the results of continuous wavelet analysis of the daily values of the TSI and of the Wolf sunspot numbers respectively. Obviously, fine structure is seen in both cases. The periodicity of the Wolf numbers is very noticeable in the 27 day spectral region during the epochs of the 11 year cycle maxima. The 27 day periodicity is connected to the recurrence of the solar active regions, the complex structure probably being caused by harmonics or arising because of the effects of the variation in the latitude of the solar rotation rate. As to the TSI wavelet spectrum, it looks much more complicated and has higher contrast. In the TSI spectrum the brightest areas display a larger amplitude and a more complicated structure. Within the solar cycle maxima there is a set of periods in the area from 15 to 60 days. Within the minima the signal is totally absent in both cases.

The 27 day period has also been searched for by application of integral wavelet analyses. Figures 3(b) and (d) present the global wavelet spectra for the two arrays of the data (the Wolf

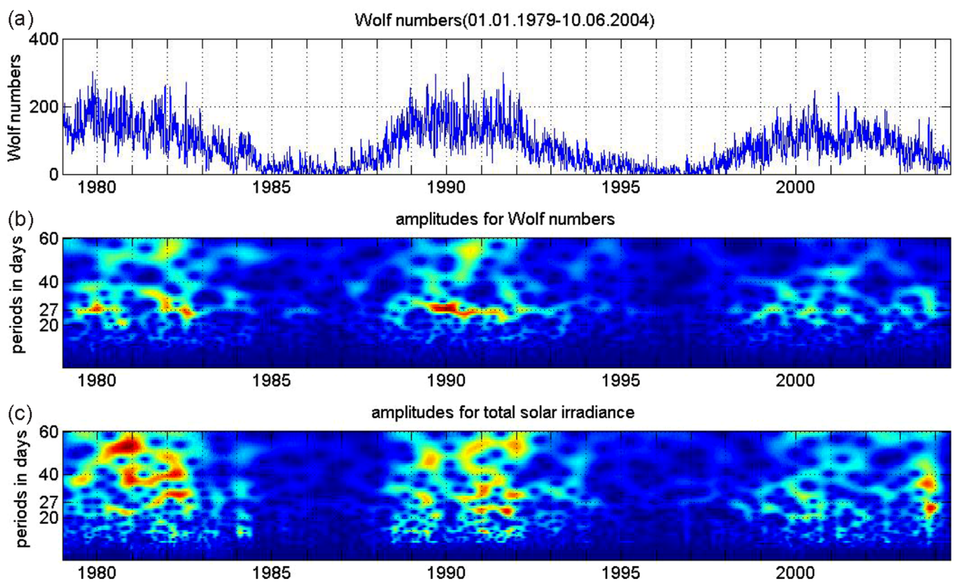

Figure 2. (a) The original time series of the daily Wolf numbers; (b), (c) the amplitudes of the wavelet local power spectrum (b) for the Wolf numbers and (c) for the TSI data. The horizontal axes correspond to the period 1 January 1979–10 June 2004. The vertical axes correspond to the periods in days.

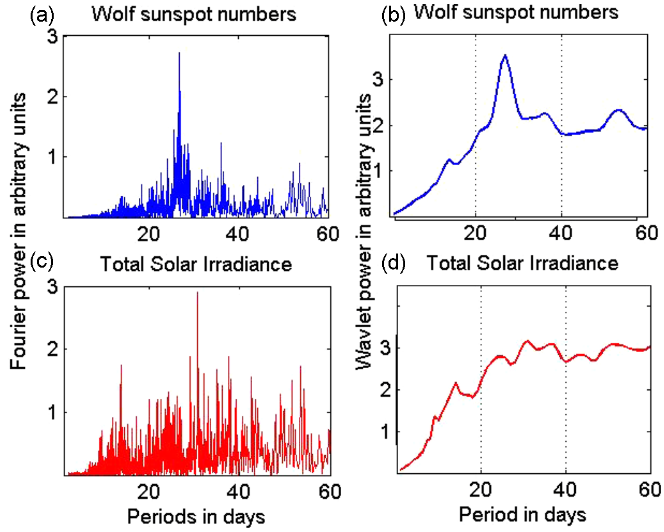

Figure 3. (a), (c) The Fourier power spectra (a) for the daily sunspot Wolf numbers and (c) for the TSI; (b), (d) the global wavelet power spectra (b) for the sunspot Wolf numbers and (d) for the TSI during the period 1 January 1979–10 June 2004.

numbers and the TSI respectively). In figure 3(b) (for the Wolf numbers), the 27 day peak is very pronounced. In figure 3(d) in the same area there is a maximum of complex structure in the field from 20 to 40 days. The TSI shows a much wider maximum as if it were due to the effects of the variation in the latitude of the solar rotation rate. In this case, the TSI variations are probably be due to the energy from all solar latitudes. For comparison, figures 3(a) and (c) show the Fourier spectra for both cases. The Fourier spectrum of the Wolf numbers clearly shows a period of 27 days. The Fourier spectrum of the TSI contains strong noise. Thus, a comparison of the methods allows us to conclude that application of wavelet analysis reveals the spectral features of the studied phenomena better.

In both data arrays, the presence of other short periods and in particular the occurrence of short periods in the spectrum was studied. This comparison is presented in figures 4 and 5. In figures 4(a) and (b) the amplitudes of the wavelet local power spectrum are presented for the

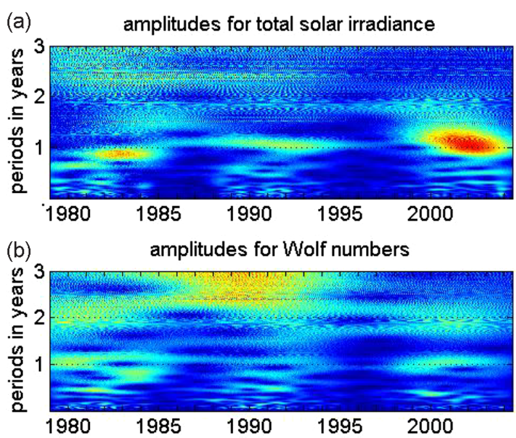

Figure 4. The amplitudes of the wavelet local power spectrum (a) for the TSI and (b) for the Wolf sunspot numbers. The horizontal time axis corresponds to the period 1 January 1979–10 June 2004. The vertical axis corresponds to the periods in years.

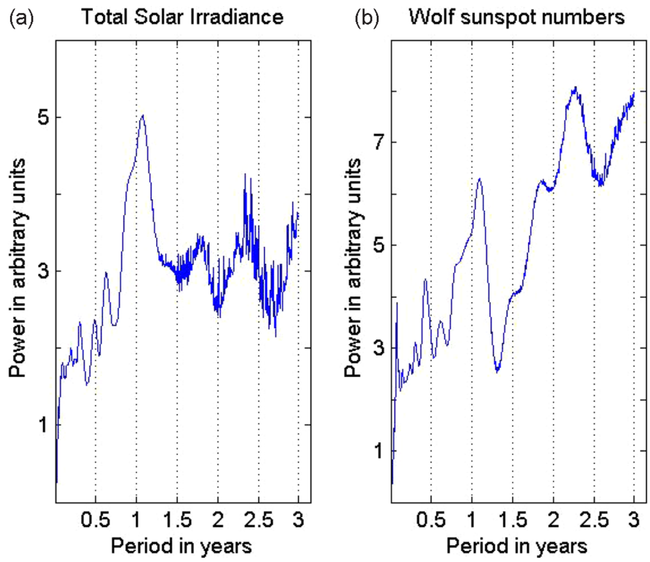

Figure 5. The global wavelet power spectrum (a) for the TSI and (b) for the Wolf sunspot numbers for the period 1 January 1979–10 June 2004.

Wolf numbers and for the TSI, respectively, in the time range from 0 to 3 years. The presence of the period in the area of 1 year in both figures is highly visible. In figure 4(a) for the TSI there is an obvious dependence of the period on time; it increases from almost 0.8 years for 1979–1985 to 1.2 years for 2000. In figure 4(b), for the Wolf sunspot numbers, such a trend is not visible. In both figures there is a stripe in the field of the quasibiennial period. For the Wolf numbers it is much weaker than in the spectrum for the TSI. Figures 5(a) and (b) show the global wavelet power spectra for the TSI and for the Wolf sunspot numbers respectively. The 1 year peak occurs for both numbers (1.07 for the TSI and 1.09 for the Wolf numbers). In both spectra also the quasibiennial peak occurs in the area of 2–2.5 years.

5. Conclusion

Comparison of the daily solar data utilizing the Wolf numbers and TSI data variations has revealed a noticeable period of about 27 days in the Wolf numbers, connected to the low-latitude active regions. The periodicity of the TSI values is about 15-60 days, probably owing to the additional activity of the whole Sun and its high-altitude structures such as polar faculae and X-ray bright points.

In both data arrays, maxima in the quasibiennial area (periods of about 2–2.5 years) are observed, together with a confidently fixed period of about 1 year.

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