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PERIODICITIES IN IRRADIANCE AND IN OTHER SOLAR ACTIVITY INDICES DURING CYCLE 23

T. ATAÇ and A. ÖZGÜÇ
Kandilli Observatory and E.R.I, Boğaziçi University, Çengelköy, Istanbul, Turkey
(e-mails: atac@boun.edu.tr; ozguc@boun.edu.tr)

and

J. RYBAK
Astronomical Institute, Slovak Academy of Sciences, 05960 Tatranska Lomnica, Slovak Republic
(e-mail: choc@ta3.sk)

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Abstract. Magnetic fields give rise to distinctive features in different solar atmospheric regimes. To study this, time variations of the flare index, sunspot number and sunspot area, each index arising from different physical conditions, were compared with the solar composite irradiance throughout cycle 23. Rieger-type periodicities in these time series were calculated using Fourier and wavelet transforms (WTs). The peaks of the wavelet power of these periodicities appeared between the years 1999 and 2002. We found that the solar irradiance oscillations are less significant than those in the other indices during this cycle. The irradiance shows non-periodic fluctuations during this time interval. The peaks of the flare index, sunspot number and sunspot total area were seen around 2000.4, 1999.9 and 2001.0, respectively. These periodicities appeared intermittently and were not simultaneous in different solar activity indices during the three years of the maximum phase of solar cycle 23.

1. Introduction

Highly variable conditions in the geospace environment and on the Sun persist throughout the maximum phase of solar activity. Expressing aspects of that activity in terms of a single index is useful in investigating its role as a driver for various space and terrestrial phenomena. Solar physicists have tried to quantify the variation of solar activity with time, beginning with Wolf's classical formula for the relative numbers of sunspots. The index of solar activity is a quantity intended to describe some aspect of activity for the Sun as a whole. For studying the Sun's long-term behaviour and its interaction with the near-Earth environment, many indices may be used to represent different aspects of solar activity. For example, the Wolf number, the 2800 MHz radio flux, X-ray and EUV indices.

Sun–Earth space weather related to high solar activity affects the geospace environment and the Earth's atmosphere. During such activity periods, the number and intensity of the solar X-ray flares and the coronal mass ejections (CMEs) increase. Barbieri and Mahmot (2004) reported that between mid-October and early November 2003, 59% of the spacecraft and about 18% of the instrument groups experienced some effects from the unusual increase in high-energy particle fluxes.

There were many terrestrial effects. Radio blackouts disrupted communications. Solar protons penetrated the Earth's upper atmosphere, exposing astronauts and some air travellers to radiation doses equal to a medical chest X-ray. Among the solar activity indices, the irradiance is a very important geophysical quantity for modelling and understanding most of the terrestrial processes including global climate changes and space weather. The dark sunspots and bright faculae of the photosphere are sites of local depletion or enhancement of solar radiation. The variable occurrence and inhomogeneous distribution of the solar activity on the solar disk produces net fluctuations in the irradiance throughout the cycles. Recently, Wenzler, Solanki, and Krivova (2005), using the data from the spectromagnetograph of Kitt Peak covering parts of the cycles 22 and 23, reconstructed the total solar irradiance and compared it with the observational data. They found that their model, based on the assumption that the solar irradiance changes are entirely caused by the evolution of the solar surface magnetic fields, could reproduce the observed irradiance in both cycles 22 and 23. We now know from helioseismology that a dynamo seated near the bottom of the convection zone creates this magnetic flux, which produces a variety of features such as sunspots, faculae, plages and coronal holes. In addition to these features, numerous solar phenomena, including irradiance, solar wind fluctuations, flares and CMEs, arise from emerging magnetic fields.

Helioseismic data have shown that the rotation rate of the Sun near the base of its convective zone changes with a period of roughly 1.3 years (Howe *et al.*, 2000). Another periodicity in solar activity indices around 150 – 160 days is seen to vary approximately in phase with the 1.3-year variation. Based on this, Krivova and Solanki (2002) have proposed that the 150 – 160-day period is the third harmonic of the 1.3-year period. If so, we can expect that any fluctuation in the dynamo will manifest itself in the intermediate-term variations of the solar activity indices as a periodic emergence of magnetic flux with harmonics of this period. In the light of these findings, could similar high solar activity periods have been predicted?

In this study, we attempt to find some additional results on the simultaneous variations of the sunspot and flare activities with the solar irradiance. We have investigated the intermediate-term periodicities and their statistical significance during cycle 23. Also, these efforts could help us to add some new information for the prediction of future solar cycles.

2. Data and Method of Analysis

Our data set (http://www.koeri.boun.edu.tr/astronomy/findex.html) comprises the daily values of the above-mentioned indices, which cover solar cycle 23 between the years 1996 and 2004 (see Figure 1). In many studies in the solar-terrestrial field, solar flares are found to be among the most important solar events affecting the Earth.

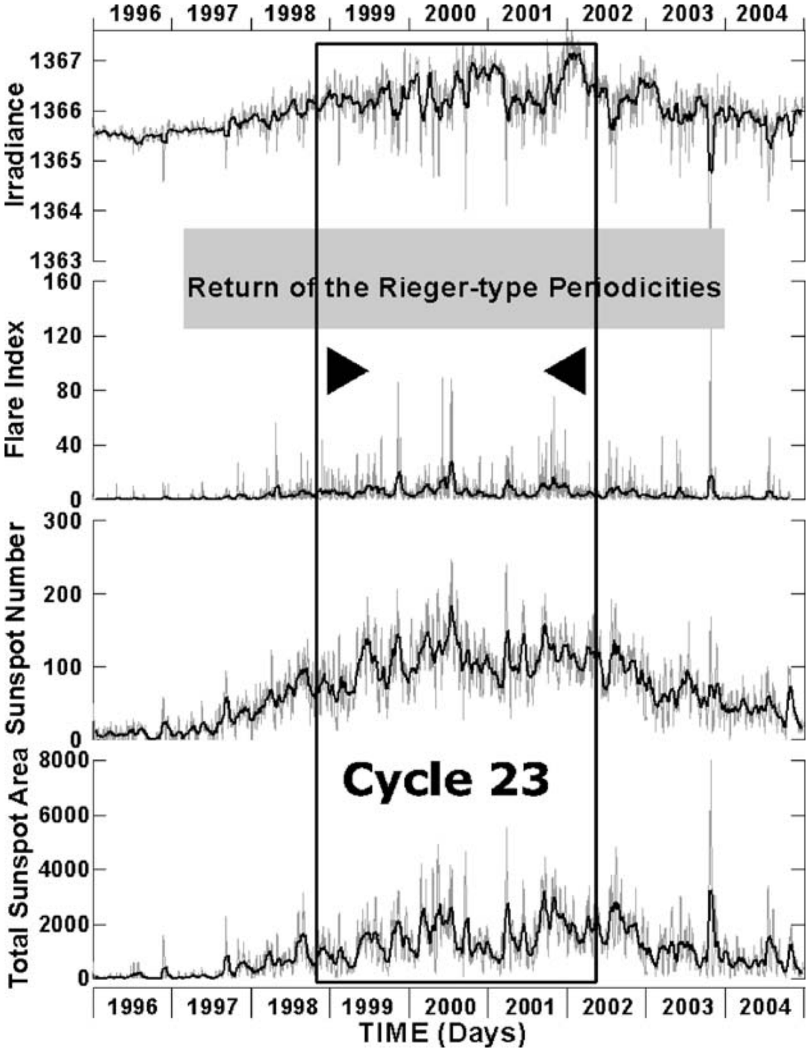

Figure 1. The plots of the time variations of the four solar activity indices from 1 January 1996 to 31 December 2004. *Thick lines* show 25-day running mean. Units of the sunspot area and the composite of the solar irradiance are millionths of solar hemisphere and W m^{-2}, respectively. *Thin lines* demonstrate the daily values.

Kleczek (1952) introduced the quantity $Q = it$ to quantify the daily flare activity over a 24-h period. He assumed that this relationship roughly gave the total energy emitted by the flare and named it ‘flare index’ (FI). In this relation, i denotes the intensity scale of importance of a flare in Hα and t denotes the duration of the flare in minutes. The daily sunspot areas are taken from the Royal Greenwich Observatory (RGO). They compiled sunspot observations from a small network of observatories to produce a data set of daily observations starting in May 1874. The observatory concluded this data set in 1976 after the US Air Force (USAF) started compiling data from its own Solar Optical Observing Network (SOON). This work was continued with the help of the US National Oceanic and Atmospheric Administration (NOAA) with much of the same information being compiled through to the present (http://science.msfc.nasa.gov/ssl/pad/solar/greenwch.htm). The sunspot number is the oldest solar activity index. The daily data of the international sunspot numbers provided by the Sunspot Index Data Center of the Royal Observatory of Belgium were used for our analysis (http://sidc.oma.be/html/dailyssn.html). These data represent the definitive relative numbers of the sunspots calculated on the basis of all observations available from different observatories. The daily values of the Sun's total irradiance have been measured using radiometers on different space platforms since November 1978: HF on Nimbus7, ACRIM I on SMM, ERBE on ERBS, ACRIM II on UARS, VIRGO on SOHO and ACRIM III on ACRIM-Sat. The composite record of the Sun's total irradiance (IR) is compiled from measurements made by these space-based radiometers. More information about the determination of this composite can be found in the paper of Fröhlich and Lean (1998). The composite data that we used in this study are available from ftp://ftp.pmodwrc.ch/pub/data/irradiance/composite/.

In order to study Rieger-type periodicities of the activity indices, one can use daily values as a time series. To search for intermediate term periodicities in all the time series, the power spectra were calculated using the discrete Fourier transform. The results are presented in Table I. Also, we show the distribution of the power values corresponding to the normalized power spectra in Figures 2 – 5. The method used to normalize the power spectra has been described in several previous papers by the authors (e.g. Özgüç, Ataç, and Rybák, 2004). After calculating a power spectrum, one has to calculate the significance of a peak in the spectrum. We used the false alarm probability (FAP), which is defined as the probability of finding by chance a peak with a value of Z_m in the search window (Scargle, 1982). It is given by the expression

$$\mathrm{FAP} = 1 - [1 - \exp(-Z_m)]^N, \tag{1}$$

TABLE I

The intermediate-term periodicities found by Fourier power spectral analysis with their false alarm-probability values in parenthesis.

Periods (day)	Irradiance	Flare index	Sunspot number	Sunspot areas
110 – 120	113.4 d (5%)	–	114.2 d (10%)	112.6 d (5%)
120 – 130	121.8 d (10%)	120.4 d (5%)	–	–
130 – 140	–	133.4 d (5%)	133.7 d (5%)	134.0 d (10%)
140 – 150	–	–	148.1 d (10%)	–
150 – 160	–	–	–	158.0 d (10%)

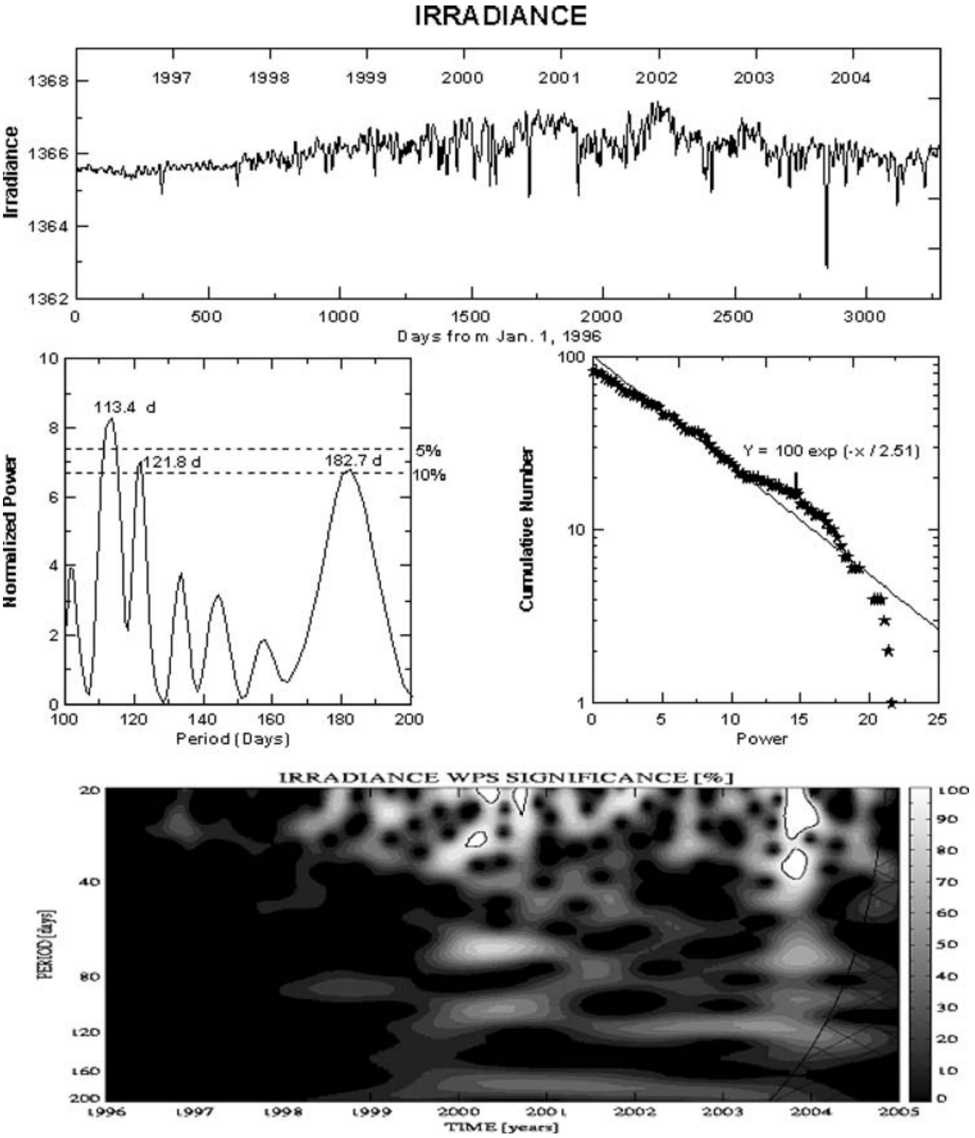

Figure 2. Behaviour of the daily values of the solar total irradiance (*top panel*). Normalized power spectra of the solar total irradiance (*middle left panel*) and power distribution of discrete Fourier transform (*middle right panel*). The wavelet power spectra of the solar irradiance time series for the period range 20 – 200 days (*bottom panel*). Grey-scale coding of power from black to white represents the confidence levels of the local power above the noise level assuming noise independence on periods. The cone of incidence is marked by the *cross-hatched regions*.

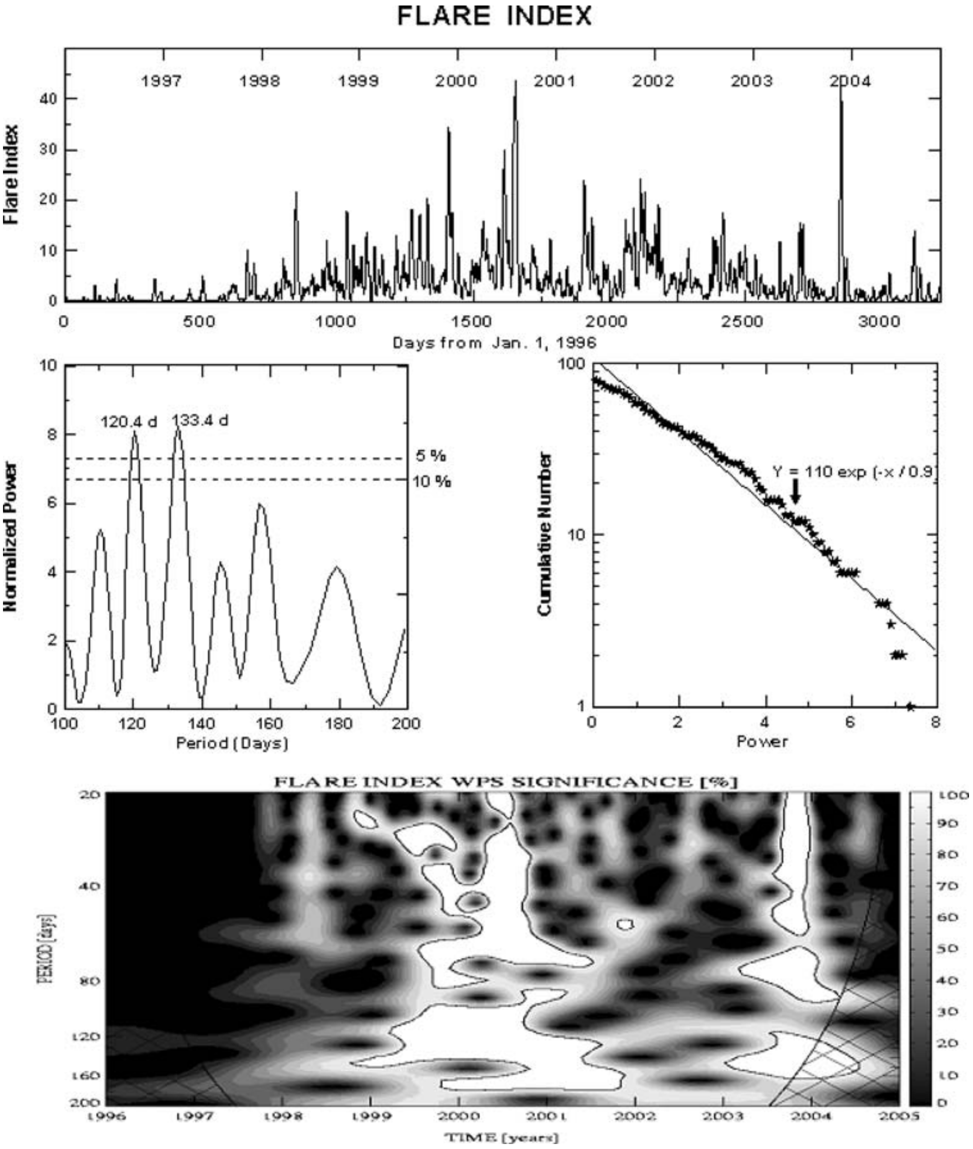

Figure 3. Same as Figure 2, but for the flare index.

where Z_m is the height of the peak in the normalized spectrum and N the number of independent frequencies. Here, the power spectra have been calculated for the frequency range 57.9 – 115.8 nHz with 0.70-nHz interval. This interval corresponds to the time interval of 100 – 200 days. If we have a discrete power spectrum giving the power at each of N independent frequencies for a set of random data, then F indicates the probability that the power at one or more of these frequencies will exceed Z_m by

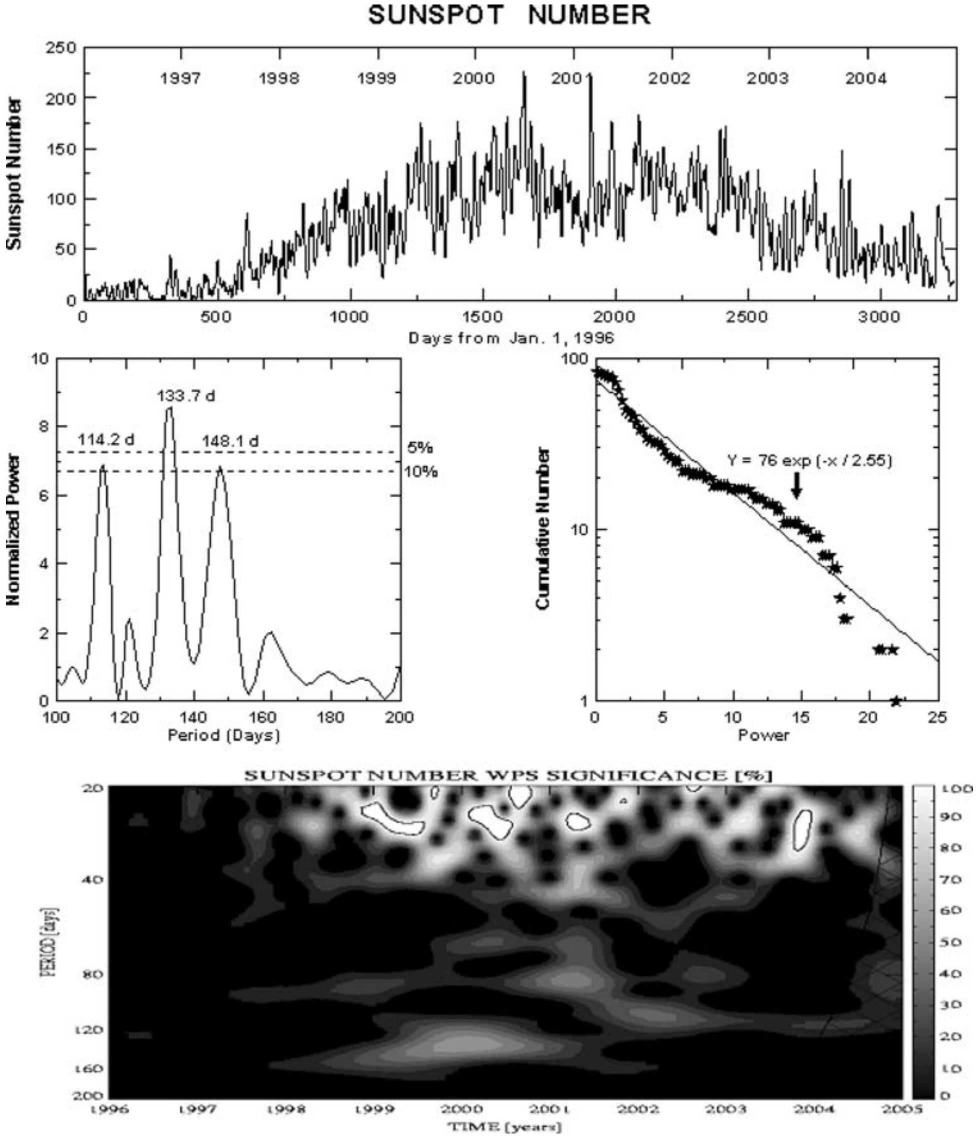

Figure 4. Same as Figure 2, but for the sunspot numbers.

chance. Fourier components calculated at frequencies at intervals of the independent Fourier spacing (ifs), $\Delta f_{\text{ifs}} = \tau^{-1}$, where τ is the time span of the data, which are totally independent (Scargle, 1982). For $\tau = 3288$ days $\Delta f_{\text{ifs}} = 3.52$ nHz. Thus, there are 16 independent frequencies in the 57.9 – 115.8 nHz intervals. The FAP is calculated for each peak as follows: if we take the height of the peak and the number of independent frequencies (16) in Figure 2 and substitute them in the FAP's expression, we would underestimate the FAP (in our case, we would obtain 0.44%).

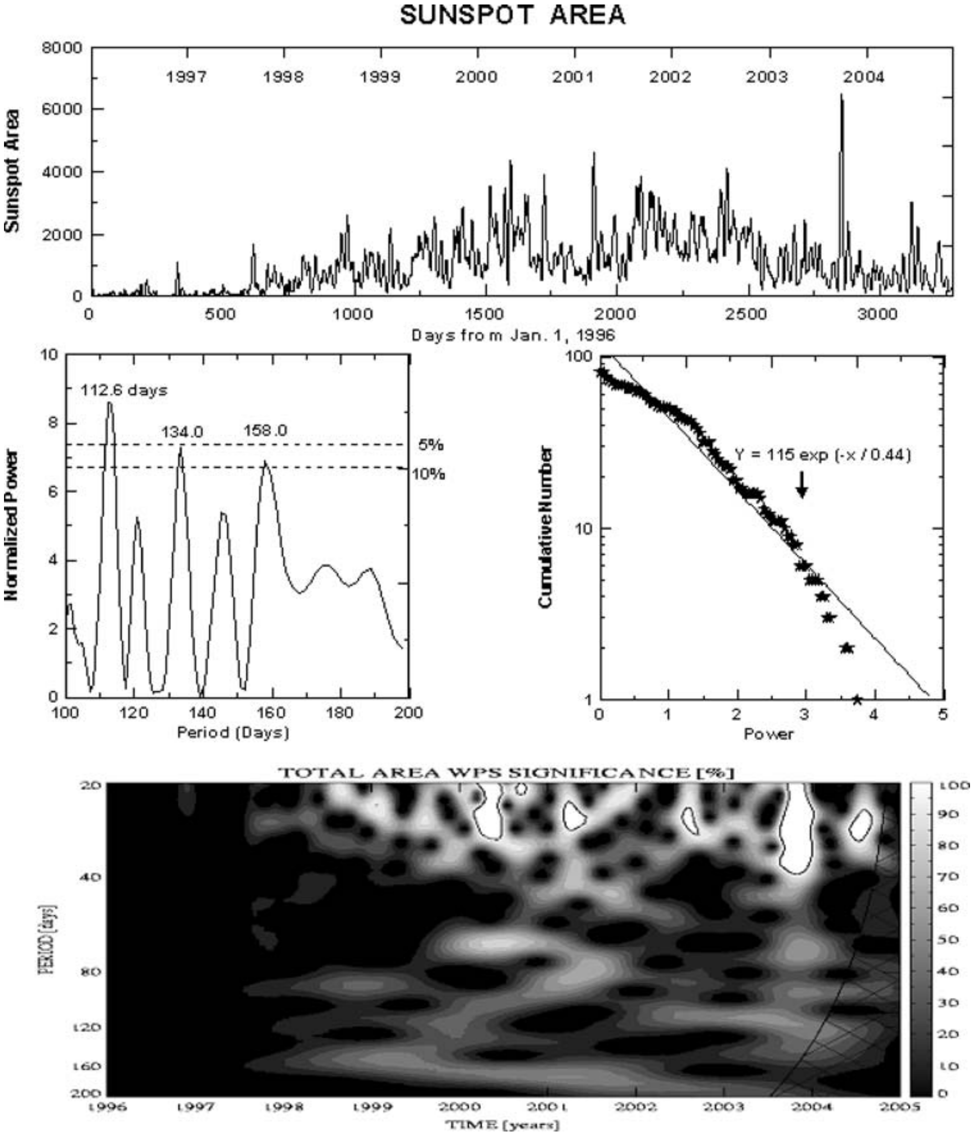

Figure 5. Same as Figure 2, but for the total sunspot areas.

However, when substituting $N = 57$ we compensate for the effect of the increase of the peak value by over-sampling. The over-sampling tends to more accurately estimate the peak value. Therefore, if we substitute $Z_m = 8.2$ and $N = 57$ (since we searched 57 frequencies with 0.7 nHz intervals) in Equation (1), we get the false alarm probability FAP $= 0.0155$, i.e., the probability of obtaining such a high peak by chance is about 1.5%. The same analysis has been applied to the corresponding time series and the results can be seen in Table I.

Wavelet transform (WT) analysis yields information on periodicities in both time and frequency domains, so we have applied wavelet analysis to the time series of the daily solar activity indices mentioned above, to study the temporal variation of the intermediate-term periodicities. The algorithm of the continuous WT (Torrence and Compo, 1998) was applied within the period range 20 – 200 days. The Morlet wavelet, a plane sine wave with an amplitude windowed in time by a Gaussian function, was selected to search for variability of the time series of the solar total irradiance, flare index, sunspot number and daily sunspot area data. The period resolution used varied from 0.4 to 11.2 days. The calculated wavelet power is suppressed on the edges of the time domain due to the applied WT algorithm within the cones of influence located at the temporal edges of the domain which is indicated in our plots by cross-hatched regions. The non-dimensional frequency has been set to six fixing the length of all wavelets according to their scale. The significance level of the calculated WT power was derived using the null hypothesis assuming existence of a red-noise power spectrum. In general, the mean power spectrum of the time series can be modelled using either a white-noise or a red-noise spectrum and the assumption of a red-noise background spectrum to compute the power spectrum of a solar activity time series is somewhat more restrictive. Higher values of power are required for a peak to be significant in a red-noise spectrum at a given significance level compared to a white-noise background spectrum (Torrence and Compo, 1998). The 90% confidence level, used in this study, implies that 10% of the wavelet power should be above this level for each period. Plots of wavelet power spectra (WPS) are given in Figures 2 – 5 for each activity index.

3. Results and Discussion

Extensive analyses have been made to find the intermediate-term periodicities in the range 24 days to 11 years in similar solar activity indices. Among these, the period around 150 – 160 days is the best known one, which was discovered by Rieger *et al.* (1984) in the occurrence of high-energy flares. Since then, many researchers have continued to investigate Rieger-type periodicities using different solar activity indices (Zieba *et al.*, 2001; Ballester, Oliver, and Carbonell, 2002, 2004; Krivova and Solanki, 2002; Bai, 2003; Lou *et al.*, 2003; Özgüç, Ataç, and Rybak, 2003; Knaack, Stenflo, and Berdyugina, 2005; Richardson and Cane, 2005; Joshi and Joshi, 2005).

In the present study, we applied Fourier and WT analyses to the time variations of solar total irradiance, flare index, sunspot number and sunspot total area during solar cycle 23. Wavelet power spectra were obtained for the 20 – 200 days range. To provide a complete view of the temporal variability and to compare the Fourier and wavelet periods of each activity index, all the plots were combined as shown in Figures 2 – 5. As can be seen from the figures and from Table II, statistically

TABLE II

The operation times of the Fourier periods found by wavelet analysis and their significances.

Periods (day)	Irradiance	Flare index	Sunspot number	Sunspot areas
110 – 120	113.4 d (2000.3) (43%)	–	114.2 d (1999.9) (32%)	112.6 d (1999.9) (35%)
120 – 130	121.8 d (1999.8) (24%)	120.4 d (2000.3) (98%)	–	–
130 – 140	–	133.4 d (2000.4) (98%)	133.7 d (2000.1) (54%)	134.0 d (1999.9) (33%)
140 – 150	–	–	148.1 d (1999.9) (51%)	–
150 – 160	–	–	–	158.0 d (2000.9) (50%)

significant periods appeared only during the time interval 1999 – 2002, which covered the maximum phase of solar cycle 23. Previous cycle analysis has shown that Rieger-type periodicities operated mainly during maximum phases of solar cycles for only short time intervals. The operation times for different indices can be seen in Table II over which the power of the Rieger-type periods has peaked. This helped us to see that the wavelet analysis of the solar total irradiance shows very weak evidence of power near 110 – 120 days (significance level around 45%) and near 120 – 130 days (significance level close to 20%). Other important results may be noted by comparing our values of periods in Table II.

1. The peaks of the wavelet power of these oscillations were between the years 1999 – 2002.
2. The peaks of the irradiance, the flare index, the sunspot number and the sunspot total area were in the years of 2000.3, 2000.4, 1999.9 and 2001.0, respectively.
3. The peaks that seen in the plots of the three activity indices at the end of the year 2003 were mostly due to the unexpectedly large increase of solar activity during the interval October – November 2003. All flux came from only two big sunspot groups. That is why we could not see these peaks in the wavelet plot of the sunspot number.
4. The four activity indices that we studied do not show simultaneous wavelet peaks.
5. The periodicities in the range 120 – 140 days appeared strongly in the wavelet diagram of the flare index at a significance level of 98%, while the significance levels for solar total irradiance, sunspot number and sunspot area are only 24, 54 and 33%, respectively.
6. Periodicities in the range 140 – 160 days were not present in the wavelet diagram of solar total irradiance and flare index, and they are barely present

for sunspot number and total sunspot area, with significance levels 51 and 50%, respectively.

Many other studies of different solar activity data sets covering solar cycle 23 have given strong evidence of the return of these periodicities. Recently, mid-range periodicities in solar flare occurrence (X-ray flares of class $\geq$ M1.0) have been analyzed by Bai (2003), who found that 129 and 33.5 days periodicities were present in the interval 9 September 1999 to 5 June 2001, during which five epochs of high activity were identified. A return of the near-160-day periodicity in the photospheric magnetic flux during cycle 23 was found by Ballester, Oliver, and Carbonell (2004). They reported that the periodicity has appeared with a frequency similar to that of solar cycle 21, again at the epoch of solar activity maximum. They also showed that the sunspot areas display weak evidence of power near 160 days with a weak significance level (45%). Richardson and Cane (2005) reported that variations in the occurrence of solar energetic particle events, interplanetary CMEs and sunspot number show an intermittent quasi-periodicity of $\sim$150 days during cycle 23. It is manifested most clearly in their wavelet analysis during $\sim$3 years around solar maximum and it was only present intermittently both with time and between the data sets considered. Very recently, Joshi and Joshi (2005) have analyzed the intermediate-term periodicities in soft X-ray flare index using the Lomb – Scargle periodogram method. They have found that a significant peak appears only in the interval May 1996 to October 2002, with a period of 123 days.

4. Conclusions

All of the studies mentioned, including this, have shown that the reappearance of the Rieger-type periodicities during solar cycle 23 is a fact. The level of significance of these periodicities in various solar activity indices was different. These periodicities appeared intermittently and were not simultaneous in different solar activity indices during the three years of the maximum phase of cycle 23. Our results obtained from the wavelet diagram of the solar total irradiance showed a very weak evidence of power of the Rieger-type periodicities. One can conclude from Table II that, of the indices considered, only the irradiance shows non-periodic fluctuations during this time interval. However, our wavelet analysis of the daily flare index shows very strong evidence of periodicity with a significance level greater than 98%. Ballester, Oliver, and Carbonell (2004) found that the periodic emergence of magnetic flux was strong during the maximum phase of the current cycle. However, the flare index is a measure of the short lived activity on the Sun. It is also roughly proportional to the total energy emitted by the flare. This means that the flare index gives us information about the numbers of flares and the energy emitted from these flares. Thus, we can say that the periodic production of solar flares is very closely related to the emergence of the new magnetic flux which triggers the flare production.

Besides this periodic behavior of the solar activity during the maximum phase of the current cycle, the unpredictable high solar activity periods such as October – November 2003, November 2004 and January 2005 showed us that we need other mechanisms to explain the unexpected increases of the solar activity during the descending branch of solar cycles.

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