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Flare index variability in the ascending branch of solar cycle 23

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[1] A brief description and the results of the determination of the flare index as a measure of solar activity on the ascending branch of cycle 23 up to 31 December 2000 are presented. The patterns of similar activity indices that arise under different physical conditions during the rising activity phase are compared with the flare index. All studied solar indices rise more slowly in the current cycle than the last one, except the total solar irradiance. The intermediate-term periodicities in the daily flare index data were studied using the Fourier transform, and it was found that the 35-, 62-, 116-, 198-, and 276-day periodicities are in operation during the ascending branch of cycle 23. Contrary to the previous three cycles, 155-, 73-, or 51-day periodicities were not detected by the Fourier transform in this branch of the cycle. The wavelet transform results show that the occurrence of flare index power is highly intermittent in time, and the most pronounced power peaks were found to be present at 35 days (the temporal locations at 1998.3, 1999.9, and 2000.5 years), 116 days (the temporal interval 1999.7–2000.4 years) and 276 days period (interval roughly from 1999.5 until the end of the flare index data). Comparison of the Fourier and wavelet transform results has clarified the importance of different periodicities, whether they are (62, 198 days) or are not (35, 116, 276 days) the harmonics of the basic ones, as well as the temporal location of their occurrence. *INDEX TERMS:* 7519 Solar Physics, Astrophysics, and Astronomy: Flares; 7524 Solar Physics, Astrophysics, and Astronomy: Magnetic fields; 7536 Solar Physics, Astrophysics, and Astronomy: Solar activity cycle (2162); 7522 Solar Physics, Astrophysics, and Astronomy: Helioseismology; 7538 Solar Physics, Astrophysics, and Astronomy: Solar irradiance; *KEYWORDS:* Flare, periodicity, activity, cycle, Fourier, wavelet

1. Introduction

[2] Solar activity variations demonstrate themselves not only in electromagnetic radiation from radio frequencies of a few kHz to powerful gamma rays but also in particle flux. In broad physical terms, solar activity may be understood in terms of the properties and the behavior of the magnetized solar plasma. Solar structures and phenomena all arise from magnetic fields embedded in dynamic plasma. Images of the Sun show that solar flares are one of the most powerful and explosive of all forms of solar activity. Many studies in the solar terrestrial field classified solar flares as one of the most important solar events affecting the Earth like coronal mass ejections (CMEs). "...before 1973 nobody observed CMEs, but for many decades prior to that time people observed flares and associated them (successfully in most cases) with disturbances at the Earth. Thus, also for the sake of continuity of data, one should still pay full attention to flares as co-sources of geomagnetic disturbances" [*Švestka*, 2001, p. 144].

[3] The quantitative flare index first introduced by *Kleczek* [1952], $FI = i\ t$, may be roughly proportional to the total energy emitted by the flare. In this relation, i represents the intensity scale of importance of a flare in H_α and t the duration in H_α (in minutes) of the flare. Table 1 lists values of i used for the determination of *FI*. The daily sums of the index for the total surface are divided by the total time of observation of that day. Because the time coverage of flare observations is not always complete during a day (sometimes 75% or 90%), it is corrected by dividing by the total time of observations of that day to place the daily sum of the flare index on a common 24-hour period. The daily total time of observation is calculated from *Solar Geophysical Data Comprehensive Reports*. Calculated values are available for general use in anonymous ftp servers of our observatory and NGDC: ftp://ftp.koeri.boun.edu.tr/pub/astronomy/flare_index and ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_FLARES/INDEX. Some reviews of flare activity using the flare index are given for each day from 1936 to 2001 by *Kleczek* [1952], *Knoška and Petrásek* [1984], *Ataç* [1987], and *Ataç and Özgüç* [1998, 2001].

[4] In this paper the results of the determination of the flare index on the ascending branch of solar cycle 23 are presented. Its relation with other solar activity indices is described. Comparison with the similar solar indices of the flare index is examined. To estimate intermediate-term periodicities the discrete Fourier transform (FT) was

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Table 1. Values of *i* Used for the Determination of *FI*

Importance	*i*
SF, SN, SB	0.5
1F, 1N	1.0
1B	1.5
2F, 2N	2.0
2B	2.5
3F, 3N, 4F	3.0
3B, 4N	3.5
4B	4.0

employed for the rising branch of current cycle. Since commonly used FT is not able to disclose possible changes in the periodicities over the period studied, the wavelet transform (WT) was applied to search for temporal variability.

2. Flare Index on the Ascending Branch of Solar Cycle 23 and Its Relation to Some Other Activity Indices

[5] The idea of comparing the pattern of similar activity indices that arise under different physical conditions led us to investigate how *FI* agrees with other full-disk solar indices. The indices to be compared are as follows:

(1) Stanford University, Wilcox Solar Observatory's measurement of the net magnetic field intensity in microteslas summed over the disk. Such integrated light measurements of the mean solar magnetic field (*MMF*) have been made daily since May 1975 [*Scherrer et al.*, 1977] (http://quake.stanford.edu/~wso/wso.html).

(2) Daily corrected total areas of sunspot groups (*TSA*). These are observed, measured and compiled by USAF/NOAA (http://science.msfc.nasa.gov/ssl/pad/solar/greenwch.htm).

(3) The relative sunspot number (*RSN*). This is an index of the activity of the entire visible disk of the Sun calculated by the Sunspot Index Data Center (SIDC), (http://sidc.oma.be/index.php3).

(4) *IR*, a composite record of the Sun's total irradiance, is compiled from measurements made by five independent space-based radiometers since 1978. We used Version 23 of that data set. More information about the determination of this composite can be found in the paper of *Fröhlich and Lean* [1998] (ftp://ftp.pmodwrc.ch/data/irradiance/composite/).

[6] In Figure 1, we plot the similar solar activity indices with the 27-day running means to show their changes during the previous and the current cycles. Two time intervals of 51 months, each starting from the beginning of their minimum years were compared. We can see that the current cycle rises more slowly than the last one, except the total solar irradiance in the same time interval. The numbers of the major flares (X & M) per month remains at a lower level during the ascending branch of the current cycle (see Figure 1). Also, the monthly mean flare index has been at a very low average level this cycle, but there have been spikes lasting one or two months that reach similar levels to those seen in the previous cycle.

[7] The first important increase of the flare activity due to the active region NOAA 8210 was seen in April 1998 on the southern hemisphere. This active region mainly enhances flare activity without increasing the sunspot number much. This matter will be discussed later.

3. Intermediate-Term Periodicities During the Ascending Phase of Solar Cycle 23

[8] After the discovery of the 154-day Rieger periodicity [*Rieger et al.*, 1984], a number of authors have reported the detection of this periodicity in the rates of flares selected by additional criteria such as soft X-ray peak flux [*Rieger et al.*, 1984], hard X-ray emission [*Dennis*, 1985; *Bai and Sturrock*, 1987], Hα importance [*Ichimoto et al.*, 1985], microwave peak flux [*Bogard and Bai*, 1985], solar flare index [*Özgüç and Ataç*, 1989, 1994], production of interplanetary energetic electrons [*Dröge et al.*, 1990], production of interplanetary energetic protons [*Bai and Cliver*, 1990; *Gabriel et al.*, 1990], 10-cm radio wave peak flux [*Kile and Cliver*, 1991], as well as in other solar activity indicators such as sunspot area [*Lean and Brueckner*, 1989; *Carbonell and Ballester*, 1990; *Oliver et al.*, 1998] and sunspot numbers [*Ballester et al.*, 1999]. Besides this period range of ~150–160 days, other notable Rieger-type periods are 51, 77, 103, and 128 days during maxima of different solar cycles [*Bai and Sturrock*, 1991; *Bai*, 1992] from various data sets. These periodicities are not continuously in operation but rather are episodic in nature [*Bai and Sturrock*, 1991, 1993]; therefore they are called 'Intermittent Periodicities'.

[9] We employed the discrete Fourier transform to estimate, which periodicities are in operation during the ascending branch of cycle 23, which covers about 1547 days. We examined the flare index time series by computing the periodograms after tapering 5% of the data at the ends of the time intervals by applying a split bell cosine window [*Bloomfield*, 1976]. Figure 2 shows the normalized power spectra of the time series for the ascending branch of cycle 23. There are five prominent peaks at 276, 198, 116, 62 and 35 days. For this figure power spectra were calculated for the 38–558 nHz (21–300 days) range with 1.50 nHz intervals. The flare index is not independent but is correlated with a characteristic correlation time of a week. Therefore the power distribution follows an exponential distribution [*Horne and Baliunas*, 1986]; i.e., the probability of the power density at a given frequency being greater than K by chance is given by

$$P(z > K) = \exp\left(-K/\sigma^2\right). \quad (1)$$

Even if we use a normalized time series

$$X_{ii} = (X_i - X_{av})/\sigma$$

where X_i is the *FI* on the *i*th day, X_{av} is the daily mean flare index value, and σ is the variance, because of the interdependence of occurrence of some big flares, the Fourier periodogram turns out to be not normalized. Therefore, whatever analysis method is used, the best way

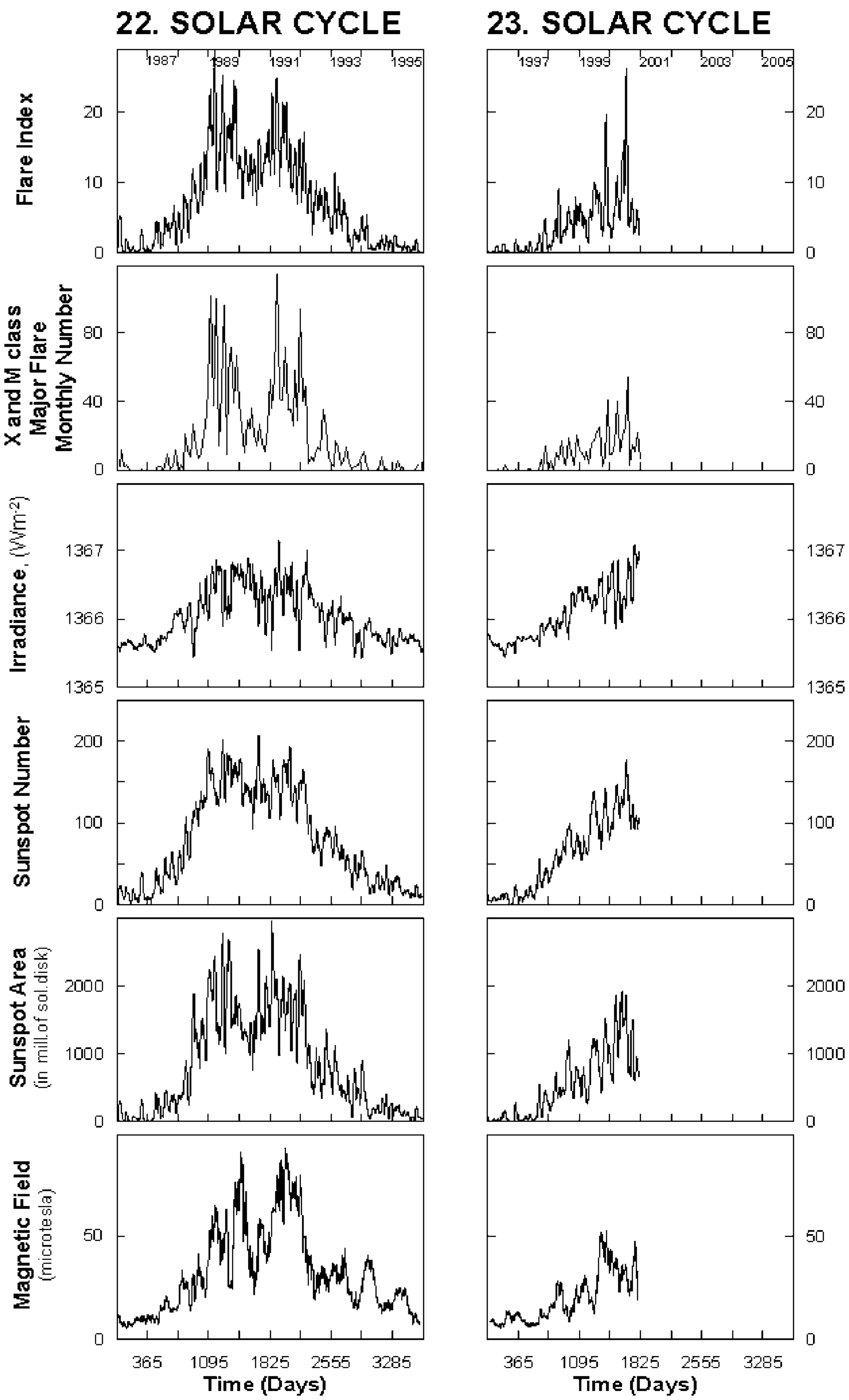

Figure 1. Plots of the 27-day running means of the similar solar activity indices for the previous and the current cycles. Note that the time delays between the increase in MMF and the increase in RSN, and low level of major flare activity and high level IR.

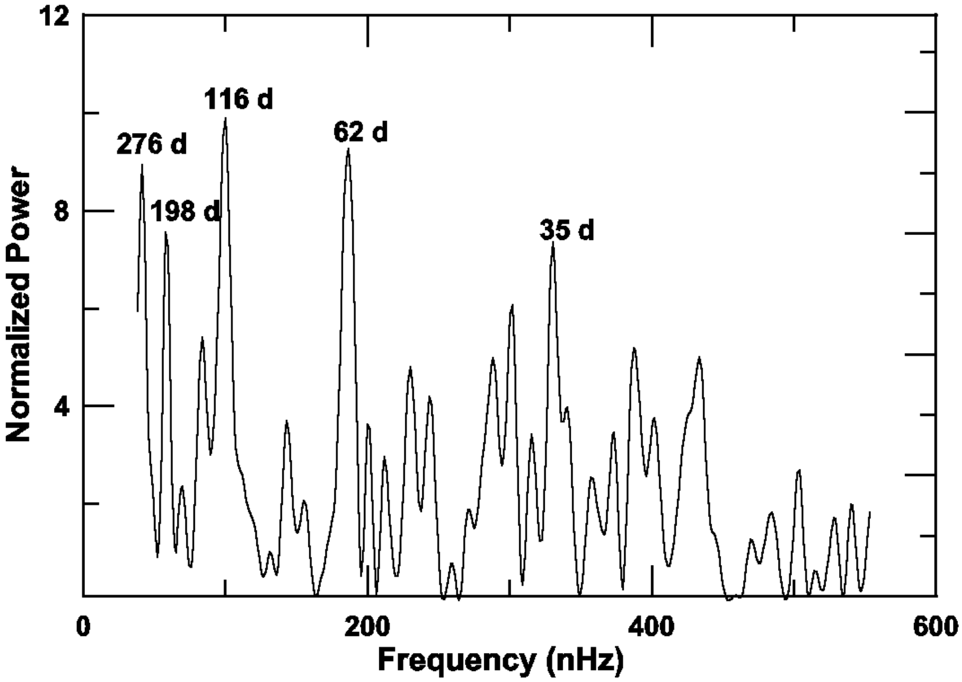

Figure 2. Normalized power spectrum of the flare index for the time interval from 1 October 1996 to 31 December 2000.

to normalize the power spectrum is to fit the actual power distribution to Equation (1) [*Bai and Cliver*, 1990]. Figure 3 shows the distribution of the Fourier power values corresponding to the normalized spectrum shown in Figure 2. The vertical axis shows the cumulative number of frequencies for which the power exceeds a certain value; of course for all 346 frequencies the power exceeds zero; thus, we have a point at (x = 0, y = 346). At only one frequency (100.25 nHz, which is equivalent to 116 days) the power was 9.88 its maximum value. For lower values of power, the distribution can be well fitted by the equation $Y = 466 \exp(-x*0.13)$, as expected from Equation (1). Thus, we normalize the power spectrum by multiplying the powers by 0.13 to obtain Figure 2.

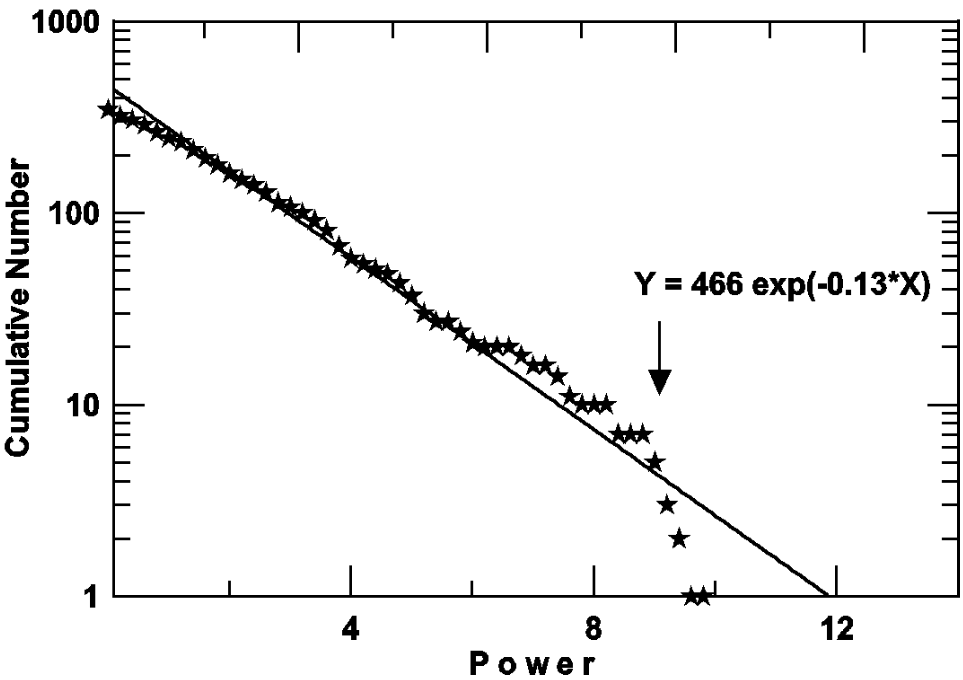

Figure 3. The power distribution of discrete Fourier transform. The vertical axis is the number of frequencies for which power exceeds X. The straight line is the fit to the points for lower values of power.

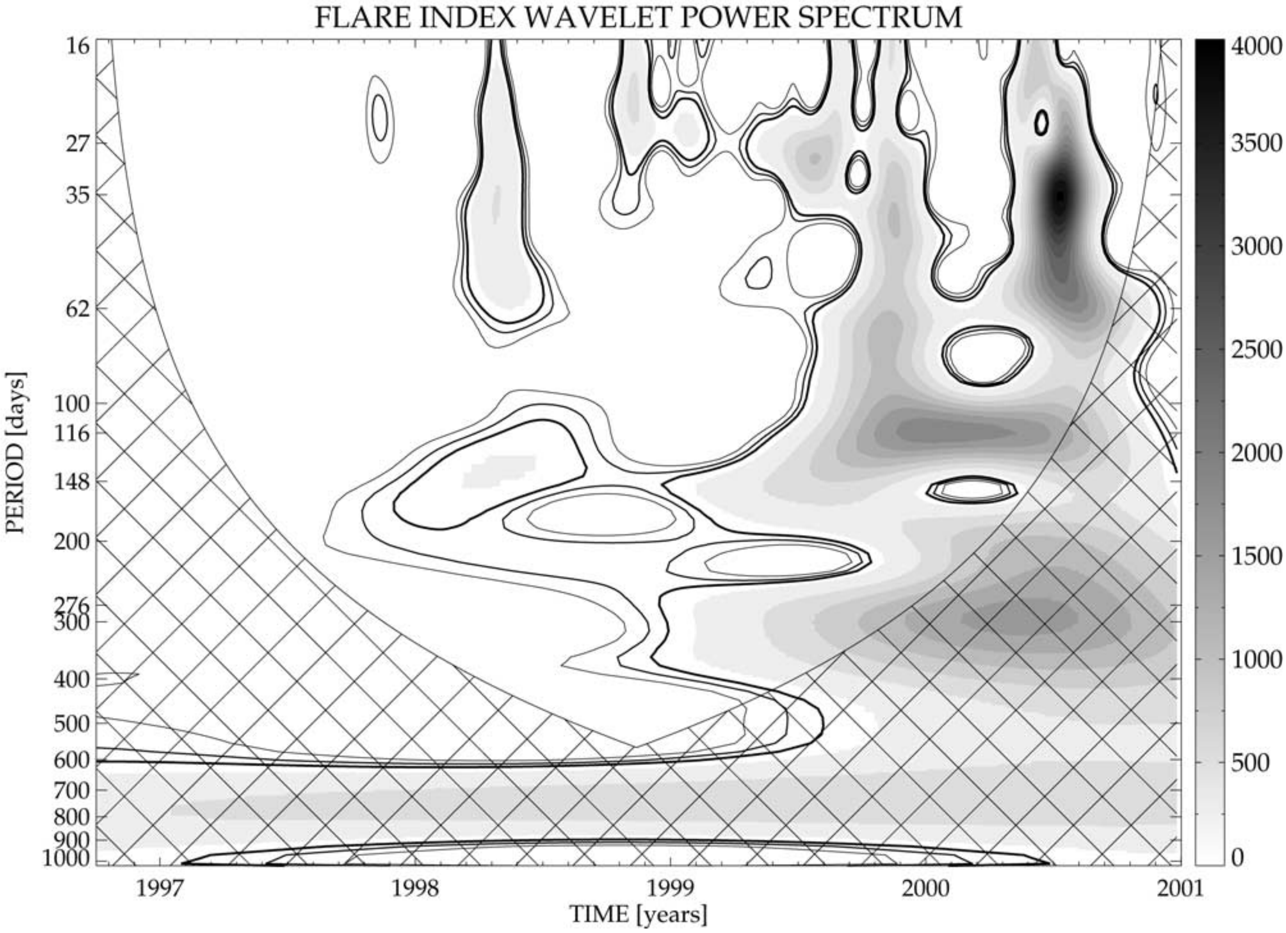

Figure 4. The wavelet transform power spectrum of *FI* for the epoch between 1 October 1996 and 31 December 2000 and the period range 16–1000 days. Greyscale coding from white to black represents the power (a.u.) in a linear scale. The different solid lines show the confidence levels of 95, 90 and 80% with the decreasing line thickness. The cones of incidence are marked by the cross-hatched regions.

[10] In estimating the statistical significance of the peaks in the power spectrum, the 'false alarm-probability' (FAP) may be used. It is given by the expression

$$F = 1 - [1 - \exp(-Z_m)]^N, \tag{2}$$

where Z_m is the height of the peak in the normalized power spectrum and N is the number of independent frequencies [*Scargle*, 1982; *Horne and Baliunas*, 1986]. If we have a discrete power spectrum giving the power at each of N independent frequencies for a set of random data, F indicates the probability that the power at one or more of these frequencies will exceed Z_m by chance.

[11] Fourier components calculated at frequencies at intervals of the independent Fourier spacing (ifs), $\Delta f_{ifs} = \tau^{-1}$, where τ is the time span of the data, are totally independent [*Scargle*, 1982]. By Monte-Carlo simulations, *de Jager* [1987] has shown that the Fourier powers taken at intervals of one-third of the independent Fourier spacing are still statistically independent. For τ = 1547 days Δf_{ifs} = 6.88 nHz. Thus, there are 75 independent frequencies in the 38–558 nHZ interval (according to *de Jager* [1987], 225 independent frequencies). We oversampled to obtain the power spectrum shown in Figure 2 in which the height of the peak at 116 days is 19.77. The oversampling tends to estimate more accurately the peak value. Therefore, if we substitute Z_m = 9.88 and N = 346 (since we searched 346 frequencies with 1.5 nHz intervals) in Equation (2) we get the false alarm probability F = 0.018. Using the same formula, FAP for the periodograms in Figure 2 is found to be F = 0.032 for a peak of height 9.26 (62-day), and F = 0.044 for a peak height 8.94 (276-day).

[12] Since peaks in a periodogram may arise from aliasing or other phenomena not present in gaussian noise (e.g., spectral leakage arising from the spacing of the data and from the finite length of the time series), the FAP criterion, alone, is insufficient for establishing whether or not a strong peak in a periodogram is indeed a real periodicity in the time series. We test for spurious peaks by recomputing the periodogram after randomizing the data on the time grid. This procedure [*Delache et al.*, 1985] destroys coherent signals in the time series, but preserves the window and noise characteristics. Before randomizing, we have to consider the effect of flare clustering. We first cut the data with intervals varying from 20 to 40 days, then shuffle them to obtain a randomized data set. Then we calculate the power of the randomized data set at the 225 independent frequencies in the 38–558 nHz interval. We repeat these simulations

1000 times. In 46 cases out of 1000 simulations (4.6%) the power at any frequency in the range from 38–558 nHz exceeds the measured power at 116 days. Therefore, the probability of obtaining such a high peak near 116 days at any frequency in the 38–558 nHz range by random chance is as large as 4.6%. The result of this test gives us confidence that the peak near 116 days in Figure 2 arises from coherent signals. Although there is a difference between FAP and randomizing test results, it may arise from the selected randomizing method, which yields insufficient randomizing in some cases.

[13] Classical Fourier transform analysis (FT) allows the study of a signal only in the frequency domain, whereas wavelet transform (WT) analysis yields information in both time and frequency domains [e.g., *Daubechies*, 1990; *Kumar and Foufoula-Georgiou*, 1997]. Therefore, we have also applied wavelet analysis to a time series consisting of daily flare index between 1 October 1996 and 31 December 2000 to study the temporal variation with timescales of intermediate-term periods. The algorithm of the continuous wavelet transform was applied after *Torrence and Compo* [1998] within the period range 16–1000 days using the Morlet mother wavelet. The calculated wavelet power spectrum is suppressed on the edges of the time domain within the cones of incidence due to the applied WT algorithm. The significance levels of the calculated WT power were derived using the null hypothesis according to *Torrence and Compo* [1998] assuming noise distributed independently on periods.

[14] Figure 4 shows the time/period diagram of the WT power spectrum (power in arbitrary units) of *FI* for the whole studied epoch. Results of the WT transform show that only the periods of 35, 116 and 276 days, found by FT, are determined by this method. Additionally the WT algorithm enables to locate occurrence of these periods: 35 days at 1998.3, 1999.9 and finally the most significant at 2000.55 years (with the additional power of period 29 days at 1999.5 years), 116 days within the temporal interval from 1999.7 until 2000.4 years and 276 days period within the interval roughly from 1999.5 until the end of the *FI* data. Moreover the weak power peak at about 150 days, found also by FT, is clearly determined in the WT power spectrum to be present only around 1999.3 years simultaneously with the enhanced power at 35 days. It is of the particular importance that WT does not produce the harmonics of the present signal so both periods are really present in the *FI* at the same time. The two last periods, found by the FT algorithm, 62 and 198 days, can be detected also in the WT power spectrum but only as small anomalies of the power distribution around the more dominant power peaks at 35 days (2000.6 years) and at 276 days (at the same time). The last significant *FI* WT power spectrum peaks are visible at very short periods of only 22 days at 1999.8 years and 26 days at 2000.0 years. Finally it should be emphasized that the WT allows the temporal intervals to be determined even when *FI* does not show any power at particular periods. Therefore, the presented *FI* WT power spectrum could provide more detailed information for comparison with other solar indices.

4. Discussion

[15] Comparison of the monthly mean plots of the similar activity indices with the previous cycle shows that the current cycle rises at a lower level of activity during the ascending phase. However, a weaker 11-year cycle is not completely unexpected [*Komitov and Bonev*, 2001]. This is confirmed by comparison of the major flare events of the two consecutive cycles.

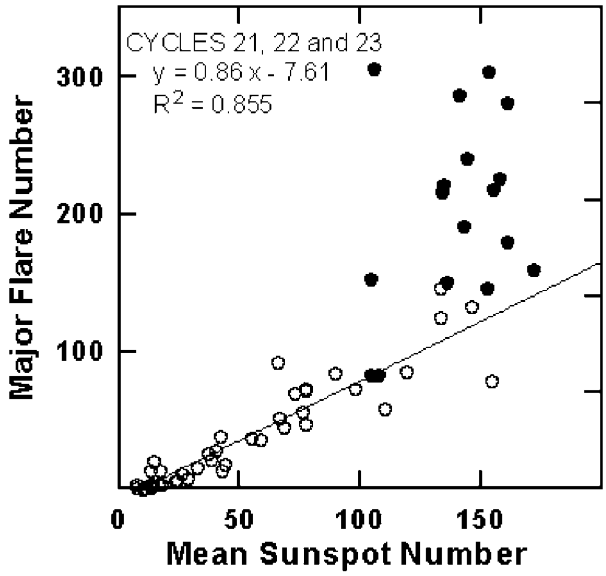

Figure 5. Sunspot number vs. number of major flares (all M and X classes) for the cycles 21 and 22 and ascending part of cycle 23. For time bins of 5-month length, we took the mean sunspot number and the number of major flares. The data points are separated into two groups-filled circles are the data for time intervals when the 154, 77 or 116 day periodicities were in operation; open circles are remainder. The straight line is linear regression line for open circles.

[16] To make a quantitative study of the relation between sunspot number and the major flare number (M and X class), we tabulate the 5 month averages of the relative sunspot number starting from 1976, and the total of the major flare number into 5-month intervals. The result is plotted in Figure 5 for the cycles 21, 22, and 23. Here data points are separated into two groups. The data points for 5-month bins that include the peak phase of the 154-day periodicity for cycle 21 and the data points that include the peak phase of the 77-day periodicity for cycle 22 are selected as a separate group and denoted by filled circles in Figure 5. We repeated this selection by taking 116-day periodicity for the cycle 23 in the same figure. The straight line is linear regression line for the data points denoted by open circles. Most of the filled circles are far above the regression line in Figure 5. Similar calculation was done by *Bai* [1992] by using the major flare number. He concluded that the intermediate term periodicities are caused by an exciter, which mainly enhances flare activity without increasing the sunspot number. Figure 5 confirms this conclusion.

[17] *Hathaway et al.* [1994] suggested that as the cycle progresses, the activity amplitude of the cycle could be better determined at 42 months into the cycle. Therefore, we can conclude from the rising phase of this cycle that the flare production will be lower than the previous one at the rest of the current cycle.

[18] Using the flare index, *Özgüç and Ataç* [1994] showed that the 73-day periodicity was in operation during the ascending branch of cycle 22. Contrary to the previous cycle, during the ascending branch of the current cycle the 116-day periodicity is in operation between mid 1999 and mid 2000. *Lean and Brueckner* [1989] reported this 116-day period in their analysis of 31 years of sunspot blocking function data, which covers the cycles of 19, 20, and 21. Very recently, *Caballero and Valdés-Galicia* [2001] have examined the sunspot numbers, flare index, hard X-ray flux and cosmic ray intensity for the years of 1990–1999. They have reported that the 116-day periodicity is seen only in cosmic ray intensity between 1990–1991. Since 116-day periodicity was in operation between mid 1999 and mid 2000, they could not find this periodicity in the portion of the current cycle, that they studied. There are cases where a periodicity is seen to disappear for a long interval in a cycle and then reappear at the same phase or 180 deg out of phase [*Wolff*, 1992]. The 155-day periodicity is an example; therefore, we may expect the reappearance of this periodicity after the maximum of cycle 23. We know that 11-year solar cycles may contain more than one maximum [*Bazilevskaya et al.*, 2000]. Also *Rybák and Dorotovic* [2002] showed that the green-line coronal index has two maxima in cycles 19, 20, and 21 with the first peak before the main sunspot maximum and the second peak after it.

[19] Two of the five periods with the most prominent peaks in the power spectrum (35 and 62 days) were also detected by *Caballero and Valdés-Galicia* [2001]. They found these two periodicities in sunspot number, hard X-ray flux and cosmic ray intensity for the time interval of 1990 and 1999. *Prabhakaran Nayar et al.* [2001] also found 35-day periodicity from the yearly average values of solar wind, and geomagnetic activity index Ap during 1965–1999.

[20] Although *Antalova* [1999] found a peak near 276 days in the power spectrum of the non-flare full-disk soft X-ray background observations for cycle 21; but according to *Wolff* [1992], the 276-day period matches the alias caused by the 11-year cycle.

[21] *Zieba et al.* [2001] have found the 151 day periodicity by using the solar radio flux, sunspot number and mean magnetic field data during the rising phase of solar cycle 23. This periodicity power peak is very weak in our analysis. Since they cut the data at 31 July 1999, 116 day periodicity also could not be detected by them.

[22] In conclusion, we have found evidence for a 116-day periodicity in the flare index during the ascending branch of cycle 23 and a very weak evidence for the fundamental period reported by *Bai and Sturrock* [1993]. This may arise because of the different characteristics of the current cycle. Comparing with the previous cycles the current cycle shows lower activity at most of the solar indices except proton events. However, the periods of higher activity later in our time period may dominate the results. For the exact conclusion we have to wait until the end of cycle 23.

[23] Understanding the solar influences on global change and space weather is increasingly important as society becomes more reliant on technology. Solar flares and coronal mass ejections are the largest explosions in the solar system which are the primary sources of energetic particles from the Sun. The ability to understand solar variations requires the development of physical models based on observational results.

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