FLARE INDEX OF SOLAR CYCLE 22

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Abstract. A brief description and final results of the flare index (FI) of solar activity are given. The calculation of the daily flare index of cycle 22 was determined using the final grouped solar flare files from National Geophysical Data Center A. The final data of FI are presented in graphical form over cycle 22. Daily calculated values are available for general use in Kandilli Observatory's and NGDC's anonymous ftp servers. The pattern of similar activity indices that arise under different physical conditions during cycle 22 are compared with the flare index. The north – south asymmetry in the daily flare index data was studied.

1. Introduction

Magnetic fields undergo some instability at the base of the convection zone. As the fields extend into the convection zone, they become buoyant and rise and determine the behavior of the outer layers of the Sun, including the corona (Zwaan, 1985; Pecker, 1996). All the observed time-dependent phenomena are called solar activity and are seen in different wavelengths as a changing appearance of the Sun. 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. Attempts have been made to develop theories which would help to explain the physical mechanisms underlying these changes in solar activity. Daily photographs of the Sun in Ca II K, Hα and white light began sometime around or just after 1900. With the improvement of observational techniques, solar physicists started to photograph our closest star, the Sun, with the high-time-resolution Hα images in 1936. The images of the Sun showed that solar flares were 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.

Kleczek (1952) introduced the quantity $FI = it$ to quantify the daily flare activity over 24 hours per day. He assumed that this relationship roughly gave the total energy emitted by the flare and named it 'flare index' (FI). In this relation, i represents the intensity scale of importance and t the duration of the flare in minutes. Catalogues of flare activity using Kleczek's method are given for each day from 1936 to 1986 by Kleczek (1952), Knoška and Letfus (unpublished), Knoška and Petrášek (1984), Ataç (1987) and for 1986 – 1995 by Ataç and Özgüç (this paper).

The flare index is an interesting parameter and is of value as a measure of the short-lived activity on the Sun. Therefore the authors will continue to compile this

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Table I
Values of i used for the determination of FI

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

index in the future. In this paper the results of the determination of the flare index for cycle 22 are presented. Its relation with other solar activity indices is shown in Section 2. Its comparison with the similar solar indices is given in Section 3. North–south asymmetry of the flare index is described in Section 4, and concluding remarks are presented in Section 5.

2. Flare Index of Solar Cycle 22 and Its Relation with Other Solar Activity Indices

The daily flare index of solar cycle 22 was determined using the solar flare files from the National Geophysical Data Center (NGDC). Table I lists values of i used for the determination of FI.

The daily sums of the index for the northern and the southern hemispheres and 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 flux 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 our observatory's and NGDC's anonymous ftp servers

ftp://ftp.koeri.boun.edu.tr/pub/astronomy/flare_index

and

ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_FLARES/INDEX.

They are shown in Figure 1 as daily plots of northern and southern hemispheres and together with daily plots of Stanford Solar Observatory's net magnetic field intensity summed over the solar disk. Such integrated light measurements of the mean solar magnetic field have been made daily since May 1975 (Scherrer *et al.*, 1977). We can see from this figure that the frequency of flares on the Sun increased as the Sun became magnetically more active.

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

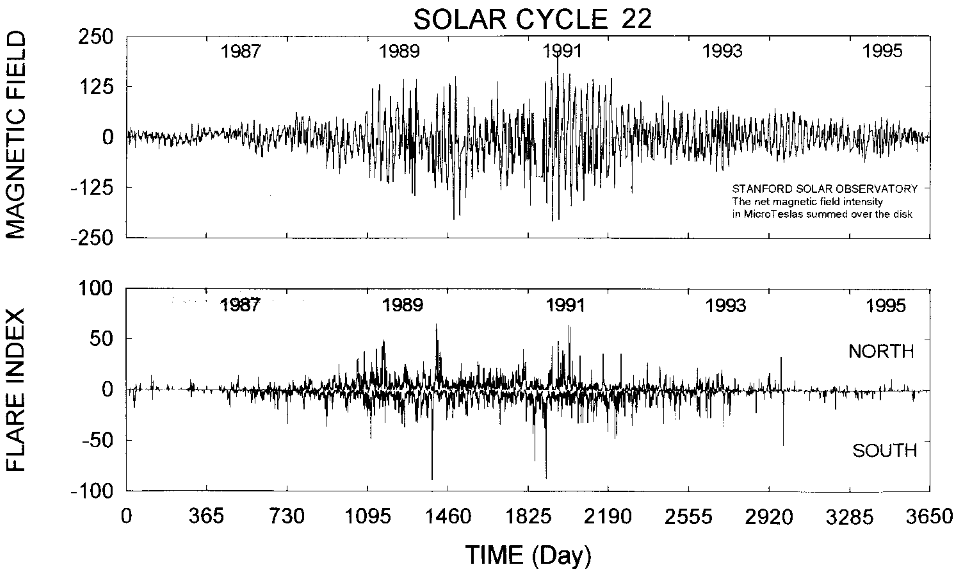

Figure 1. Comparison of daily plots of the northern and southern hemisphere flare index with daily plots of Stanford Solar Observatory's net magnetic field intensity summed over the solar disk.

(1) The relative sunspot number. This is an index of the activity of the entire visible disk of the Sun calculated by the Sunspot Index Data Center (SIDC).

(2) Monthly mean of daily corrected total areas of sunspot groups. These are observed, measured and distributed by the solar group of the Rome Astronomical Observatory.

(3) The monthly mean of total solar irradiance values. This is measured by an Earth Radiation Budget Satellite (ERBS) only on a biweekly basis (Lee *et al.*, 1995). Total solar irradiance describes the radiant energy emitted by the Sun over all wavelengths that falls on 1 m^2 each second outside the Earth's atmosphere. This observed quantity and the 'solar constant' observed earlier in this century are defined in the same way.

(4) Monthly mean of the daily solar radio flux values. These are derived from the daily measurements of the integrated emission from the solar disc at 2800 MHz (10.7 cm wavelength) which have been made by the National Research Council of Canada since 1947. The flux values are expressed in solar flux units (1 s.f.u. $= 10^{-22}$ W m^{-2} Hz^{-1}). The characteristics of the observations are reviewed in 'solar radio emission at 10.7 cm' (Covington, 1969).

(5) The coronal activity index. This is derived by Rybanský *et al.* (1994) from the measurements of the total energy emitted by the Sun's outermost atmospheric layer (the corona) at a wavelength of 530.3 nanometers. It gives the radiant energy emitted by the entire visible corona within the Fe XIV spectral line. Lomnický Štít in the Slovak Republic served as the reference station for calculating the index.

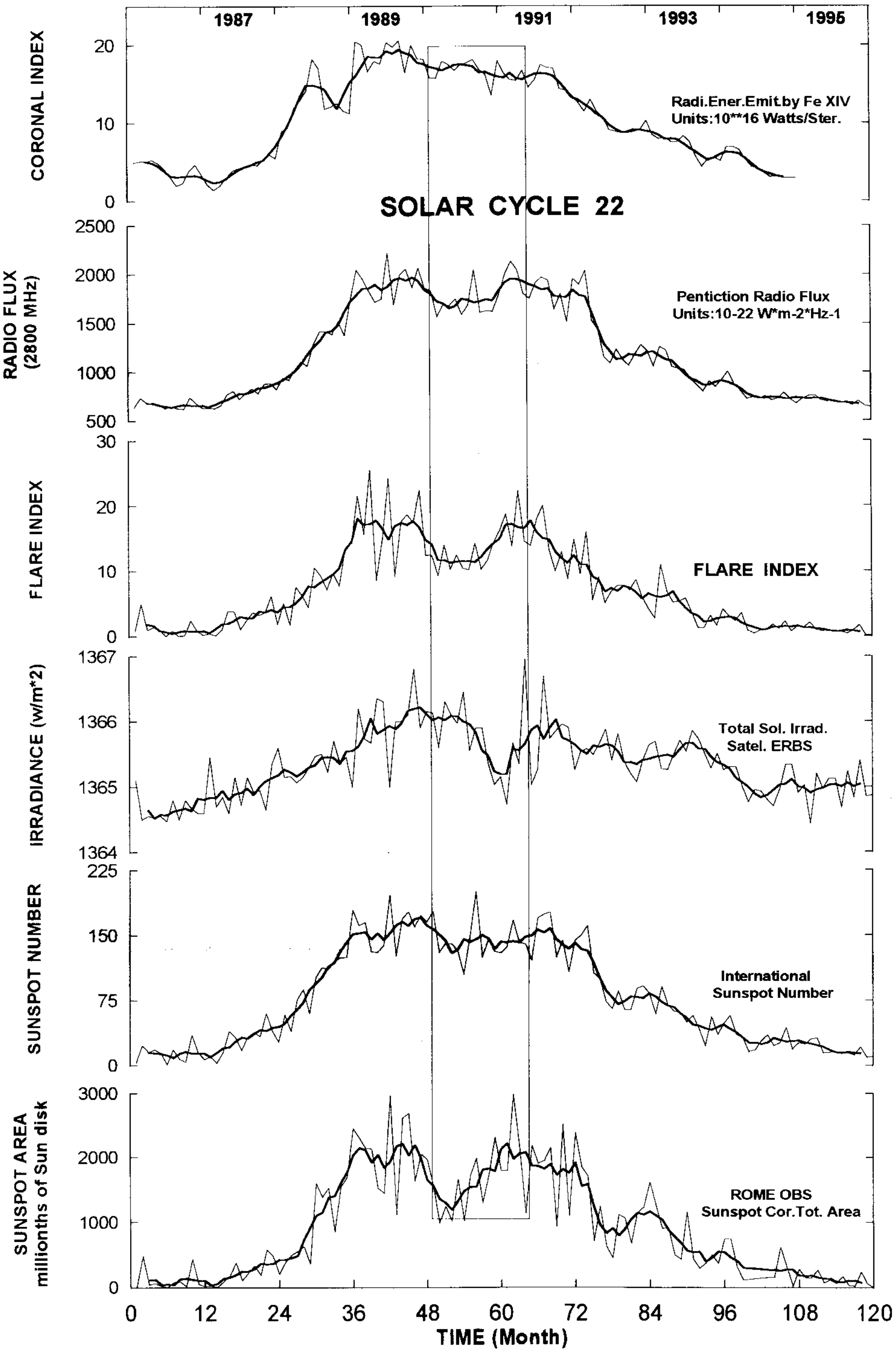

Figure 2. Comparison of the monthly mean plots of similar solar activity indices. Five-month running means are shown as a bold curve.

As can be seen from Figure 2, FI is one of the best indicators of activity variations in the chromosphere. It is of value as a measure of the short-lived (minutes to hours) activity on the Sun. This feature makes the flare index a suitable full-disk solar index for comparison with similar solar indices which reflect different physical conditions from the different layers of the solar atmosphere. The comparison of FI with these similar indices should indicate how well they correlate, and this will be useful to model the temporal variations of solar activity.

3. Comparison of Similar Solar Indices

Figure 2 shows the monthly means of the observed values of some indices during cycle 22. The peaks in the monthly means of the coronal index (CI), radio flux (F_{10}) and flare index (FI) are seen early in 1989; the irradiance peak (I_r) early in 1991, and the peak of sunspot number (R) in mid-1990. The sunspot area (A_s) has two peaks; the first one is early in 1989 and second one is early in 1991. In the same figure, 5-month running means are shown as a bold curve. Monthly mean observed values of all full-disk indices except CI showed a second maximum in 1991. They also showed several maxima, each lasting for a few months (Figure 2). However power spectral analysis of the time series of the daily FI reveals short-term (73 and 53 day) periodicities for this cycle (Özgüç and Ataç, 1994). The deep valley seen in the FI curve began late 1989. All of these curves have valleys which show slight deviations only in the starting time. In the CI curve the valley that begins in late 1988 is much more remarkable than the 1990 valley.

The year 1990 was found to be an unusual year in terms of sudden decreases in activity. To see more clearly what happened in 1990 the daily observed values are plotted for all indices in Figure 3. The sign of the slope of the linear fit to each curve is positive for FI, F_{10}, and A_s, but it is negative for I_r, CI, and R. It can easily be seen from Figure 3 that I_r values decrease in contrast to the increase of observed A_s values. The variability in the total solar irradiance is a known fact (Willson and Hudson, 1988). As pointed out by the authors, it results from the disk passage and presence of sunspots, faculae, and the enhanced or active network (Willson, 1981; Nishikawa, 1990; Steinegger, Brandt, and Haupt, 1996, and references therein). Over periods of weeks to years, the brighter faculae have a slightly larger effect than the darker, short-lived sunspots. Models of the facular and sunspot contributions to total irradiance agree quite well with the observations (Steinegger, Brandt, and Haupt, 1996).

Some other aspects of Figure 3 caught our attention. During 1990 the areas of the sunspots increased, but the relative numbers of the sunspots decreased. In addition to this, the flare production rate increased continuously until the end of 1990 and in 1991 it reached the same activity level as 1989, the year when the sunspot numbers reached their maximum numbers during cycle 22 (Figure 2). This event was seen in the earlier cycles (Zirin, 1988). According to Harvey and Zwaan

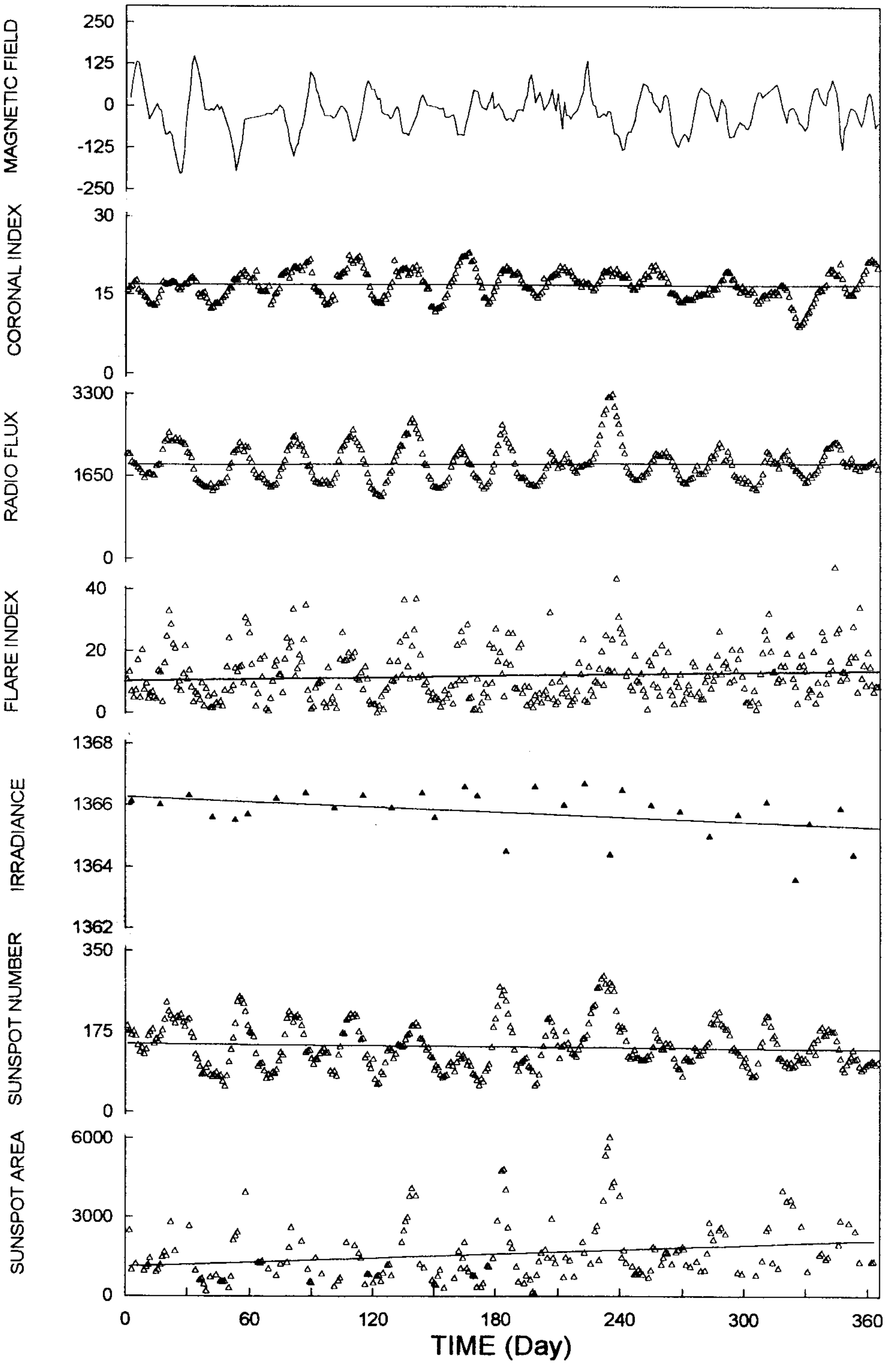

Figure 3. Comparison of the daily plots of similar solar activity indices during 1990.

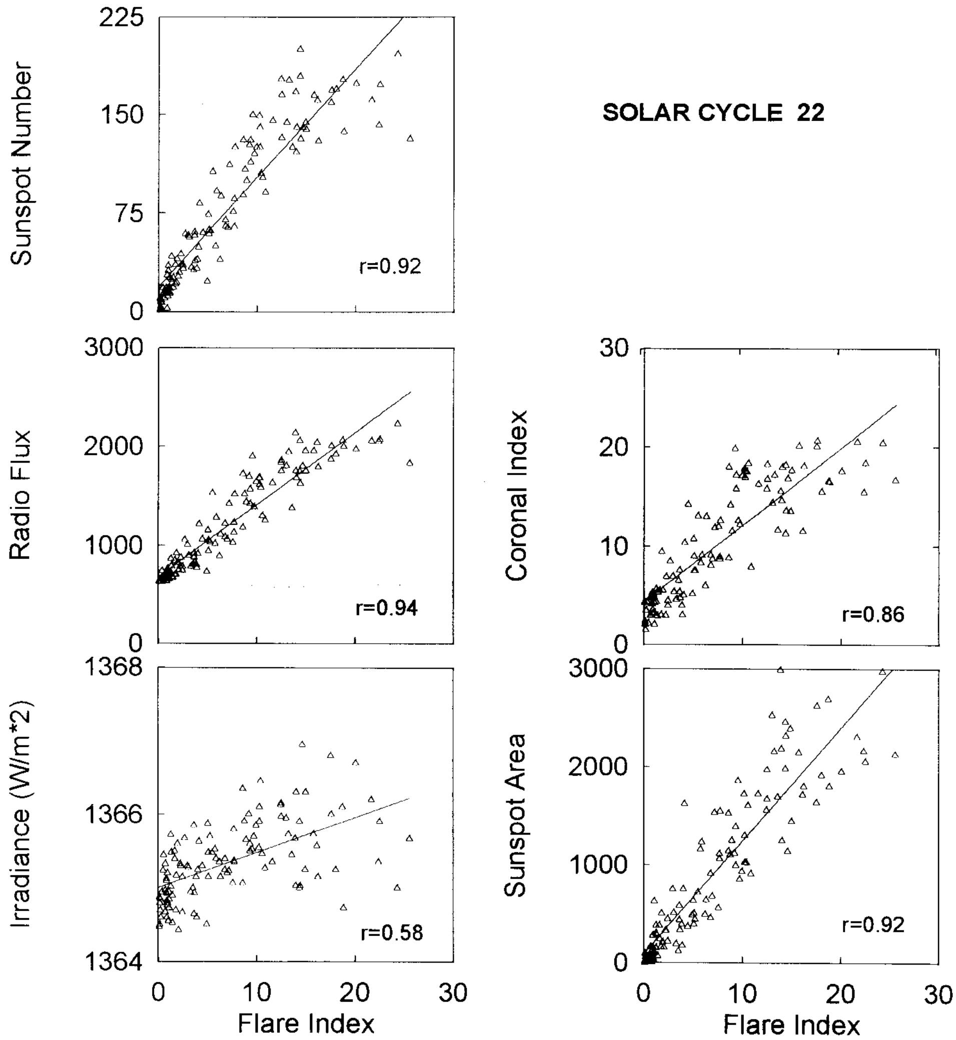

Figure 4. Correlation plots of the monthly mean of the similar full-disk solar indices with the flare index; r indicates the correlation coefficient.

(1993), the shape of the size distribution of active regions does not vary over the cycle. The statistical result of the past solar cycles has shown that most of the largest sunspots and flares occurred several years before or after the 'sunspot maximum'. Sunspot maximum is based on a 13-month running mean of mean monthly sunspot number and where the 1st and 13th month enter the mean at half value.

Finally, Figure 4 shows the correlation plots of the similar full-disk solar indices with the flare index for monthly means over the whole cycle. Good correlation is found between FI and F_{10}, R, CI, A_s, but a poor correlation exists between FI and I_r.

4. North–South Asymmetry of the Flare Index during Solar Cycle 22

It has been known for a long time that the occurrence of different features on the northern and southern part of the solar disk is not uniform, and that more features occur in one or the other part of the disk in different time intervals. This phenomenon is called the north–south (N–S) asymmetry. Many authors have used different features of solar activity to study N–S asymmetry: major flares (Roy, 1977; Verma, 1987, 1993); X-ray flares (Garcia, 1990); flare index (Knoška, 1985; Ataç and Özgüç, 1996); sunspot number and sunspot areas (Swinson, Kyoma, and Saito, 1986; Carbonell, Oliver, and Ballester, 1993; Oliver and Ballester, 1994, 1996; Watari, 1996); sudden disappearances of solar prominences (Vizoso and Ballester, 1990; Joshi, 1995); sunspot groups and solar flares numbers (Yadav and Badruddin, 1980; Verma, 1993; Joshi, 1995). Joshi (1995) has shown the existence of a constant and persistent N-S asymmetry of sunspot groups, Hα flares and active prominences during the maximum phase (1989–1991) of this cycle and confirmed that this asymmetry is real and not due to random fluctuations, following the method of Letfus (1960).

The north–south asymmetry for the flare index (AFI) is defined as

$$AFI = (N - S)/(N + S) ,$$

where N and S stand for the daily north and south flare-index values, respectively. To show the statistical significance of the asymmetry series, a sign test introduced by Gleissberg (1947) was performed. According to this test, the probability, p, that the variations in a time series are due to chance can be calculated from

$$p = 1 - \text{erf}(x) ,$$

where 'erf' denotes the error function. If $p \simeq 1$, then we can say that variations in the time series are due to chance; alternatively, if $p \ll 1$, the asymmetry time series can be considered significant. The method of calculating erf(x) is given by Balli (1955). Following Balli, we have determined that $p \ll 1$, which shows that the distribution of the asymmetry index is highly significant during solar cycle 22, suggesting that it is a real feature of solar activity in this cycle.

Plots of AFI for cycle 22 are given in Figure 5 where the first curve (a) represents the yearly mean observed values. From this curve the dominance of the activity for the southern hemisphere throughout the whole cycle can easily be seen. The flow of flare activity from one hemisphere to the other is easily seen in the second curve (b) which shows 13-day running means of the daily AFI values for the whole cycle. From the second curve (b) it is clear that the activity began in 1986 in the northern hemisphere and drifted to the southern hemisphere, then swept from the southern hemisphere again to the northern hemisphere during 1987. From 1988 to 1993, the flare activity showed drift behavior in an alternating way between the two hemispheres every two years. Starting with 1994, the same behavior was

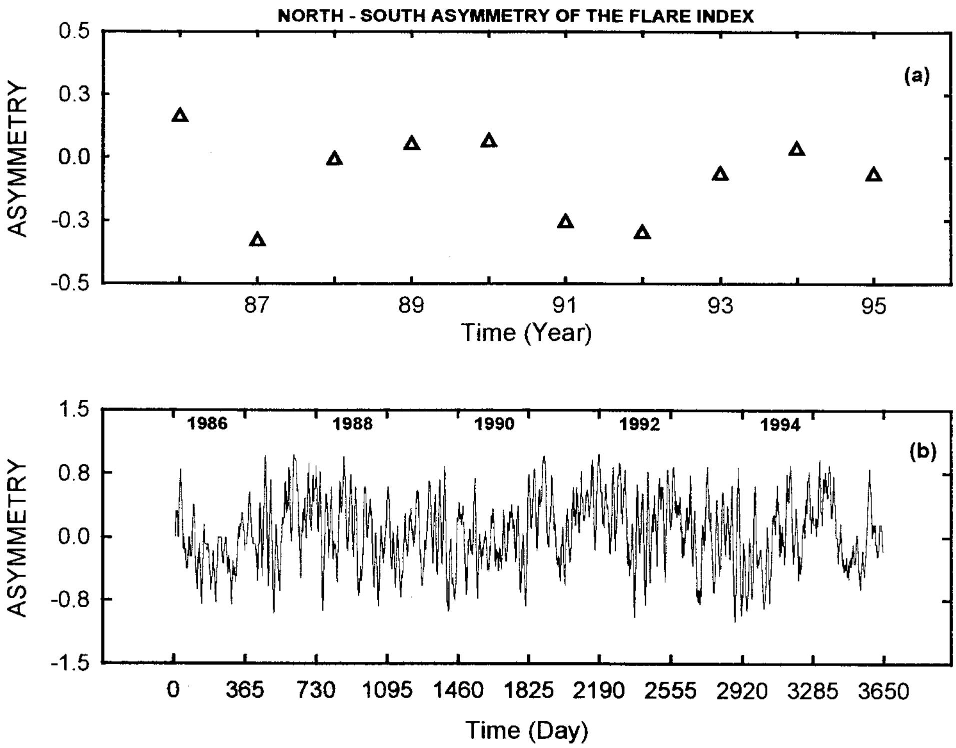

Figure 5. Plots of the north–south asymmetry of the flare index for the whole cycle 22. (a) shows yearly mean of AFI and (b) shows the 13-day running means of AFI.

observed in the flare activity except that this was every year instead of being every two years.

5. Conclusions

From our study FI appears to be a good index to study the activity variations in the chromosphere. In addition to this, FI as a full-disk solar index could be easily compared with similar indices that arise under different physical conditions. In this connection FI shows good correlation with indices of magnetic changes, area and number of sunspots in the photosphere, as well as the changes in the corona. However, FI is not in good agreement with I_r values.

We can conclude from the results of the comparisons:

(a) I_r showed an increase while FI showed a decrease in the beginning of 1990. This behavior continued until mid 1990 and then towards the end of the year, FI started to increase whereas I_r decreased. The total solar irradiance did not necessarily increase at times of higher flare production. Higher flare production is a result of magnetically complex great sunspot areas which are also responsible for short-term decreases in the total solar irradiance. This is clearly seen in cycle 22.

(b) Monthly mean observed values of all full-disk indices except CI showed a second maximum in 1991. They also showed several maxima, each lasting for a few months (Figure 2).

(c) The flare activity showed a drift behavior between the two hemispheres every two years from 1988 to 1993. Garcia (1990) found that large flares occurred in the north during the early part of the cycle and then moved south as the cycle progressed. He also concluded that flare occurrence is related to a weak global magnetic variation by considering the association of active zones with large-scale magnetic structure, and the association of flare N–S asymmetry with the coronal green line. His conclusion is verified by the close agreement of the daily net magnetic field intensity with the daily north–south FI values during cycle 22 (Figure 1).

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