DOI: 10.31401/WS.2021.proc.15

Temporal Variation of Solar Flare Index for the Last Solar Cycle (Cycle 24)

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Abstract: In this study we compared selected some monthly and yearly mean solar activity indices with hemispheric and total Hidrogen-alpha Flare Index (FI) during the last solar cycle (Cycle 24). First we plot the temporal variations of 11 step running average smoothed data sets. Then the cross correlation analyses were performed between FI and other solar indices. Finally, we performed hysteresis analysis by using the yearly mean data sets. We found following results; 1) In general FI data sets show higher correlations with F10.7 compared to other parameters. 2) Total FI shows higher correlation with all other parameters compared to the hemispheric FI data. 3) All data sets show some amount of time delay with FI data sets except F10.7 which does not show any time delay. 4) Hysteresis behavior generally appears during the ascending and descending phases of the cycle.

Introduction

Solar activity variations display themselves in electromagnetic radiation from radio frequencies of a few kHz to powerful gamma rays and also in particle flux. 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 as coronal mass ejections (CMEs). The long-term evolution of solar activity, on time scales of the solar cycle and beyond, has been studied from different perspectives using a variety of short and long-term solar activity indicators (Barbieri, and Mahmot, 2004; Knaack, Stenflo, et al, 2005). Kleczek (1952) introduced the quantity $Q = i\ t$ 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. Calculated values are available for general use in our observatory website (https://astronomi.boun.edu.tr/flare-index). Some reviews of flare activity using the flare index are given for each day from 1936 to 2001 by Kleczek [1952], Knoska and Petrasek [1984], and Ataç and Özgüç [1998, 2001]. In this paper the results of the determination of the flare index during the solar cycle 24 are presented. Its relation with other solar activity indices is described. Comparison with the similar solar indices of the flare index is examined.

Data and Methods

We compared the amplitudes of cycle 24 by using similar activity indices which are produced at different layers in the solar atmosphere and by different processes. Each of them reflects different physical conditions in the solar atmosphere. The indices to be selected are as follows:

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

(2) 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 (https://wwwbis.sidc.be/silso/datafiles)

(3) Composite record of the Sun's total irradiance (IR) is compiled from measurements made by five independent space-based radiometers since 1978. We used EMPIRE daily reconstruction data set. (*http://www2.mps.mpg.de/projects/sun-climate/data.html /*).

(4) Coronal index (CI) introduced by Rybansky (1975) represents the total irradiance of the green corona emitted from the Sun's visible hemisphere (http://www.suh.sk/online-data).

(5) The Mg II index was first proposed by Heath and Schlesinger (1986). According to Cebula and DeLand (1998), the Mg II index is defined as the ratio between the core emission and the solar continuum intensity in the wings. This index is a dimensionless quantity measuring mid-UV solar activity. We used GOME-2A Mg II Index version. http://www.iup.uni-bremen.de/UVSAT/datasets/mgii

(6) solar radio flux (F10.7) is derived from the daily measurements of the integrated emission from the solar disc at 10.7 cm wavelength, which have been made by the National Research Council (NRC) of Canada since 1947. The flux values are expressed in solar flux units (1 s.f.u.=10^{-22} $Wm^{-2}Hz^{-1}$) and originate in the chromosphere and corona. (http://www2.mps.mpg.de/projects/sun-climate/data.html)

Analysis and Results

To investigate the possible relationship between hemispheric/total solar FI and other data sets used in this study the temporal variation, the cross correlation and the hysteresis analysis were performed. In Figure 1 we presented the temporal variation plots of all data sets used in this study for the whole Solar Cycle 24 (from 2009 to 2020). To remove the short term fluctuation and reveal the long term variations an 11 step running average smoothing method were applied. From this figure we obtained the following results; 1) North and south hemisphere FI data show different temporal behavior that the north hemisphere FI data access to its maximum around 2012 while the south hemisphere data reach its maximum around 2015 like all other solar indices used in this study. 2) All data sets used in this study have a double peak structure that this structure was not so remarkable in south hemisphere FI, CI and TSI data sets. 3) The second peaks dominated in all data sets except north hemisphere FI data.

The cross-correlation analyses have been performed between hemispheric/total FI and the other studied parameters in order to find the highest correlation with delay times. The cross-correlation function is derived up to a time lag of ±48 months, with a step of one month. Calculated correlation coefficients between the FI and other solar activity indicators (CI, F10.7, RSN, Mg II, TSI, and MMF) are shown in Figure 2, and calculated correlation coefficients for the most probable time lags and their Fisher's test errors at a 95 % significance level are presented in Table 1.

From Figure 2 and Table 1 we access the following results: i) North and South hemisphere FI data sets show the same amount of correlations with all other data sets used in this study, ii) the highest correlations exist between total FI and other parameters in all cases without any exception, iii) all data sets show their maximum correlation with FI data sets by some amount

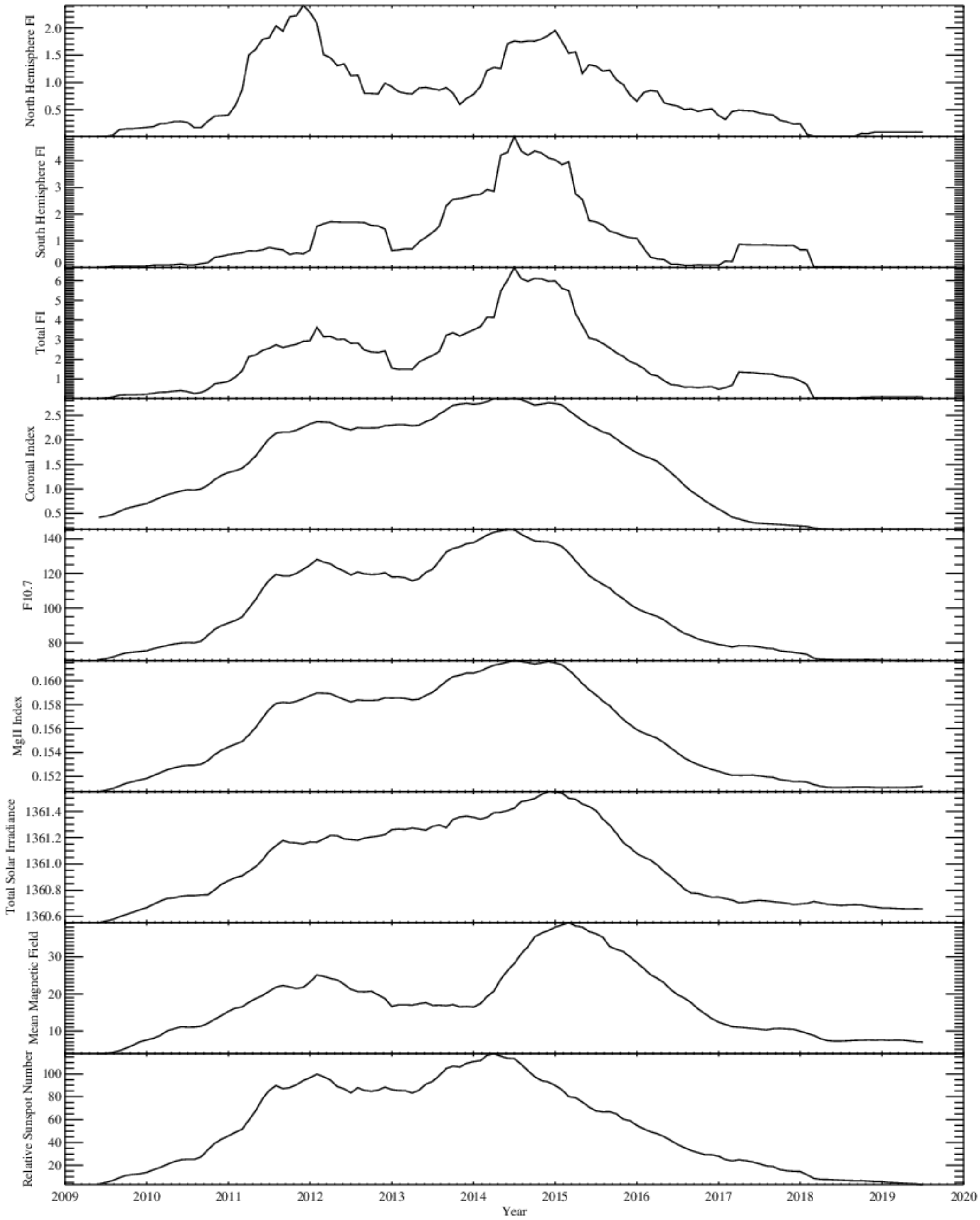

Figure 1. The temporal variation of all data sets used in this study during the Solar Cycle 24 (2009-2020).

of time delay except F10.7 data. It has the highest correlation coefficient and zero time delay in all cases.

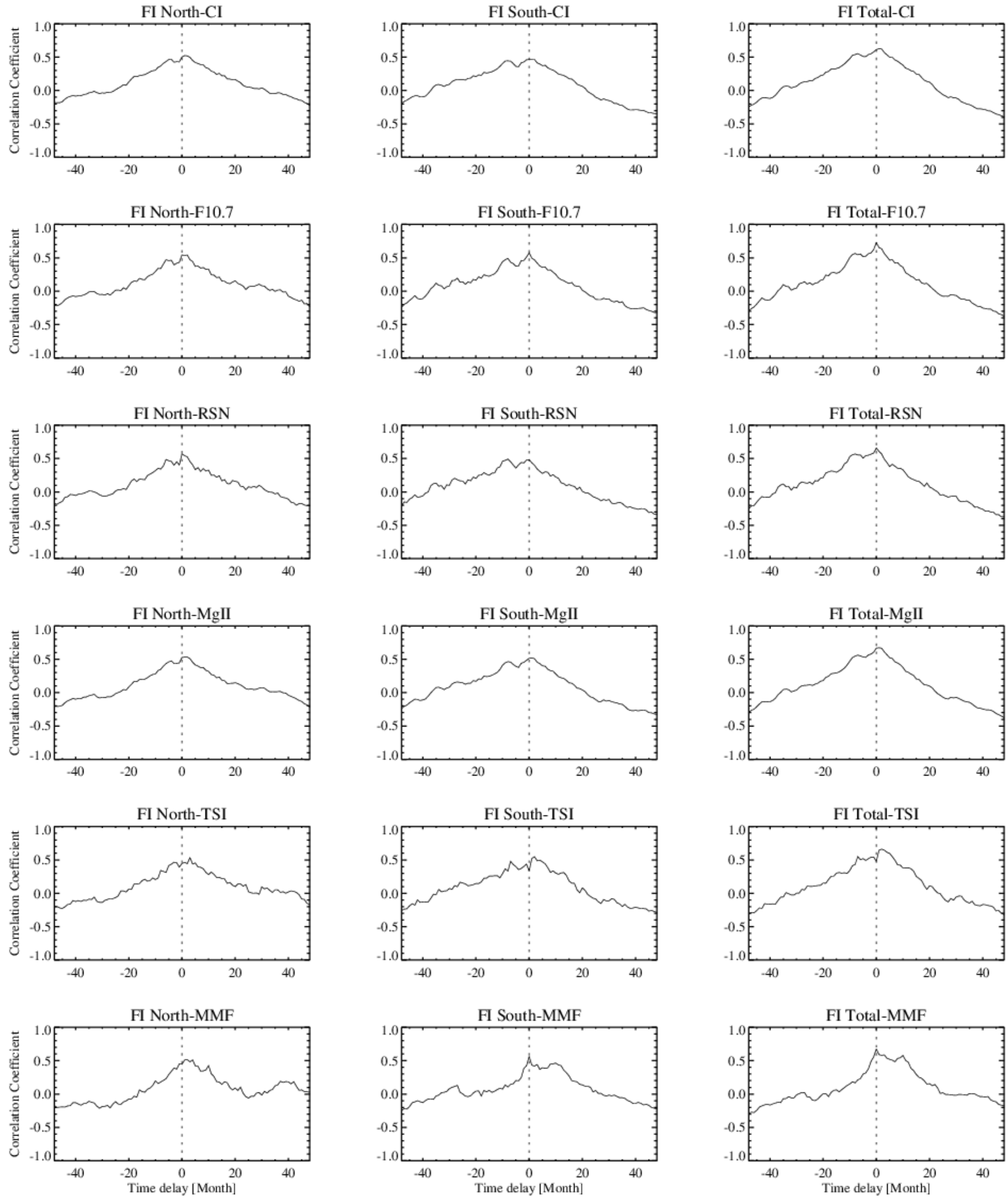

Figure 2. Cross correlation analysis results of hemispheric/total FI data and other solar activity indices used in this study.

Figure 3 shows a clear example of anticlockwise (e.g. the descending path follows an upper track) hysteresis between FI and two indices (MMF and TSI), during solar cycle 24. The hysteresis pattern is not the same for all the indicators, but with some difference in the widths: MMF, RSN and TSI depict broad loops, while the others depict narrow hysteresis loops.

Other Properties of Solar Cycle 24

One of the interesting features of this cycle is the clear appearance of the double maximum. Two peaks are seen during the maximum phase separated by 1–2 years from Figure 1, which shows the time plot of the 11-month moving average of all activity indices. However, most other authors believe that it is better using 13-month moving average for cyclic behavior studies. Because of the limited time interval which we studied, 13-month moving average

Table 1. Cross correlation analysis results for the hemispheric/total FI and other solar activity indices used in this study.

	FI North	Time Delay [Month]	FI South	Time Delay [Month]	FI Total	Time Delay [Month]
Coronal Index (CI)	0.52±0.14	1	0.47±0.15	1	0.63±0.12	1
10.7 cm solar radio flux (F10.7)	0.54±0.13	0	0.58±0.13	0	0.73±0.10	0
Relative sunspot number (RSN)	0.57±0.13	0	0.49±0.15	8	0.66±0.11	0
Magnesium II index (MgII)	0.53±0.14	2	0.52±0.14	1	0.67±0.11	1
Total solar irradiance (TSI)	0.54±0.13	3	0.55±0.13	2	0.66±0.11	2
Mean magnetic field (MMF)	0.52±0.14	2	0.56±0.13	0	0.68±0.11	0

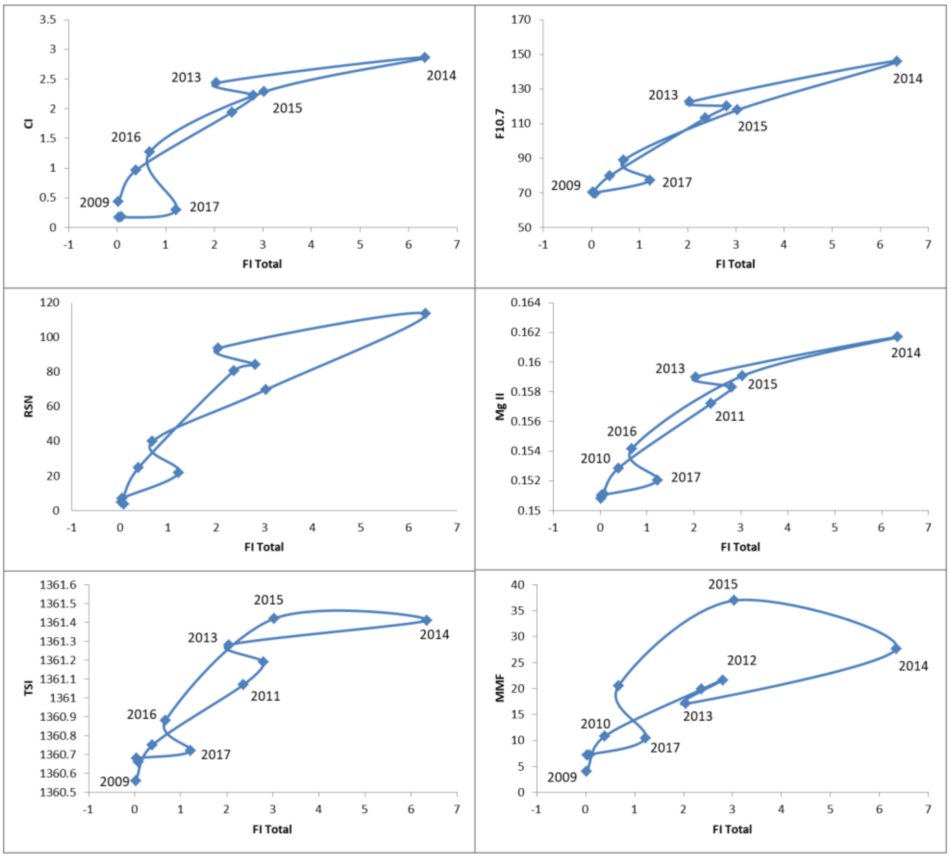

Figure 3. Hysteresis behavior of total FI and other parameters used in this study.

procedure can cause to disappear some properties of activity variations. The existence of a complex structure of the maximum phase of the 11-year solar cycle was recognized in 1960s by Gnevyshev (1963, 1967). He suggested that 'the 11-year cycle does not contain one but two waves of activity with different physical properties'. Thus, it was decided to call this time interval of the solar activity maximum phase in which the dip or valley periods were seen as Gnevyshev gap (GG) after the Russian astronomer who initiated this concept (Storini et al., 2003). Until 2011 there has been no clear understanding of the GG's nature. Kilcik et al (2011) and Kilcik and Ozguc (2014) brought a clear description about this nature; they analyzed sunspot groups in two categories as large (D, E and F) and small (A, B, C, and H) classes and found that the large classes sunspot groups reach to their maximum about two years later than the small ones. They suggest that two different dynamo mechanisms responsible from this behavior and as a result of these different dynamo processes the double-peaked structures appear during the solar maximum.

North–South Asymmetry of the Flare Index during Solar Cycle 24

It has been known for a long time that the occurrence of different features on the northern and southern hemispheres 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. As shown in Figure 1 the temporal variation of the solar FI for the north and south hemispheres show remarkable differences. This different behavior is also seen in the results of correlation analysis that different hemispheric FI data show different amount of correlation and delay with other solar activity indicators.

Discussion

We have studied the final results of the FI and some other indices of the solar activity for cycle 24 from January 1, 2009 to December 31, 2020. We examined in the FI data the N–S asymmetry and the relations with other activity indices. The solar cycle 24 with its weak magnetic activity throughout its progression merits all this detailed studies which was done with different indices. Recent research of the long-term solar variability shows that our epoch is at the onset of an upcoming minimum of the 100-year Gleissberg cycle (Bonev et al., 2004). So, it can be expected that the ongoing cycle may be magnetically weaker than the solar cycle 24.

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