DOI: 10.31401/WS.2023.proc.14

Proceedings of
the Fifteenth Workshop "Solar Influences on the Magnetosphere, Ionosphere and Atmosphere"
June, 2023

Temporal Offsets between Solar Flare Index and Cosmic, Geomagnetic, and Interplanetary Indicators during Solar Cycle 24

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Abstract

We analyzed modulation of cosmic-ray intensities (CRIs) during Solar Cycles 24 by using the solar flare index (FI), interplanetary magnetic field strength, and the geomagnetic Ap and Dst indices. Temporal variations, cross-correlations, and hysteresis patterns of CRI, FI, scalar B, Ap and Dst data were investigated. As a result, we concluded that the FI better describes solar modulation of the CRI as compared to the other solar indicators. We also analyzed the temporal offsets between the flare index and the above-mentioned cosmic, geomagnetic, and interplanetary indices. It is found that this solar activity index, analyzed jointly with cosmic, interplanetary parameters, and geomagnetic activity indices, shows a hysteresis phenomenon. It is observed that these parameters follow different paths for the ascending and descending phases of Cycle 24. The hysteresis phenomenon represents a clue in the search for physical processes responsible for linking the solar activity to near-Earth and geomagnetic responses.

Keywords: solar flare index; geomagnetic activity; temporal variation

Introduction

The sun is not a-quiet star, and the amount of its energy emits variously over time. Changes observed in the sun can be revealed using many indices called solar activity indicators. The majority of these indices are based on the observation of active events such as sunspots, solar flares, coronal mass ejections, etc. All solar activity indices show cyclic variation from days to hundreds of years and they are strongly related to each other (Hathaway, et al. 2002; Özgüç et al. 2022; and reference therein). Active events in the sun such as solar flares, coronal mass ejections, and solar winds are closely related to changes in the geomagnetic field. Observed changes in geomagnetic activity can also be measured using various indices of geomagnetic activity such as Ap, Dst, aa, AE, etc. and all these indices are also closely related to each other (Verbanac et al. 2011; Sarp and Kilcik, 2018; and reference therein).

Statistical properties of solar activity and their relations with the geomagnetic indices has been investigating for a long time (e.g., Obridko and Shelting, 2009; Kirov et al., 2013; and reference therein). Trends in geomagnetic indices were reported by many authors in the literature (Demetrescu and Dobrica, 2008; and reference threein).

The hysteresis behavior can be described as a manifestation of unclear relationships between two different parameters. Since hysteresis plots provide useful information about the phase switches of non-stationary variables, hysteresis analysis has a wide range of applications in many disciplines like Astronomy, Physics, Engineering, etc.

Here we analyzed modulation of cosmic-ray intensities (CRIs), solar flare index (FI), interplanetary magnetic field strength, and the geomagnetic Ap and Dst indices for solar cycle 24. Temporal variations, cross-correlations, and hysteresis patterns of CRI, FI, scalar B, Ap and Dst data were investigated. Data and Methods are presented in Section 2, the Results in Section 3, and the Conclusion and Discussion in Section 4.

Data and Methods

In this study we focused on the temporal and periodic variation of solar and geomagnetic activity indices during Solar Cycle 24 and the data covers January 2009 - December 2020 (complete solar cycle 24) time interval. We used hemispheric and total flare index (FI), which is a rough measure of the total energy emitted by a flare as solar data which is taken from Boğaziçi University Kandilli Observatory web page (https://astronomi.boun.edu.tr/flare-index). Cosmic-ray Intensities (CRI), Ap index, Dst index and the interplanetary magnetic field (IMF)/Scalar B as geomagnetic activity indices used in this study are taken from Oulu/Finland neutron monitor station (https://cosmicrays.oulu.fi/#solar), while Ap, Dst and IMF data sets are downloaded from https://omniweb.gsfc.nasa.gov.

To investigate the possible relationship between above mentioned data sets first we plotted the time variation of them. To remove the short term fluctuations all monthly mean data sets were smoothed with 11 step running average smoothing method. Then to show the hysteresis effects occurred between the CRI, solar FI, Dst index, IMF/Scalar B, and Ap index during solar cycle 24 the hysteresis analysis were performed. To measure the degree of relationship between investigated parameters the cross correlation analysis were performed. This method gives the maximum correlation between two data sets together with possible time delay between the data sets. If the delay is negative that means the first parameter leads the second one and vice versa. The error levels of obtained correlation coefficients were calculated by using Fisher's test that gives the upper and lower boundary of the correlation coefficient with 95 % confidence level.

Results

The temporal variation profiles of the 11 step smoothed data sets are presented in Figure 1.

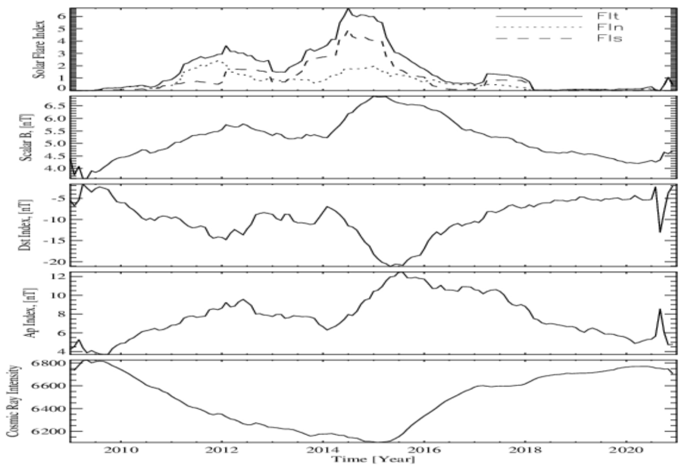

Figure 1. The temporal variations of investigated time series. In the upper panel of the figure, Fit is total FI, Fin is FI in the north hemisphere, and Fis is the FI in the south hemisphere of the sun.

Upper panel of this figure shows hemispheric and total FI temporal variation. In this plot, North and South hemisphere FI show different behavior; the highest peak of North hemisphere FI is around 2012, while South hemisphere FI peaked around the middle of the year 2014. In general the South hemisphere FI was dominant during the investigated cycle (Cycle 24). The temporal variations of all data sets show clear double/multiple peak structures except CRI data set. In general, both peaks of the solar FI data set occur slightly earlier than the other data sets.

To describe the hysteresis pattern of used data sets we first calculated the yearly mean values. As a first step cosmic ray intensity was chosen to be the abscissa of the plots with the equal scale in this figure to display the effects of hysteresis most clearly (see Figure 2).

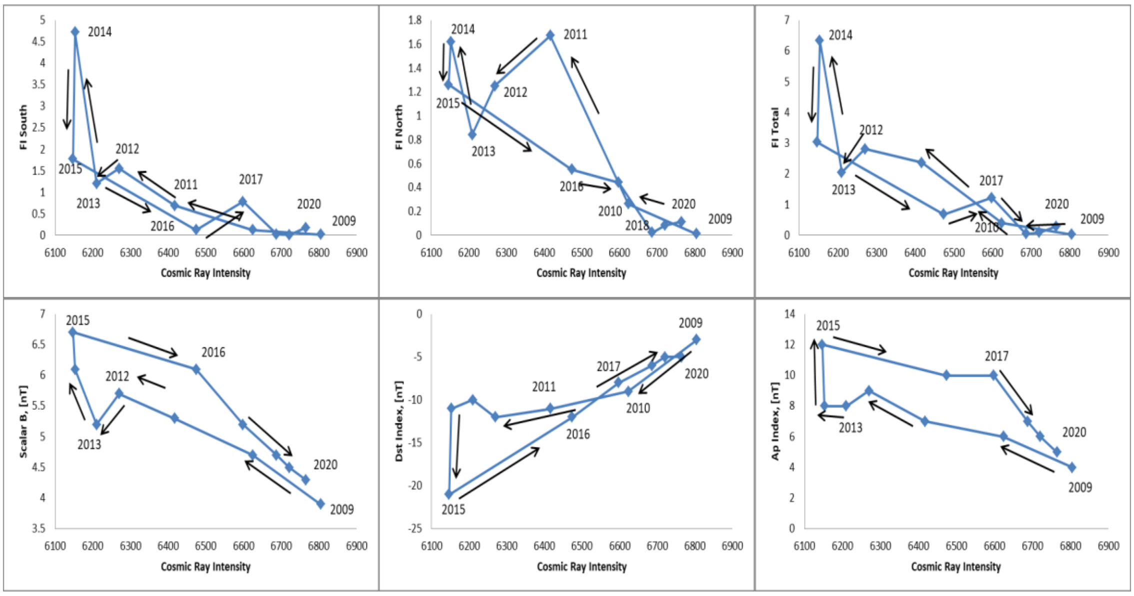

Figure 2. Hysteresis plot of CRI versus other data sets.

From these plots we obtained following results; i) FI data shows hysteresis behavior in all phases of the cycle, while geomagnetic activity indices show hysteresis only around the maximum phase of the cycle 24, ii) all FI and Dst data show counter clockwise circulation, while the Ap Index and Scalar B show clockwise circulation which is not a normal characteristic of hysteresis in magnetic materials.

As a second step of hysteresis analysis total FI was chosen to be the abscissa of the plots with the equal scale (see Figure 3).

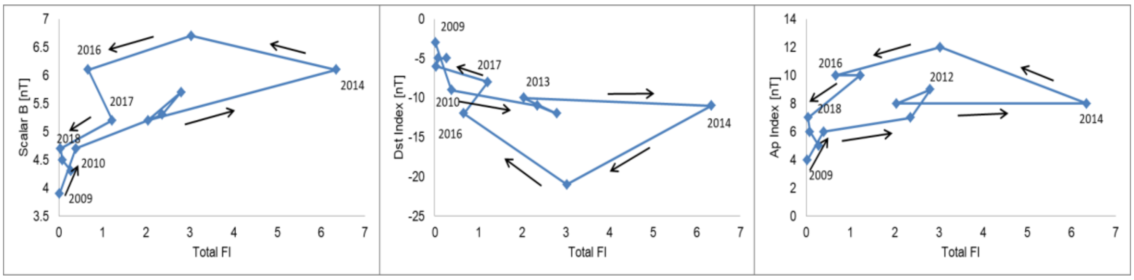

Figure 3. Hysteresis analysis of total FI and other data sets used in this study except CRI.

From these plots we obtained following two results; 1) FI data and Dst data show clockwise circulation while the Ap Index and Scalar B show counter clockwise circulation. 2) The hysteresis behavior generally exists in the maximum and the descending phases of the cycle for all data sets.

The cross correlation analysis results between CR intensity and other parameters are shown in Figure 4 and the list of correlation coefficients are given in Table 1

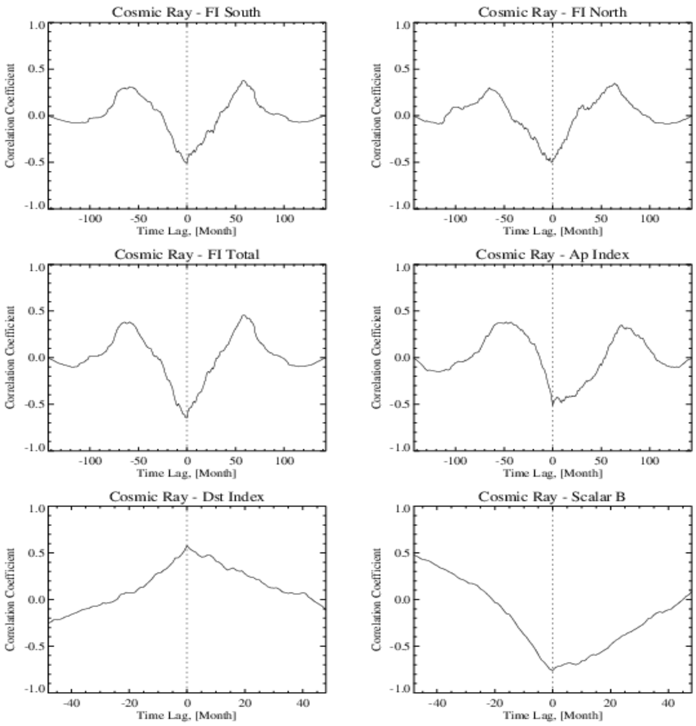

Figure 4. Cross correlation analysis between CR intensity and other parameters

Table 1. list of cross correlation analysis results between CR intensity and other parameters

Data	Correlation Coefficient	Time Lag
CIR-FI South	-0.51 ± 0.11	0.00
CIR-FI North	-0.50 ± 0.12	-1.00
CIR-FI Total	-0.65 ± 0.10	0.00
CIR-Ap Index	-0.51 ± 0.11	0.00
CIR-Dst Index	0.58 ± 0.11	0.00
CIR-Scalar B	-0.76 ± 0.08	0.00

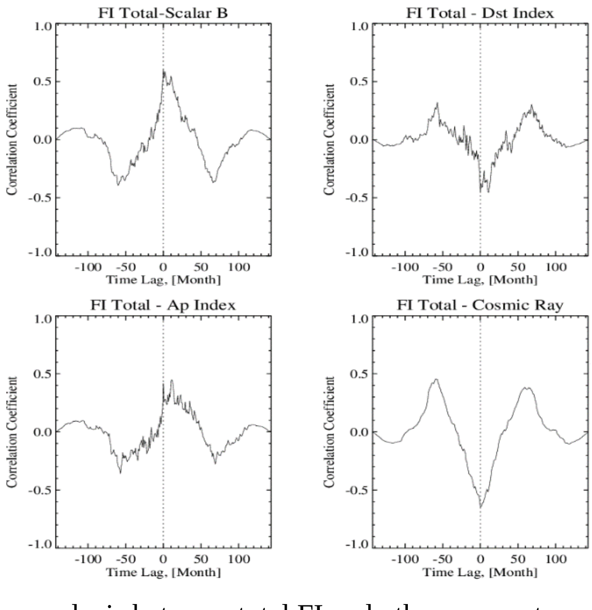

Figure 5. Cross correlation analysis between total FI and other parameters

Table 2. List of cross correlation analysis results between total FI and other parameters

Data	Correlation Coefficient	Time Lag
FI Total-Scalar B	0.60 ± 0.1	0.00
FI Total- Dst Index	-0.46 ± 0.13	0.00
FI Total- Ap Index	0.45 ± 0.13	11.00
FI Total- Cosmic Ray	-0.65 ± 0.10	0.00

Conclusions and Discussions

The hysteresis phenomenon between a pair of indices, which is due to a temporal offset between their variations, can be used as a diagnostic tool to better understand the chain of phenomena linking various manifestations of solar activity, interplanetary medium, the Earth's magnetic field and CRI. In the present study we have compared CRI, with solar activity parameter FI and some geomagnetic activity parameters (IMF/Scalar B, Ap and Dst indices). We found following results;

- Except North hemisphere FI data, all smoothed monthly data sets reach to their maxima at around of the second peak of solar cycle 24.
- South hemisphere FI was dominant during the Solar Cycle 24
- The temporal variations of all data sets show clear double/multiple peak structures except CRI data set.
- In general, both peaks of the solar FI data set occur slightly earlier than the other data sets.
- In the comparison of CRI, FI data shows hysteresis behavior in all phases of the cycle, while geomagnetic activity indices show hysteresis only around the maximum phase of the Solar Cycle 24. Also, all FI and Dst data sets show counter clockwise circulation while the Ap Index and Scalar B show clockwise circulation which is not a normal characteristic of hysteresis in magnetic materials.
- In the comparison of FI, the Dst data shows clockwise circulation while the Ap Index and Scalar B show counter clockwise circulation. Also, the hysteresis behavior generally exists in the maximum and in the descending phases of the cycle for all data sets.
- All data sets used here show meaningful correlation with both CIR and total FI data sets.
- The only Ap index data shows remarkable time lag (11 month) that the Ap index follows the total FI.

Verbanac et al. (2011) analyzed some yearly solar (sunspot number and 10.7 cm solar radio flux) and geomagnetic activity indices (IMF, Ap and Dst) for the period 1960 – 2001. They found that during the analyzed time span, all geomagnetic activity indices show a double peak maximum with a variation from cycle to cycle and meaningful correlations between solar and geomagnetic activity indices. Here we did similar comparison and further confirm their results for Cycle 24(th.SİL) They reported time lag between Ap index and solar indices that we also confirm this result for the Cycle 24.

As shown in Table 1 and 2 the scalar B shows the highest correlation with both solar FI and CIR data sets during the solar cycle 24. Verbanac et al. (2011) reported the higher correlation between geomagnetic activity indices and IMF compared to solar indices and IMF. From their results, we may argue that scalar B/IMF can be used as a geomagnetic activity index as we did in this study.

The hysteresis phenomenon has long been known in solar and solar-terrestrial physics (Bachmann and White, 1994; Bruevich et al. 2016). Bruevich et al. (2016) reported that solar, ionospheric and geomagnetic activity parameters have hysteresis behavior. They concluded that the hysteresis behavior of the Ap index is due to the hysteresis of solar dynamo. Later Sarp et al. (2019) analyzed hysteresis behavior between CIR and sunspot number for solar cycle 23 and 24. Contrary to cycle 23 they conclude weaker link between two parameters during cycle 24. Here we found hysteresis behavior for all data sets especially during the maximum and descending phases of solar cycle 24 and thus confirm their results for cycle 24.

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