Solar flare and geomagnetic activity relations

Volkan SARP[*], **Ali KILÇIK**

Department of Space Sciences and Technologies, Faculty of Science, Akdeniz University, Antalya, Turkey

Abstract: Two x-ray solar flare parameters (number of flares and peak flux) are compared to geomagnetic and space weather activity indices. The first solar flare parameter, X-ray solar flare number (SFN), is the total number of solar flares observed in a given month. The second one is the monthly maximum of X-ray solar flare peak fluxes (SFP). In order to compare these two parameters, both of them are cross-correlated with some other indices of geomagnetic activity (aa, Dst, and AE indices) and space weather (maximum coronal mass ejection speed index and solar wind speed). Maximum correlation was found (∼0.63) between both flare time series (SFN and SFP) and maximum coronal mass ejection speed index with no lag. Our results show that X-ray solar flare peak flux better describes those geomagnetic and space weather activity indices than X-ray solar flare numbers. This is mostly because of high time delays between flare numbers and studied indices.

Key words: Solar flares, coronal mass ejections, geomagnetic indices, solar wind, cross-correlation

1. Introduction

Various activities are continuously exposed by the Sun, such as solar wind, sunspots, coronal mass ejections, coronal holes, and solar flares. The solar flare phenomena are sudden luminosity rises on the solar disk and are related to powerful explosions releasing vast amounts of energy. Space weather effects of the energy release may cause various problems for modern technology such as disruption of high-frequency radio communication, degraded satellite navigation, and power grid failures.

1.1. Solar flares

Solar flares usually occur in active regions, which are areas on the Sun with strong magnetic fields and are typically associated with sunspot groups. The large eruption of electromagnetic radiation triggered by a solar flare may last from minutes to hours. The solar flare mechanism, which includes reconnection, instabilities, anomalous resistivity, efficient particle acceleration, particle propagation, evaporation, mass loss, high-frequency waves, MHD oscillations, and emission processes, is evidence of complex dynamics of the corona [1]. This mechanism starts with energy build-up in the corona and ends by restructuring the magnetic configuration and releasing magnetic energy. Although the releasing energy can be observed in the form of electromagnetic radiation over a wide range (from radio waves to gamma rays), some of those ranges reveal specific properties better than others. For instance, hard X-ray observations do not reveal the preflare and decay phases of solar flares but give sufficient detail about the impulsive phase while decametric radio observations give a clear distinction between the impulsive and flash phases.

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[*]Correspondence: theneutron@gmail.com

The most energetic aspect of a solar flare is considered as the impulsive phase due to the production of energetic electrons and protons (E > 1 MeV), which may cause solar energetic particle (SEP) events. SEPs can reach Earth's vicinity in about an hour, penetrate the Earth's magnetic field, and cause ionization in the ionosphere. There are various flare-related phenomena that can be considered as Sun–Earth interactions. Apart from SEPs, another kind of geomagnetic disturbance related to solar flares was identified as sudden ionospheric disturbance (SID). SIDs cause sudden increases in radio-wave absorption and their results interrupt/interfere with telecommunication systems. A third kind of terrestrial disturbance associated with flares is known as ground-level enhancement (GLE), defined as the increase of cosmic-ray intensity. GLEs result when energetic ions (E $\sim$ 1 BeV) strike the atmosphere and produce secondary particles, which are continuously monitored by neutron detectors from Earth.

1.2. Geomagnetic activity

Among the most well-known results of Sun–Earth interactions are geomagnetic storms. A geomagnetic storm is a major disturbance of the magnetosphere and results in geomagnetically induced currents (GICs). An example of GICs is the so-called ring current, which is a torus of electrical current that flows westward at altitudes of 10,000–20,000 km above Earth's equator. The ring current arises from the differential motions of ions and electrons in this region and injection of new particles when a storm occurs. A measure of ring current, the disturbance storm time (Dst) index, has been used to identify the magnitude of geomagnetic storms since 1957. There are also other kinds of measurements and geomagnetic indices derived from these measurements, such as aa and AE indices, but it should be noted that all these indices condense the properties of a complex nonlinear system with a variety of dynamical processes into a single number [2].

The first suggestion that geomagnetic storms were associated with solar flares was the famous observation by Richard Carrington on 1 September 1859. It was a white-light observation of a solar flare followed by a large geomagnetic storm about 17 h later [3]. Following the Carrington flare, many observational and theoretical studies were performed to understand solar flares and associated extreme space weather events for 150 years. In order to reduce widespread technological damage, prediction strategies that depend on plasma physics, high-energy physics, and modeling of complex systems were developed. The desired result of a prediction is an "all-clear" period that does not include any major flares [4], but no successful forecast has been performed to date.

The aim of this study is to compare two separate X-ray solar flare parameters, namely the flare peak flux (hereafter called SFP) and the flare number (hereafter called SFN), in order to choose the most appropriate one while studying the possible relationships between solar flares and geomagnetic activity indices. We studied their temporal variations, maximum correlations, and possible time delays. The highest correlation was found between solar flare numbers and maximum coronal mass ejection speed index (MCMESI), which is an indicator of solar and geomagnetic activities described by Kilcik et al. [5]

The outline of this study is as follows: in Section 2 we have summarized the data and methods used in this study. In Section 3, the analysis and results of the study are given. In Section 4, we have presented the conclusions and a discussion.

2. Data and method

The solar flare data used in this study were taken from the National Oceanographic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC) for the time period from January 1996 through

August 2016. The GOES X-ray flux data were used to describe two different flare time series used in this study. We take into account all flares for each day, then calculate total peak flux per month and produce the SFP time series. The second dataset is the total numbers of flares per month, used as the SFN time series. Both time series are smoothed using a 13-step running-average smoothing method. There are also 5 indices used in this study; 3 of them are global geomagnetic indices, another one is the solar wind speed index (SWSI), and the last one is the MCMESI. Data sources for these indices are the Kyoto University Geomagnetic Data Service (Dst and AE indices), International Service of Geomagnetic Indices (aa index), SOHO LASCO CME Catalog (MCMESI), and NASA Goddard Space Flight Center (SWSI). These indices also cover the same time period as the SFP and SFN.

Then we took three geomagnetic indices into account, one index for each separate layer of the near-earth space environment: i) the Dst index stands for low latitudes and shows the strength of the ring current and geomagnetic storms; ii) for midlatitudes, we took the aa index, which is a global magnetic index from antipodal observatories; iii) the AE index is a measure of auroral electrojets and represents the auroral zone [6,7]. The next index that we studied is the MCMESI. It is both a geomagnetic and solar index and is derived as the monthly average of daily maximum CME speeds [8]. Solar wind speed (SWSI) is the last index that we studied. It is derived as the monthly average of solar wind speeds. Solar wind is an important index because of being the driver of geoeffective space weather activity [8].

We have studied temporal variations of these time series and applied a cross-correlation analysis method between flare datasets and index datasets to calculate the correlation coefficients and possible time delays. Correlation coefficients and time delays are studied for their confidence levels according to the Fisher test. This test gives the upper and lower bound of the correlation coefficient with the 95% confidence level [9].

3. Analysis and results

Temporal variations of the SFN and SFP follow each other quite well. Their shared peak around 2001 is the maximum of solar cycle 23. SFP shows an overall single maximum while SFN has a double peak up to December 2008. This point is the end of solar cycle 23. During cycle 24, there is an agreement that can be inferred from the overlapped fluctuations in Figure 1a. In general, SFN shows a more smoothed trend and follows the solar activity quite well, while SFP has fluctuations during the investigated time period. Both time series follow a compatible trend during cycle 24 and their maximum correlation coefficient is 0.52 with zero time lags. Cross-correlation analysis was made in a range of 400 months. One of the time series was fixed at time zero while other time series were shifted by 1 month at each step starting from 200 months before, up to 200 months after the fixed point. Correlation coefficients are derived at each step and plotted as in Figure 1b.

As can be seen in Figure 2a, the maximum of the aa index is coherent with the secondary peak of SFP between 2003 and 2004. The main peak of SFP comes about 2 years earlier than that of the aa index. After its maximum, the aa index shows a bump between 2006 and 2008. SFP has some remarkable fluctuations around that time but when we look at the temporal variation of SFN in Figure 2b, there is nothing other than an ordinary smooth decline. The aa index has a secondary peak around 2005 and also SFP is high at the same time, while SFN does not have such a remarkable peak again. The maximum correlation coefficient of SFP and the aa index is 0.54 with zero time lag (Figure 2c). It is a little lower compared to SFN and the aa index, for which the value is 0.57, but there are 16 months of time delay (Figure 2d).

The Dst index shows a complicated relation with both the SFP and the SFN. Their temporal variations can be seen in Figure 3a. The Dst index has its maximum around 2009 that corresponds to the end of cycle 23
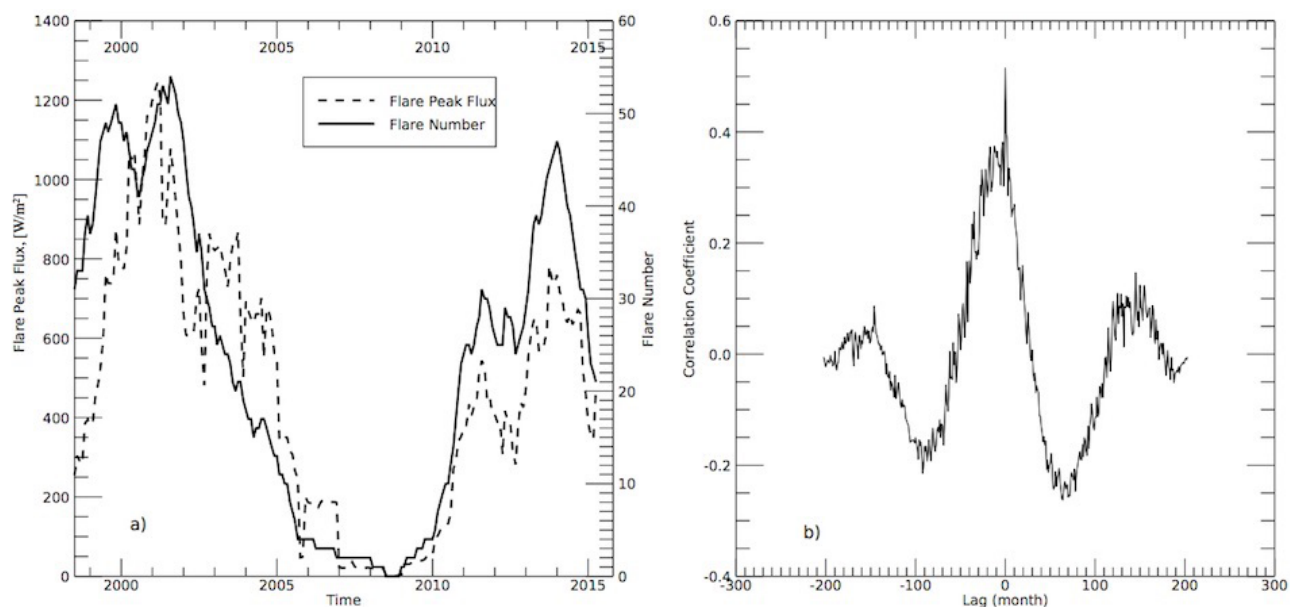
Figure 1. a) Temporal variations of SFP and SFN, b) cross-correlation analysis results of same data.
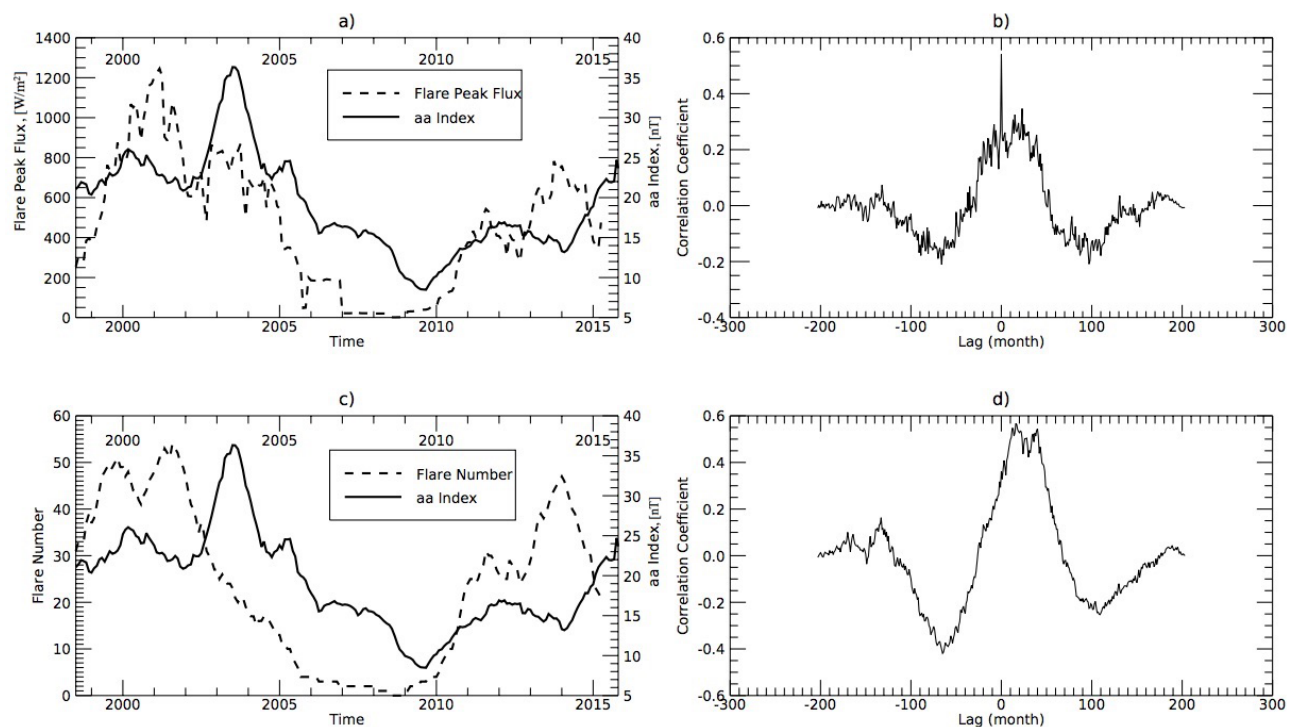

Figure 2. a) Temporal variations of SFP and aa index, b) cross-correlation analysis results of the same datasets, c) temporal variations of SFN and aa index, d) cross-correlation analysis results of the same datasets.

and the beginning of cycle 24, while both SFP and SFN have low values. Both SFP and the Dst index have a small peak around 2004, but SFN continues to decrease smoothly around that time (Figure 3b). After 2010,

Dst index values start to decrease, while flare datasets (SFN and SFP) have their peaks at that time. Thus, it is easy to see the high negative correlation between the Dst index and solar flares during cycle 23. Considering the studied time period, cross-correlation analysis results (Figures 3c and 3d) show us that there is no time delay between SFP and the Dst index and the maximum correlation is negative (r = –0.47), and for the SFN (r = –0.41), the lag is again 16 months, which is the same as the aa index. Thus, it is possible to argue that solar flare effects are experienced after the same time period at low latitudes and middle latitudes.
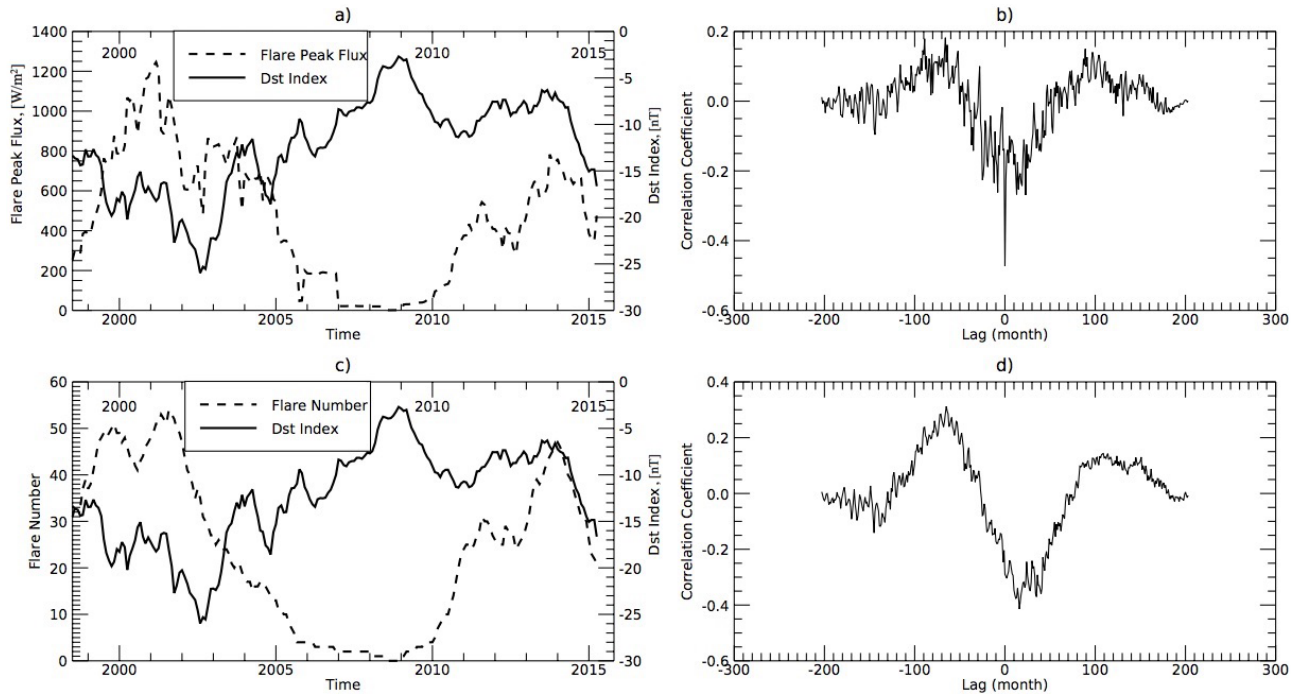

Figure 3. a) Temporal variations of flare peak flux and Dst index, b) cross-correlation analysis results between these datasets, c) temporal variations of flare number and Dst index, d) cross-correlation analysis result between these datasets.

Temporal variations of the aa index and AE index also look very similar. They have the same maximum point between 2003 and 2004 as can be seen in Figures 2a, 2b, 4a, and 4b. The minimum points of both indices also coincide around 2009. The similarity of their temporal variations allows us to say that solar flare effects are hard to distinguish between auroral zone and middle latitudes. The maximum correlation coefficient is 0.44 between SFP and the AE index with zero lag (Figure 4c) and 0.56 between SFN and the AE index with a time delay of 12 months (Figure 4d). The maximum correlation coefficient of SFN is remarkably higher and out of significance bounds compared to SFP (r = 0.44). Thus, we may argue that the AE index is mostly following the general trend of solar activity and is not strongly dependent on the active solar events.

Both flare time series are following the MCMESI very well, as seen in Figures 5a and 5b. The local peak of the MCMESI around 2005 can be explained by the secondary peaks of the SFP, but this is not so remarkable (smoothed declining trend) for the flare number time series. The first peaks of solar cycle 24 for the MCMESI are also in agreement with both flare datasets around 2012. Cross-correlation analysis results are given in Figures 5c and 5d. The maximum correlation coefficient of flare number (r = 0.63) is a little higher than that of flare peak flux (r = 0.60), but the difference is not meaningful and the maximum correlations have no time delays in either case.
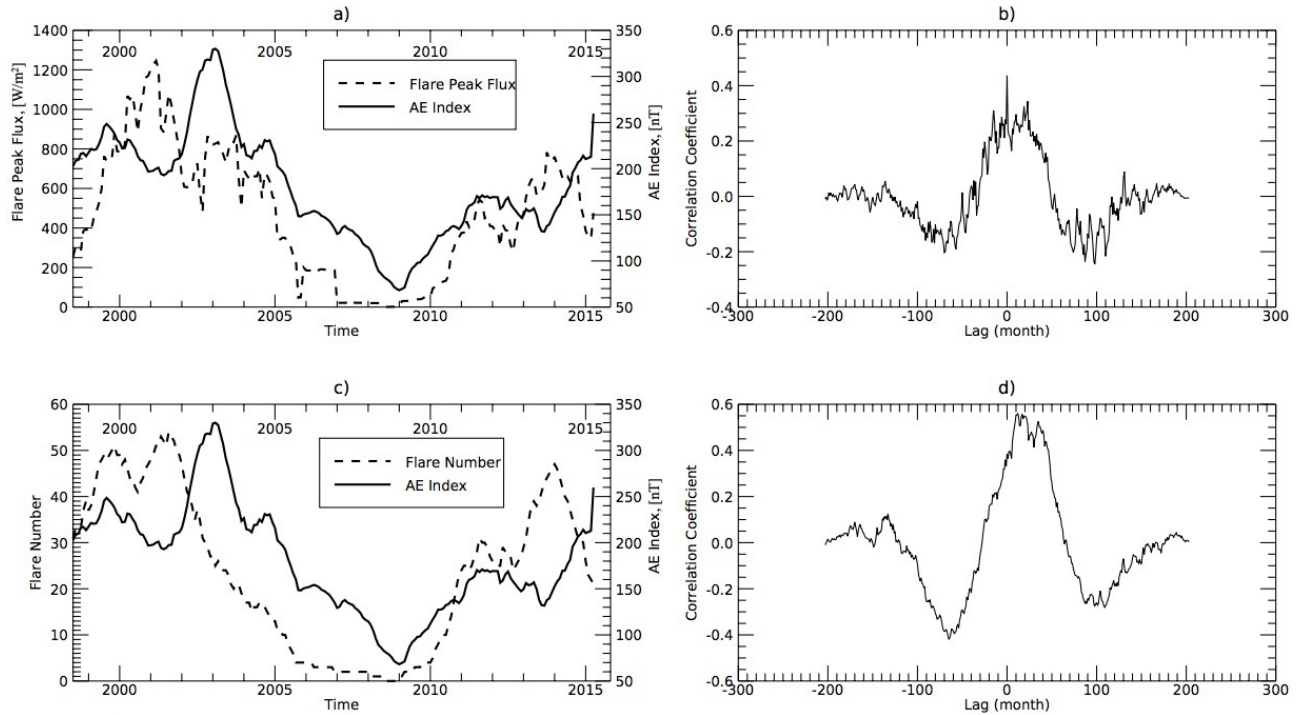
Figure 4. a) Temporal variations of SFP and AE index, b) cross-correlation analysis results for the same datasets, c) temporal variations of SFN and AE index, d) cross-correlation analysis results for the same datasets.

The maximum of SWSI (SW speed) is around 2004 and there is a local maximum around 2008 (Figures 6a and 6b). The minimums of both SWSI and SFP are around 2009. When we look at Figure 6b, SFN and SWSI seem to have a time delay between each other. Cross-correlation analysis results, which can be seen in Figures 6c and 6d, give the time delay between SFN and SWSI as 39 months (r = 0.46), while there are no time delays for SFP and the correlation coefficient has the same value

Maximum correlation coefficients between studied indices and their upper and lower significance bounds according to Fisher test results are given in Table 1 for SFP and Table 2 for SFN. Time delays are also added to these tables to establish an overall view. According to these results SFP has no time delays for all studied indices so it may be considered as a better index to show the relationship between solar flares and geoeffectiveness. SFN follows the general trend of solar activity but has intolerable time delays with the studied indices.

4. Discussion and conclusions

Flare datasets are determined with two different approaches in this study. Their temporal variations and correlation coefficients are derived and compared with three geomagnetic indices and two space weather indices. The main findings of this study are as follows:

1) Maximum correlation is found for the MCMESI.

2) SFN time series have lags with the studied indices at the magnitude of several months, except the MCMESI.

3) SFP time series have no lags and possible fluctuations overlapped with extraordinary variations of the studied indices.

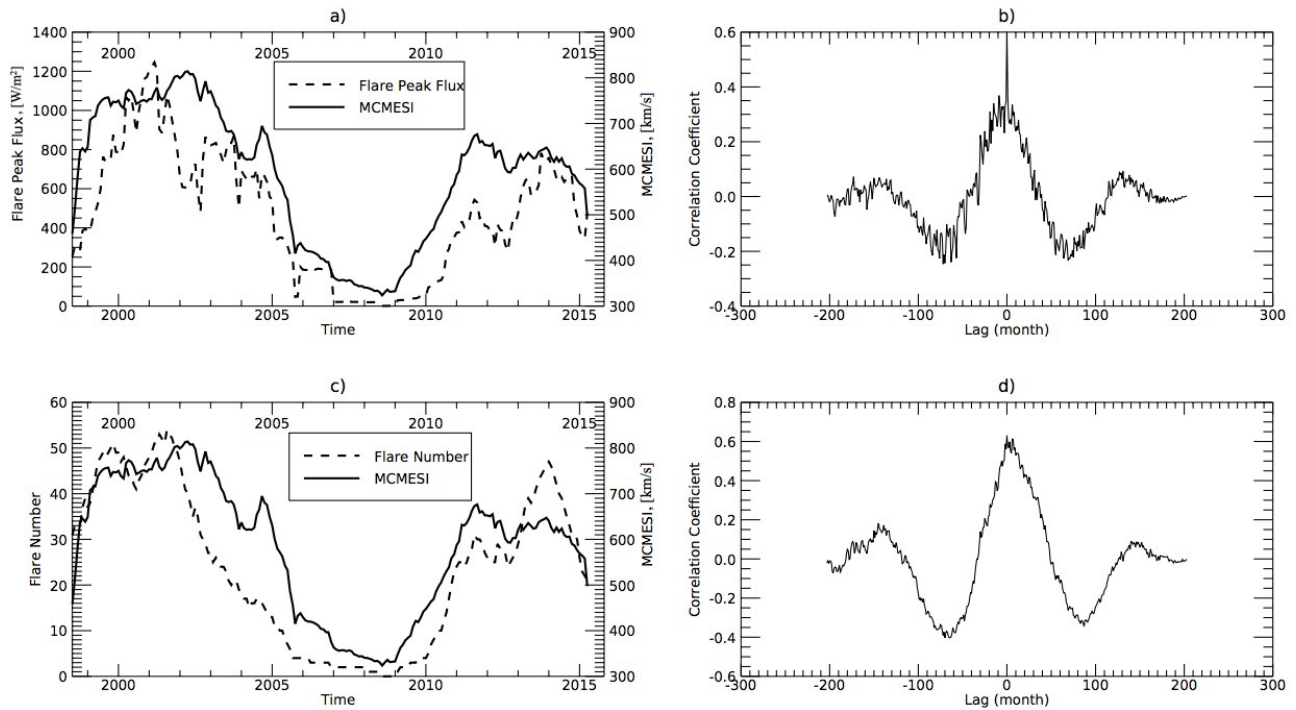4) SFP is a better index to show the relation between solar flares and geoeffectiveness.

Figure 5. a) Temporal variations of SFP and MCMESI, b) cross-correlation analysis results between these datasets, c) temporal variations of SFN and MCMESI, d) cross-correlation analysis results between these datasets.

Table 1. Maximum correlation coefficients, significance intervals, and time delays between indices and solar flare peak flux (SFP).

Indices	Correlation coefficient (r)	Upper significance limit of r	Lower significance limit of r	Time delay
aa index	0.54	0.63	0.44	0
Dst index	−0.47	0.57	0.36	0
AE index	0.44	0.54	0.32	0
MCMESI	0.60	0.68	0.50	0
SW speed	0.46	0.56	0.35	0
SFN	0.52	0.70	0.41	0

Kilcik et al. [5] introduced the MCMESI and compared these data with sunspot number and Ap and Dst indices. They concluded that this new index shows good correlation with both solar and geomagnetic activity. In this study, we compared X-ray solar flare number and X-ray solar flare peak flux with this new index and found that it is the best correlated index among the other indices that we studied in this work. Both SFP and SFN have no time delay and higher correlation coefficients with the MCMESI. Thus, we may conclude that the MCMESI is in good agreement with the solar flare events and can be used for proximity of solar activity for space weather studies.

Kilcik et al. [10] separated sunspot groups as small (A, B, C, and H) and large (D, E, and F) and found that the temporal variation of the number of groups of these two categories is quite different during a cycle. For
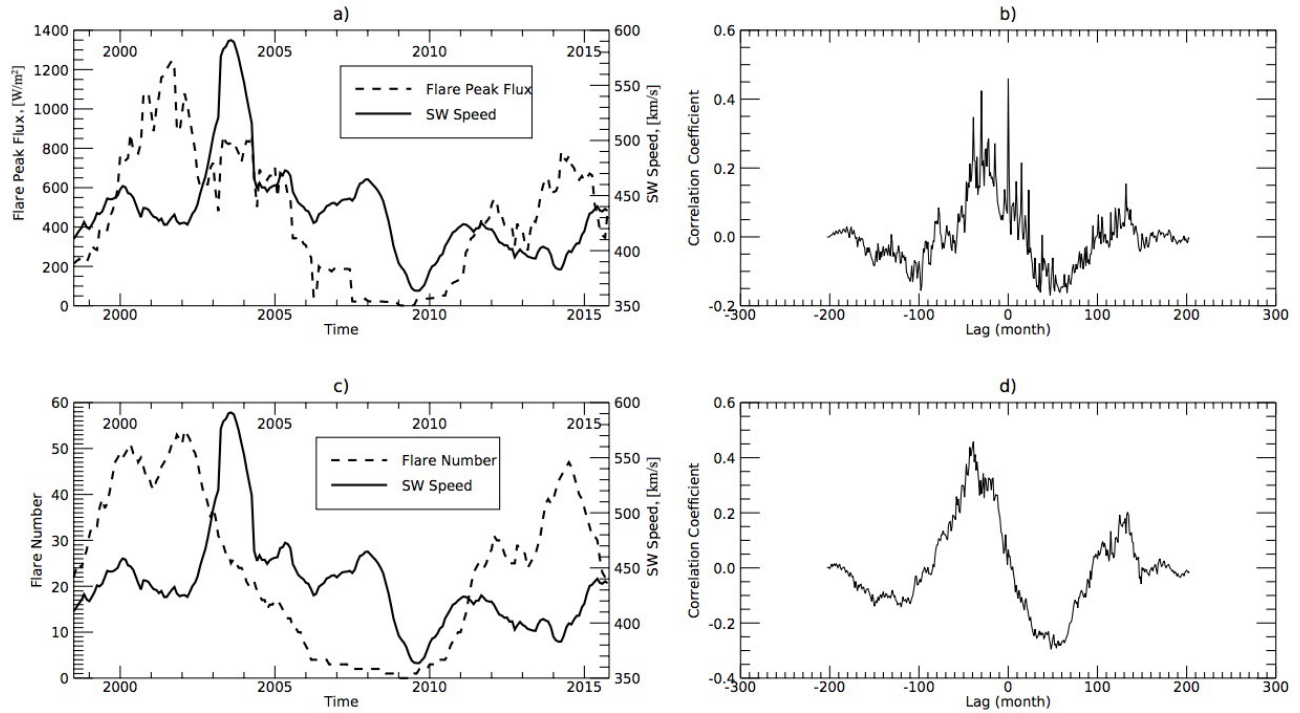
Figure 6. a) Temporal variations of SFP and SWSI, b) cross-correlation analysis results between these datasets, c) temporal variations of SFN and SWSI, d) cross-correlation analysis results between these datasets.

Table 2. Maximum correlation coefficients, significance intervals, and time delays between indices and solar flare number (SFN).

Indices	Correlation coefficient (r)	Upper significance limit of r	Lower significance limit of r	Time delay
aa index	0.57	0.65	0.47	16
Dst index	−0.41	0.52	0.3	16
AE index	0.56	0.65	0.46	12
MCMESI	0.63	0.70	0.54	0
SWSI	0.46	0.56	0.35	39
SFP	0.52	0.70	0.41	0

cycle 23 they mentioned that, contrary to a number of small groups, there is an increase in large sunspot group numbers around 2005. Here, we compared monthly flare peak flux and flare numbers and found that flare peak flux has secondary peaks in that time period, while flare number has a more smoothed declining trend. Thus, it is possible to argue that large sunspot groups produced high-energy flares compared to small ones.

Le Mouël et al. [11] stated that geomagnetic indices can be classified into two categories as range family and mean family. They studied these two family's correlation coefficients by using a 1-year running-average between 1995 and 2005 and found that range family indices (aa and Ap) have correlation coefficients higher than 0.95 all the time and mean family indices (Dst and ζ) have correlation coefficients higher than 0.95 most

of the time. They further analyzed the correlation of these indices with Wolf sunspot number and found a significant correlation in the 19th and 22nd solar cycles, but the remaining cycles had a low correlation (see fig. 6 in their paper), and even the aa index had a negative correlation during the 20th solar cycle. In this study, we found that temporal variations of the aa index and AE index are quite similar. Thus, it is possible to argue that these two indices can be considered in the same family. Also, we can speculate that despite SFN having slightly higher correlation coefficients with some geomagnetic indices, SFP represents these geomagnetic indices better because there are no lags between the studied indices and SFP.

Reyes et al. [12] studied the local variation of the geomagnetic field and its relationship with solar flares. They used solar flare index (SFI) in their study and could not find any significant correlation between SFI and Ap index. They also selected 87 solar flare events that had a total flux higher than a specific value and found that more than 80% of these flares were related to a strong disturbance of the geomagnetic field after 2–3 days from flare observation. They concluded that there is a weak correlation between the magnitude of the disturbance and the total flux of a solar flare. Here, we compared flare peak flux with geomagnetic aa, AE, and Dst indices. We found correlation coefficients between SFP and these indices (aa, AE and DST) as follows; 0.54, 0.44 and -0.47, respectively. Since we used monthly values of flare datasets in our study, it was not possible for us to catch these daily time lags, but in general we can say that there are no time delays between geomagnetic indices and flare peak fluxes on a monthly basis and using SFP gives better results than using SFI.

Kilcik et al. [13] analyzed solar and geomagnetic activity relations for the last two solar cycles. They studied solar wind, X-ray solar flare data, and geomagnetic indices that cover the time period from January 1996 to March 2014. They found that SFI and SWSI have a good correlation with Ap and Dst indices and there is no time delay. They also found that times of the maxima of SFI and SWSI have about 2 years difference and SFI peaks earlier. These results agree with our findings as we find 39 months of time delay between SFN and SWSI.

Du and Wang [14] employed an integral response model in order to analyze relationships between solar flare parameters (total importance, time duration, flare index, and flux) and sunspot activity (R_z) as well as those between geomagnetic activity (aa index). Some model parameters were determined by a nonlinear least-square fitting algorithm. As a result of this dynamic model, correlation coefficients of analyzed indices increased remarkably. Also, approximately half of the time delays at peak points of the aa index and solar flare parameters were predicted accurately. It was concluded that flare parameters can be better described by their model than by a linear dependence. Since the solar activity cycle is governed by a complex dynamo mechanism, using methods of nonlinear dynamics such as embedding dimension, false nearest neighbor estimation, or mutual information may reveal the compound structure of space weather phenomena. Recently, the stochastic and chaotic properties of solar activity were analysed by Hanslmeier et al. [15] and the robustness of nonlinear methods was demonstrated. In this study, we studied the complex time behavior of two solar flare parameters (SFP and SFN). We found that linear dependence may only be employed weakly for SFP, which has no time delays with studied indices. However, it should also be noted that there are fluctuations in SFP that could be studied further to investigate possible relations with various space weather events.

Acknowledgments

Geomagnetic Data Service, the aa index was from the International Service of Geomagnetic Indices (ISGI), CME data were from the SOHO LASCO CME Catalog, and solar wind data were from the NASA Goddard Space Flight Center for the time period from January 1996 through August 2016.

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