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Total sunspot number calculation based on flare production potential of sunspot groups: reconstruction of SSN and its relation to some geomagnetic indices

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Abstract: In this study, we modified the previously introduced X-ray flare production potential (FPP) of each modified Zurich sunspot group based on its X-ray flare peak flux. Then, using these FPPs, the daily total sunspot number (Zurich number) calculation equation was modified; thus, new sunspot number data (CRz) were produced. We also compared ISSN and CRz with some geomagnetic indices (Dst, the maximum CME speed, and Ap indices). We found that the CRz data describe the geomagnetic indices quite well compared to ISSN. By using the regression equation between CRz and the sunspot area, the CRz dataset was recalculated back to 1874. Those reconstructed datasets were compared to observational data, and it was found that reconstructed and observed monthly datasets show very good agreement. The only small differences exist in maxima and minima of cycles.

Key words: Sunspot, sunspot classification, sunspot number, solar X-ray flares

1. Introduction

Sunspots are transient dark structures observed on the solar surface. They disappear after being seen for days, weeks, or even months. They start to appear when an intense magnetic field is trapped on the sun's surface. A strong magnetic field reduces the temperature of the area from 5780 K (average photospheric temperature) to 4000 K (average sunspot temperature). Thus, they appear darker than the surrounding area. An evolved sunspot is basically composed of 2 parts. Sunspots generally appear as groups on the solar photosphere. These groups have been observed and recorded regularly since 1610 [1], and have been classified according to their appearance since the beginning of 20th century [2]. Ref. [3] introduced the Zurich classification schema to describe sunspot morphology and evolution. The currently used sunspot classification (McIntosh or modified Zurich classification) is a modification of the Zurich system [4]. This classification schema better describes the relationship between sunspots and solar flares and better explains the basic properties of sunspots compared to the previous classification system. This classification schema is based on 3 parameters: 1) Modified Zurich class, which describes the morphological structure and evolution of groups; there are 7 main classes (A, B, C, D, E, F, and H). 2) The penumbra of the largest spot in the group; sunspot groups are divided into 6 classes according to this parameter (x, r, s, a, h, and k). 3) Intermediate sunspot distribution; according to this parameter, sunspot groups are divided into 4 classes: x, o, i, and c. Thus, sunspot groups are classified by adding the above letters consecutively, such as Dso, Dkc, Hai, etc.

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The daily total number of sunspots (Zurich number or relative number) is calculated by:

$$Rz = k\,(10g + f)\,, \qquad (1)$$

where k is the correction factor, g is the number of groups, and f is the total number of individual sunspots in all groups [5]. According to this equation, all groups have the same importance, i.e. very small sunspot groups (A and B classes) have the same importance as strongly evolved sunspot groups (D, E, and F classes). However, it is well known that most of geoeffective events (solar flares and coronal mass ejections [CMEs]) occur in evolved sunspot groups [6–8].

Among the most intense events observed on the sun's surface are solar flares, which are observed as a brightness increase in the solar chromosphere. They generally occur around the sunspots. Similar to the sunspot groups, solar flares are also classified according to their X-ray peak flux in the 1 to 8 Å wavelength band (see Table 1). X-ray solar flares are classified in 5 classes (A, B, C, M, and X) according to their peak flux of 1 to 8 Å. These classes are also subdivided into 10 subclasses, while the X-class is open-ended.

Table 1. Peak flux for each X-ray solar flare classification.

Class	Peak flux (W/m^2), 1–8 Å
A	$I < 10^{-7}$
B	$10^{-7} < I < 10^{-6}$
C	$10^{-6} \leq I < 10^{-5}$
M	$10^{-5} \leq I < 10^{-4}$
X	$I \geq 10^{-4}$

Ref. [9] separated the sunspot groups into 2 categories as small (A, B, C, H) and large (D, E, F) for the previous 4 cycles (cycles 20, 21, 22, and 23). They concluded that the large and small groups behave differently during a cycle and that these differences vary from cycle to cycle. Ref. [10] further divided the small groups into 3 categories as small (A, B), medium (C), and end (H). They found that the temporal behaviors of these categories are also different during a cycle. We think that the FPP of different categories should also be different. Therefore, we analyzed each sunspot group separately according to the FPP. We then modified the daily sunspot number calculation equation based on the FPP of different sunspot groups. Thus, we have recalculated the sunspot number based on each modified Zurich class FPP and have reconstructed CRz from 1874 to 2016.

Another important subject to be addressed is how the Dst (disturbance storm time), Ap, and maximum CME speed indices are related to CRz and ISSN. These indices have different features due to underlying physical mechanisms and are affected by ISSN. For instance, the Dst index measures magnetic storm strength, while the Ap index is a daily average of geomagnetic activity. ISSN provides convenient data for describing solar activity. Therefore, we have reconstructed the daily sunspot number using the FPP of each group. Subsequently, we have analyzed the relation between CRz and geomagnetic Ap and Dst indices. We argue that it is better to use the sunspot group properties as a variable instead of a constant value in the daily sunspot number calculation equation for describing solar activity.

In Section 2, datasets, analysis methods, and results are described. The discussion and conclusions are given in Section 3.

2. Data, method, analysis, and results

In this study, sunspot area (SSA), international sunspot number (ISSN), solar X-ray peak flux, maximum coronal mass ejection speed index (MCMESI), geomagnetic Ap index, and geomagnetic Dst index datasets were used. Solar X-ray peak flux data are taken from the National Oceanographic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC) for the time period from August 1996 through December 2017.[1] ISSN data are taken from World Data Center–Sunspot Index and Long-term Solar Observations (WDC–SILSO SIDC),[2] SSA data are taken from the Marshall Space Flight Center (MSFC),[3] geomagnetic Ap and Dst indices are taken from the National Oceanographic and Atmospheric Administration (NOAA),[4] and CME data are taken from the National Aeronautics and Space Administration websites.[5]

First, we recalculated the FPP previously introduced by Ref. [6] based on the peak flux of X-ray solar flares instead of X-ray solar flare numbers (see Table 2). For this purpose, we have used only C, M, and X class flares from 1996 to 2016. To calculate the flare production potential, the M class flare's peak fluxes were used as a reference and C and X classes were converted to M class by dividing or multiplying by 10, respectively. Then FPP was calculated as follows:

Table 2. Flare production potentials for each sunspot group. C, M, and X columns show the total number of observed flares in each sunspot group.

Sunspot group	Peak flux of X-ray flare			Total number in sunspot group	Total X-ray peak flux (W/m^2)	FPP
	C	M	X			
A	173	9	0	3253	62.57	0.019
B	329	15	0	3923	106.08	0.027
C	1534	146	7	7149	903.51	0.126
D	4098	480	39	7732	3343.34	0.432
E	3738	495	50	3229	3499.48	1.083
F	2106	458	38	1120	3239.64	2.892
H	708	65	4	6939	533.15	0.076

$$FPP\, of\, a\, Zurich\, class = \frac{total\ X - ray\, flare\, peak\, flux\, of\, sunspot\, class}{total\, number\, of\, sunspot\, group\, of\, the\, same\, class}. \quad (2)$$

By using these FPPs, the Wolf number formula was modified as follows:

$$CRz = 2\sum_{i=1}^{n}\left((P_i \times g_i) + f_i\right), \quad (3)$$

where CRz describes the calculated daily total sunspot number, P_i is the FPP of the ith class sunspot group, g_i is the number of sunspot groups of the ith class, and f_i is the total number of individual sunspots in all groups of the ith class. According to this equation, each sunspot group contributes to the daily total sunspot

[1] https://www.swpc.noaa.gov/
[2] http://www.sidc.be/silso/datafiles
[3] https://solarscience.msfc.nasa.gov/greenwch.shtml
[4] ftp://ftp.ngdc.noaa.gov/
[5] ftp://lasco6.nascom.nasa.gov/pub/lasco/status/Version2_CME_Lists/

number depending on its FPP. CRz data are multiplied by 2, so that they will match the ISSN data for a better comparison. Thus, we obtained the CRz by using the above equation for 1996–2016. Temporal variations of ISSN and SSA with CRz are compared in Figure 1.

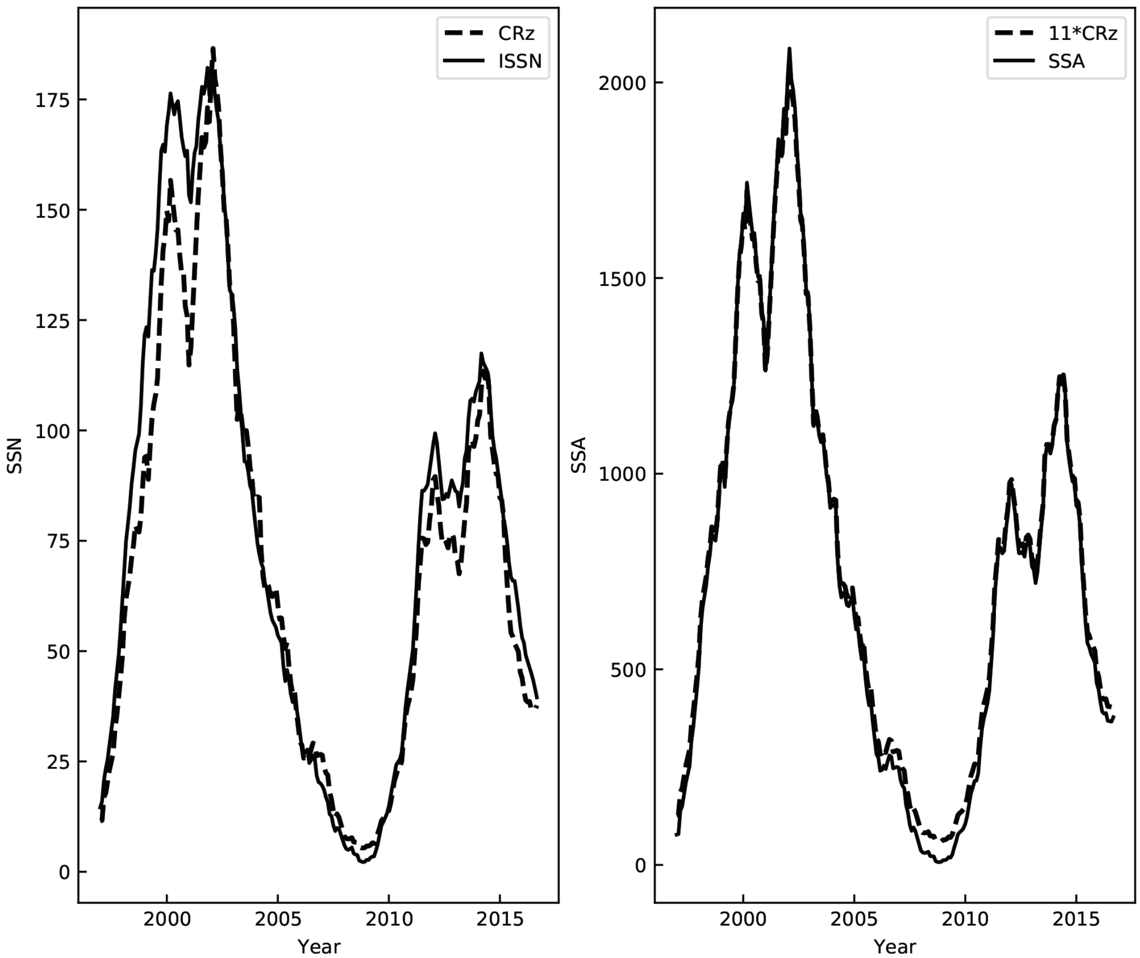

Figure 1. Comparisons of temporal variations of CRz with ISSN and SSA for the investigated time period. CRz data were multiplied by 11 to emphasize the match between CRz and SSA.

To compare CRz and ISSN with geomagnetic Ap and Dst indices and the MCMESI datasets, the cross-correlation analysis method was applied (see Table 3).

Table 3. Results from cross-correlation analysis between datasets used in this study for the 1996–2016 time period.

Datasets	CRz–Ap	ISSN–Ap	CRz–Dst	ISSN–Dst	CRz–MCMESI	ISSN–MCMESI
Cross-correlation coefficient	0.60 ± 0.09	0.57 ± 0.10	-0.38 ± 0.11	-0.37 ± 0.12	0.77 ± 0.06	0.76 ± 0.06

As shown in Table 3, CRz shows the same level or a bit higher correlation with the Ap index, Dst index, and MCMESI data compared to ISSN. Note that CRz also shows very high correlation with SSA (0.97 ± 0.01).

By using the SSA–CRz linear regression equation (see Figure 2), we first reconstructed CRz data back to 1874 and compared them with SSN data (Figure 3). It can be clearly seen that both datasets follow each other quite well, with only small differences in the minima and maxima. During the ascending and descending phases of the solar cycle, these datasets appear almost identical.

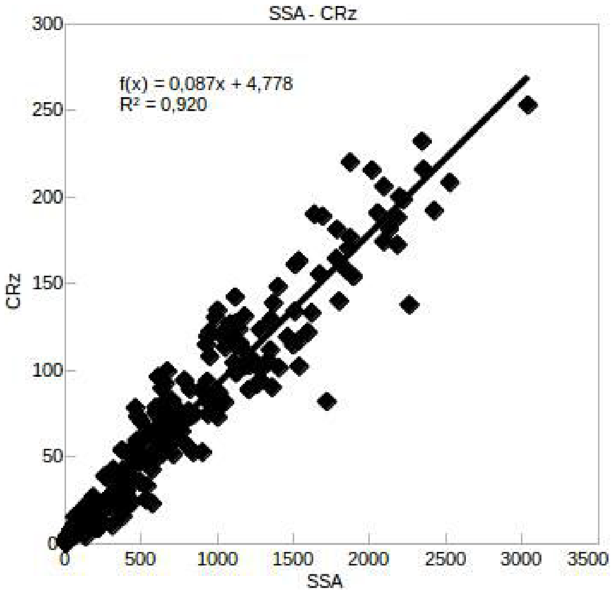

Figure 2. Comparison of observed sunspot area data and CRz datasets for the 1996–2016 time period.

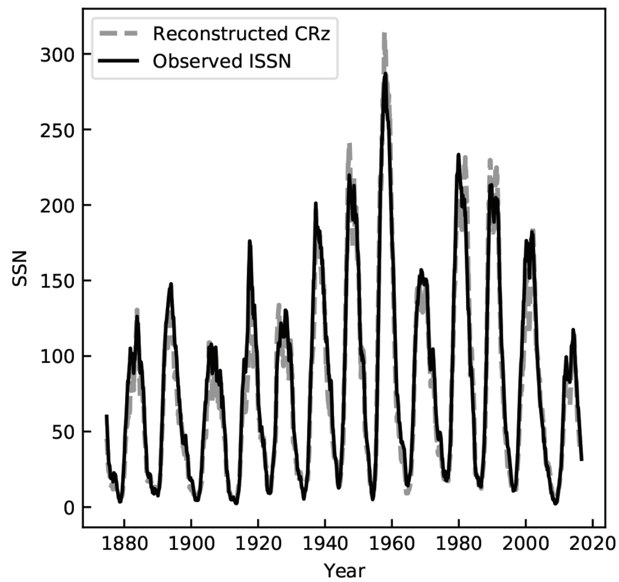

Figure 3. Temporal variations of observed SSN and reconstructed CRz datasets.

As a final step, the cross-correlation analysis method was applied to newly produced CRz data and other datasets (Figures 4–6).

Figures 4–6 show cross-correlation analysis results between the observed Ap, Dst, and MCMESI indices and the reconstructed CRz datasets. It is observed that there is no time delay between CRz and the MCMESI and Dst index. On the other hand, there is only 3 months' time delay with the Ap index (see Table 4).

Table 4. Cross-correlation analysis results between datasets used in this study for all datasets.

Datasets	CRz–Ap	ISSN–Ap	CRz–Dst	ISSN–Dst	CRz–MCMESI	ISSN–MCMESI
Cross-correlation coefficient	0.37 ± 0.06	0.38 ± 0.06	–0.40 ± 0.06	–0.38 ± 0.06	0.79 ± 0.05	0.71 ± 0.07
Lag (months)	6	22	0	3	0	0

3. Discussion and conclusions

In this study, we modified the daily total sunspot number calculation equation by using X-ray flare production potentials (M class flares selected as reference class) based on the X-ray flare peak flux of each modified Zurich sunspot class. The daily total sunspot numbers were then recalculated and projected back to 1874 by using the linear relationship between SSA and CRz data. Calculated sunspot numbers were compared with solar

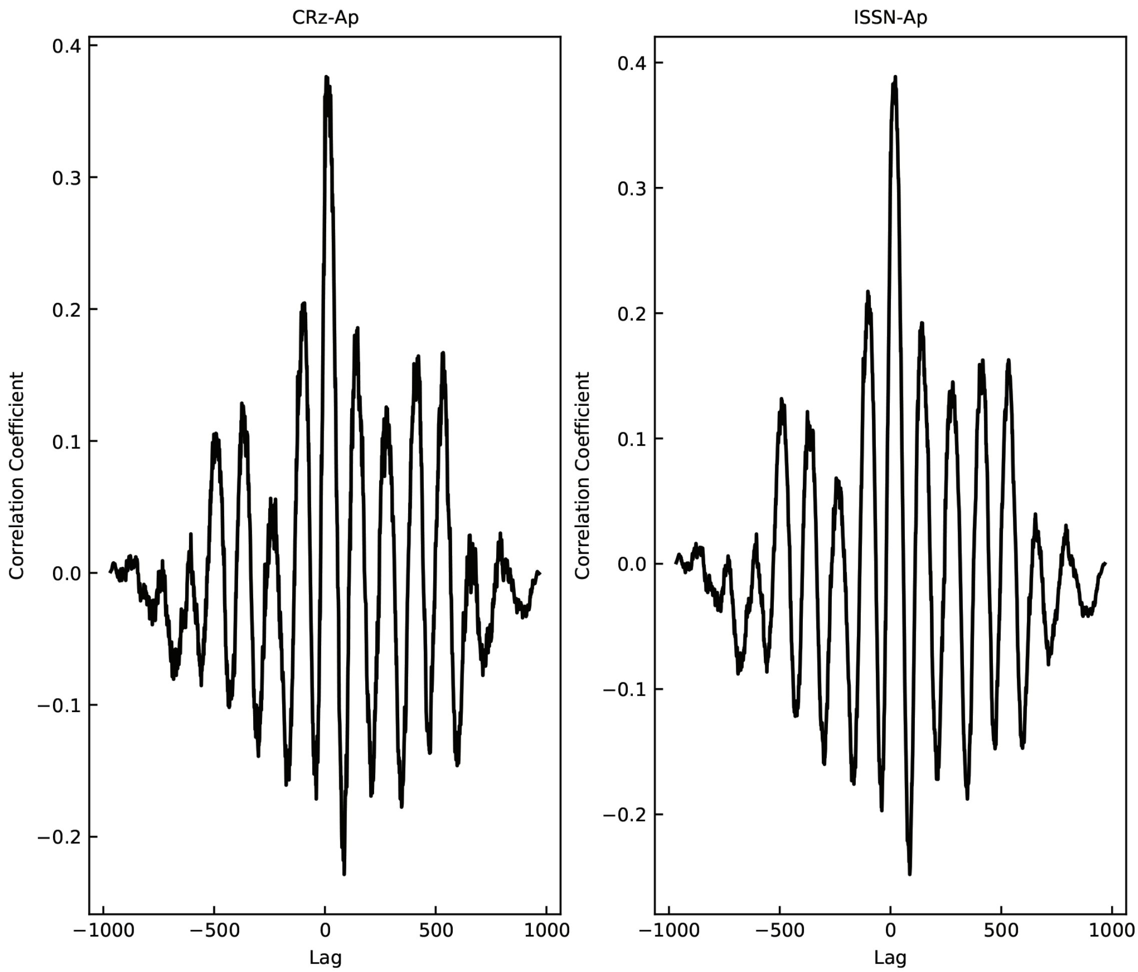

Figure 4. Cross-correlation analysis results between geomagnetic Ap index and CRz (left) and ISSN (right) datasets.

and geomagnetic indices (MCMESI, Ap, and Dst) by using temporal variations and cross-correlation analysis methods. The results are as follows:

1) The temporal variation of CRz describes SSA better than ISSN does.

2) CRz shows very good agreement with ISSN ($r = 0.98$) and also shows generally higher correlation and lower time delays with studied indices compared to ISSN.

We would like to start our discussion with Ref. [6], which introduced the FPP for each sunspot group by using the number of produced flares for each modified Zurich class for the 1996–2017 time period. We recalculated the FPP based on the peak fluxes of produced flares for each sunspot group during the period between 1996 and 2016. In order to calculate FPP, M class X-ray flare peak flux was taken as a reference. C class flare peak flux was then divided by 10; X class flare peak flux was multiplied by 10. Thus, all flares were converted to M class. Note that the FPPs obtained in this study show very good agreement with previously calculated ones with one difference: the FPP of all Zurich classes decreased a small amount except for the F class, which increased remarkably.

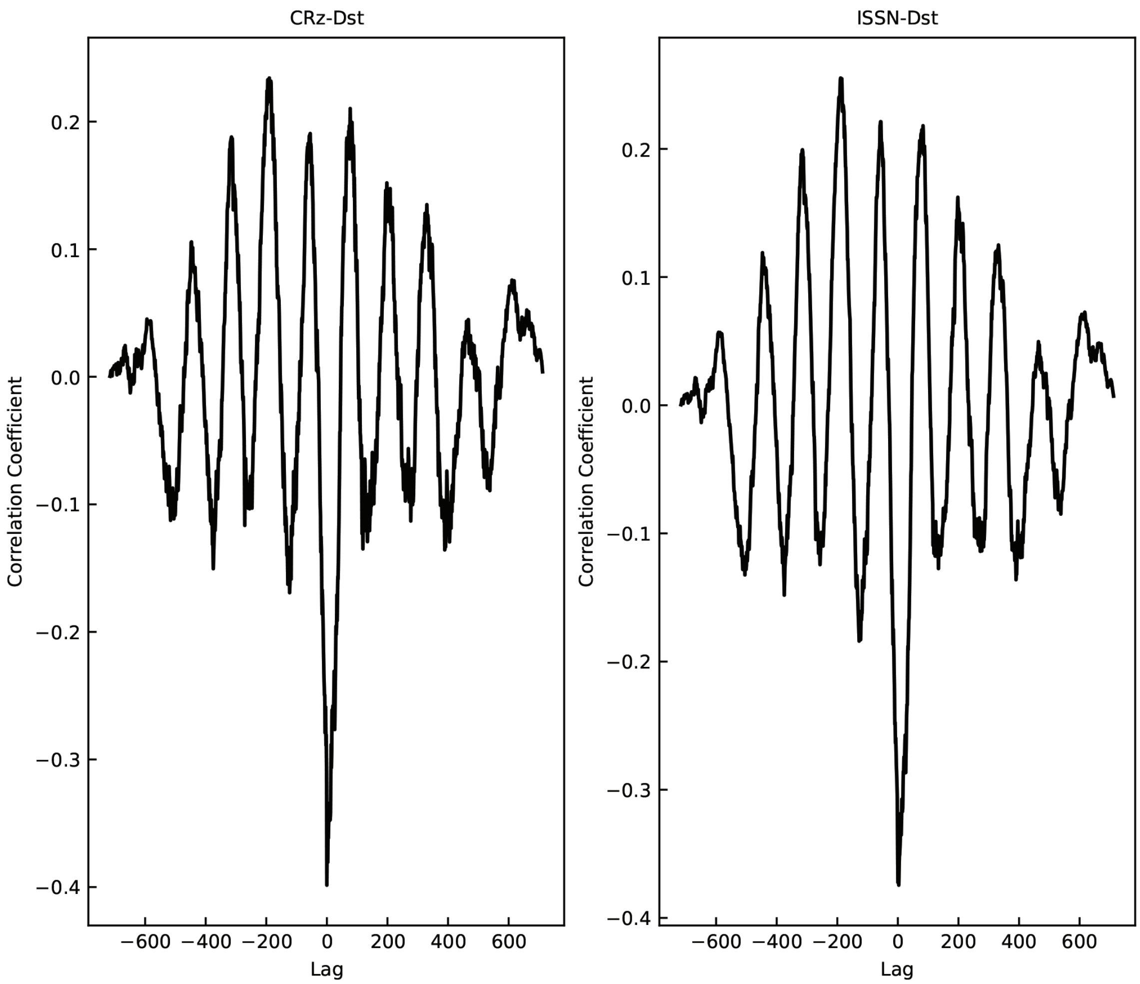

Figure 5. Cross-correlation analysis results between geomagnetic Dst index and CRz (left) and ISSN (right) datasets.

As shown in Eq. (1), all sunspot classes have the same weight in daily sunspot number calculation. However, both the numbers of observed sunspots and sunspot areas are quite different according to their Zurich class: A and B classes describe very small sunspot groups, while E and F classes describe complex and strongly evolved sunspot groups. Ref. [10] analyzed sunspot counts of different sunspot groups in 4 categories and concluded that the temporal behavior of each category is quite different during a cycle. In this study, we calculated the FPP of those groups and found that their FPPs differed drastically. We then recalculated the daily total sunspot number according to the FPPs of those classes as shown in Eq. (2). We found that the new sunspot number data (CRz) show higher correlation with SSA than ISSN. Thus, we may argue that CRz describes the solar activity better than ISSN.

Ref. [9] compared sunspot numbers and the MCMESI, Ap, and Dst indices with each other. They conclude that the MCMESI has been confirmed to be an index that can represent solar activity and geomagnetic indices at the same time. In this study, we compared CRz with the same indices that they compared and found that the results of cross-correlation between CRz and other indices are generally higher compared to ISSN. Therefore, it would be better to use the proposed equation, Eq. (3), in the calculation of the daily total sunspot number.

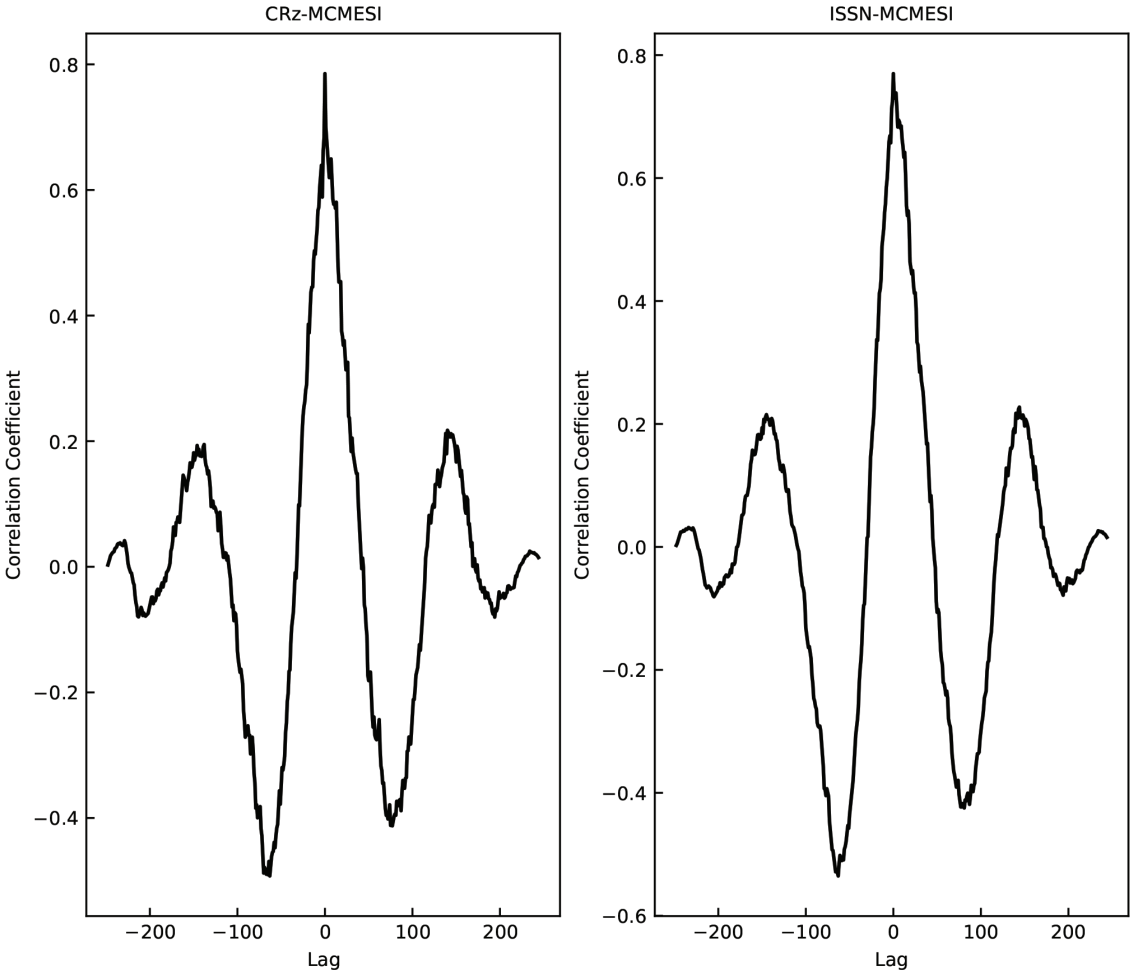

Figure 6. Cross-correlation analysis results between MCMESI data and CRz (left) and ISSN (right) datasets.

Ref. [11] analyzed correlations between yearly mean solar indices (sunspot number, group sunspot number, and cumulative sunspot area) and geomagnetic indices (Ap and Dst) between 1960 and 2001. They reported the correlation coefficient of sunspot numbers with Ap and Dst as follows: 0.55 with a time delay of 2 years, and –0.59 with no delay, successively. Here we used the monthly data between 1996 and 2016 and found the correlation coefficients of CRz with Ap and Dst to be 0.37 with a time delay of 6 months and –0.40 with no delay. Although the results may seem different, these differences mainly come from the temporal resolution and also from different time intervals used in the studies.

Acknowledgments

Solar X-ray peak flux data were taken from the National Oceanographic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC). ISSN data were taken from the Sunspot Index and Long-term Solar Observations (SIDC) website. SSA data were taken from the National Aeronautics and Space Administration (NASA) website. The F10.7 data are taken from the National Geophysical Data Center (NGDC). This study was supported by the Scientific and Technological Council of Turkey (TÜBİTAK), Project 115F031.

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