Solar and Geomagnetic Activity Relation for the Last two Solar Cycles

A. Kilcik [1], E. Yiğit [2], V. Yurchyshyn [3,4], A. Ozguc [5], J.P. Rozelot [6]

[1] Akdeniz University, Department of Space Science and Technologies, Antalya, Turkey
[2] George Mason University, Space Weather Laboratory, Fairfax VA, USA
[3] Big Bear Solar Observatory, Big Bear City, CA, USA
[4] Korea Astronomy and Space Science Institute, Daejeon, South Korea
[5] Kandilli Observ. & Earthquake Research Institute, Bogazici University, Istanbul, Turkey
[6] Université de la Côte d'Azur (OCA), Nice, France

E mail (alikilcik@akdeniz.edu.tr).

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Abstract: The long-term relationship between solar (sunspot counts in different Zurich sunspot groups, International Sunspot Number (ISSN), solar wind, and X-Ray solar flare index and geomagnetic indices (*Ap* and *Dst*) is investigated. Data sets used in this study cover a time period from January 1996 to March 2014. Our main findings are as follows: 1) The best correlation between the sunspot counts and the *Ap* index are obtained for the large group time series, while the other categories exhibited lower (final and medium) or no correlation at all (small). It is interesting to note that *Ap* index is delayed by about 13 months relatively to all sunspot count series and ISSN data. 2) The best correlation between the sunspot counts and the *Dst* index was as well obtained for the large AR time series. The *Dst* index delays with respect to the large group by about 2 months. 3) The highest correlation between the solar and geomagnetic indices were obtained between the solar wind speed and *Ap* and *Dst* indices with zero time delays ($r = 0.76$, $r = 0.52$, respectively). 4) The correlation coefficients between the geomagnetic indices (*Ap*, *Dst*) and X-Ray solar flare index ($r = 0.59$, $r = -0.48$, respectively) are a little higher than the correlation coefficients between these geomagnetic indices and ISSN ($r = 0.57$, $r = -0.43$, respectively). 5) The magnitude of all solar and geomagnetic indices (except the solar wind speed) has significantly decreased during the current solar cycle as compared to the same phase of the previous cycle.

Key words: Solar: Sunspot classification, ISSN, Solar wind, X-Ray solar flare, Geomagnetic indices: Ap, Dst

Introduction

Sun is a variable star and the best known evidence of its activity variation is the presence of sunspots. The sunspots have been observed nearly systematically with the use of telescopes since about 1610 (Vaquero, 2007). The change in the number of observed sunspots is also reflected in all solar activity indicators, such as sunspot areas (SSAs), the 10.7 cm solar radio flux (F10.7 index), the H-alpha solar flare index, X-Ray solar flare index, etc. These indicators exhibit small differences, which are due to the definition of the indices and the underlying physical mechanisms. For example, the daily sunspot number (SSN) is based on counting the dark spots observed on the solar disc on a given day, while the solar flare index is a measure of the energy released by sunspot groups during flaring activity. In general, all solar indices show strong correlative relationship between themselves (Hathaway et al., 2002). They also show certain level of correlation with geomagnetic activity indices such as *aa, Ap,* and the *Dst*. Although the relationship between the solar and geomagnetic activity indices has extensively been studied, the detailed knowledge of their nature has not been fully established (Stamper et al., 1999; Echer et al., 2004; Verbanac et al., 2011; Chertok et al., 2015; and reference therein). To reconcile the physical meaning of the entire spectrum of various solar and geomagnetic indices is indeed a challenging endeavor, but it is necessary to have a consistent picture of the solar and geomagnetic activity.

While the International Sunspot Numbers (ISSNs) is the longest suitable data for describing the solar activity, they may not accurately reflect the actual solar variations that contribute toward the geomagnetic disturbances. The daily sunspot number is defined as follows:

$$Rz = k(10g + f)$$

where f is the total number of individual spots, g is the number of observed sunspot groups (active regions), and k is a correction factor, which varies with location, instrumentation and the observer. As shown in this equation, the daily sunspot number is directly related to the observed group and individual spot numbers without taking into account the group/sunspot properties such as non-potentiality and complexity of their magnetic fields (Kilcik et al., 2011b, 2014). Monthly and yearly ISSN values produced from daily data which is calculated by above equation.

The sunspot group classification was first introduced by Cortie (1901), and later the Zurich sunspot classification was developed by Waldmeier (1947), and further modified by McIntosh (1990). This final version of the classification is known as the modified Zurich Classification, and it is currently used all over the world. This classification based on three components. The first component is the sunspot group class, which describes the morphology of a sunspot group. The second component describes the largest spot in a group, and the third one describes the spot distribution in the interior of the group (for more detail, see

McIntosh, 1990). Based on the first component of this classification scheme, sunspot groups are classified in seven types as A, B, C, D, E, F, and H. Recently, Kilcik et al (2014) divided sunspot groups into four categories which were small (A and B class groups), medium (C), large (D, E, and F) and final (H). The small group category includes small pores and sunspots without penumbra, which generally display no large-scale activity. The medium category represents small active regions of bipolar type with sunspots that developed a penumbra. The large groups are those active regions that have complex magnetic structures, often with multiple sunspots and magnetic polarity inversion lines. Such groups are known to be the source of strong flares and coronal mass ejections (CMEs), which are expelled into interplanetary space with large speeds carrying large amount of charged particles and twisted magnetic fields. The final category includes remnants of active regions of class D, E, and F and is mostly populated with single (former leading) sunspots accompanied by few pores in the trailing parts.

Flare events are often associated with CMEs as well as strong geomagnetic storms (Hudson and Li, 2010; Verma et al., 2012; Shanmugaraju and Prasanna, 2014; Gopalswamy et al., 2014; Dumbovic, et al., 2015, and references therein). CMEs are sudden bursts of energetic solar plasma that can impact Earth's upper atmosphere. This interaction between the solar wind and the geospace is the origin of the local space weather, which has great societal and technological implications. The majority of strong geomagnetic storms are driven by active region associated CMEs and only about 13% of strong geomagnetic storms are driven by a co-rotating interaction region (CIR) that forms at the leading edge of a high-speed solar wind streams originating from a solar coronal hole (Zhang et al. 2007, Gopalswamy et al. 2007). Gosling (1993) discussed in detail the role of CMEs in the context of geomagnetic storms and energetic particle events. He stated that CME-driven interplanetary disturbances are the prime cause of large geomagnetic storms and that solar flares, however, have no fundamental role in this process. Variations of plasma flows in Earth's ionosphere can greatly modulate Joule heating and ion drag which play a great thermal and dynamical role in shaping the variability and the overall morphology of the thermosphere (Yiğit and Ridley, 2011; Yiğit et al., 2012). During geomagnetic storms, these effects in the neutral upper atmosphere are much more pronounced mainly because of the enhancement of plasma flow speeds (Yiğit et al., 2016).

Here we focus on temporal and correlative relationships between the number of sunspots (sunspot counts) in different sunspot categories as defined above) and geomagnetic indices *Ap* and *Dst* during the last two solar cycles 23 and 24. It is well known that the geomagnetic activity tends to peak during the descending phase of a solar cycle because of the increase of the frequency of high speed solar wind streams originated from the coronal holes (Mursula et al., 2015). Therefore, we compared these geomagnetic indices with solar wind speed. On the other hand, it is well known that large and complex active regions tend to appear more frequently during the descending phase of the solar cycle (Kilcik et al, 2011b; 2014). They produce intense solar flares accompanied by high speed CMEs, which warrants the comparison between these geomagnetic indices and the X-ray solar flare index. To the best of our knowledge, the results to be presented are the first study that compares the sunspot count data for four categories of active regions and the geomagnetic indices *Ap,* and *Dst*.

We describe all data sets and methods in Section 2, analysis and the results are given in Section 3, while the conclusions and implications of our findings are presented in Section 4.

Observational Data and Methodology

Sunspots are the main transient structures observed in the photosphere of the Sun. They may have very strong magnetic fields up to about a few thousand Gauss. Since their temperature is much lower than their surroundings they appear generally as darker regions on the solar photosphere. The sunspot data used in this study are taken from the National Geophysical Data Center (NGDC)[1]. The database includes measurements from Learmonth, Holloman, and San Vito Solar Observatories. We used the Learmonth Solar Observatory data (LEAR) as the principal data source, while the data gaps were filled in with observational records from one of the other stations listed above, so that a nearly continuous time series was produced. The raw data set includes the modified Zurich classification, sunspot count, sunspot area, etc, for all sunspot groups observed on the solar disc for a given day. As a mean data set, the total daily sunspot counts were calculated for each group. Here, the sunspot groups were divided into four categories depending on their Zurich classification: small (A and B), medium (C), large (D, E, and F) and final (H), as described in Kilcik et al (2014). This separation reflects the complexity and flare/CME productivity of sunspot groups/active regions (ARs). The most complex groups belong to the large category and they produce more flares and CMEs, while the small category represents the least complex ARs. We thus produced the monthly averaged sunspot counts for each of the category and compared them to the other data sets used in this study.

The monthly averaged ISSN, and the raw X-Ray solar flare indices were taken from the *NGDC*[1], daily geomagnetic *Ap* and *Dst* indices were provided by the World Data Center for Geomagnetism of Kyoto University[2], and the solar wind speed data were taken from the OMNIWeb Plus data and service[3] operated

[1] http://www.ngdc.noaa.gov/

[2] http://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html

[3] http://omniweb.gsfc.nasa.gov/hw.html

by the Goddard Space Flight Center, NASA for the period from January 1996 to March 2014.

A solar flare is an explosion that occurs in the solar upper atmosphere, and it happens when stored magnetic energy is suddenly and rapidly released. They were detected for the first time in the visible spectral range as localized brightenings inside a sunspot group in 1859 (Carrington, 1859) and are regularly observed in the H-alpha line (6563 Å) since about 1930s, while in the soft X-Ray range (1 to 8 Å) flares are regularly observed since 1978. The magnitude of the flare associated X-Ray flux is classified as A, B, C, M, and X on a logarithmic scale and measured in watts per square meter (W/m^2). Each flare of a given class releases 10 times more energy than those in the lower class.

The solar wind is a plasma cloud that consists of mainly protons and electrons. The solar magnetic field is embedded and carried by this plasma that flows outward from the Sun and strongly affects Earth and the near space environment. The main source of the solar winds is coronal holes (CHs), which are of three types (Storini et al. 2006): (i) polar CHs located at the solar poles and having a lifetime comparable to that of the solar cycle; (ii) isolated CHs, which are mostly limited to the low and middle latitudes and their lifetime is comparable to few solar rotations; and (iii) transient CHs coronal holes, which have a very short life time (hours or days) and their occurrence is often associated with powerful eruptions (flares) and/or filament disappearances (Thompson et al, 1998). Polar CHs are generally dominant during the solar minimum and they disappear during the maximum of the solar cycle, while the isolated and transient CHs appear mostly during the solar activity maximum (Abramenko et al 2010).

The *Ap* index is a mean measure of the solar particle effect on Earth's magnetic field and characterizes the general level of geomagnetic activity on Earth for a given day. It is derived from *a* and *Kp* indices and measured at a number of midlatitude stations worldwide (for the detailed description see, Bartels et al. 1939).

The hourly *Dst* index is obtained from several magnetometer stations near the equator (for the detailed description see, Sugiura, 1964). The *Dst* index is a direct measure of the hourly averaged perturbation of the horizontal component of the geomagnetic field. Large negative *Dst* values indicate an increase in the intensity of the ring current (geomagnetic storm), while slow ones indicate a decrease. It is found that the *Ap* and *Dst* indices are highly correlated (Saba et al., 1997; Kilcik et al. 2011a, and reference therein).

We kept A class flares as the same, and all other classes multiplied by ten over 1, 2, 3, and 4, for the B, C, M and X, respectively. We used cross-correlation analysis which produces the maximum correlation coefficient and the time delay between the two compared data sets. For visual convenience, all monthly time series were smoothed with the 12 point running average filter. Finally, the Fisher's test was applied to determine the confidence level of these correlation coefficients by evaluating the upper and lower limits of confidence intervals. Here, we used the largest deviation from the obtained correlation coefficient as error (see Table 1).

Analysis and Results

First, we compared the monthly average sunspot counts with the geomagnetic *Ap* and *Dst* indices (see Figure 1). Several interesting points can be highlighted in this figure. (1) Sunspot counts time profiles determined for different categories (small, medium, large and final) behave differently: while the small sunspot groups reached their maximum in 2000, the large ones peaked two years later in 2002; (2) the best agreement between the geomagnetic indices and the sunspot counts was found for the ARs, while no agreement was found for the small sunspot groups; and (3) the maximum of geomagnetic indices was observed to occur about one year later than the peak of the large groups, and the first (2001) and third (2005) local maxima in *Dst* and *Ap* indices showed a good match with the large group sunspot counts.

Figure 2 shows the temporal variations of *Ap* and *Dst* indices along with the X-ray solar flare index, the solar wind speed, and ISSN. The maximum of ISSN is observed near 2000, while the *Ap* and *Dst* are reaching their maxima in 2003. There is a sharp decrease in the flare index in 2003, which is quite opposite from the *Ap* and *Dst* indices, which were still increasing. Later, the flare index is sharply increasing, corresponding to *Ap*, and *Dst* maxima; 3) ISSN data have smoothly increasing and decreasing trends for the entire time interval, while the flare index, *Ap* and *Dst* data sets show very good agreement especially during the ascending and descending phases, i.e, around 1999, 2004, 2007. It is noteworthy that all the flare and geomagnetic indices showed substantially lower magnitudes at the beginning of the current cycle 24 as compared to the same phase of the previous solar cycle.

To estimate the degree of the relationship between solar and geomagnetic parameters, we applied the cross-correlation analysis to monthly data sets and the results are given in Figures 3, 4, 5, and 6. The correlation coefficients, time delays and their significance are listed in Table 1.

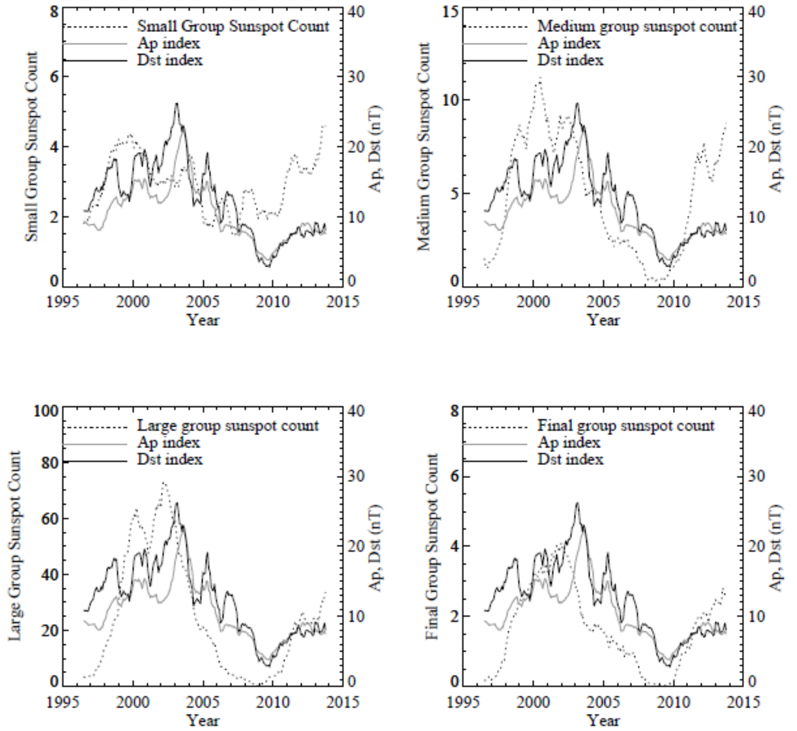

Figure 1. Temporal variations of geomagnetic indices (Ap and Dst) and the monthly averaged number of sunspot counts in each of the four categories. Clockwise from the upper left corner: small (A and B classes), medium (C class), final (H class) and large (D, E, and F classes) ARs. The dotted lines represent the sunspot counts and the Dst/Ap indices are plotted with black/gay solid lines

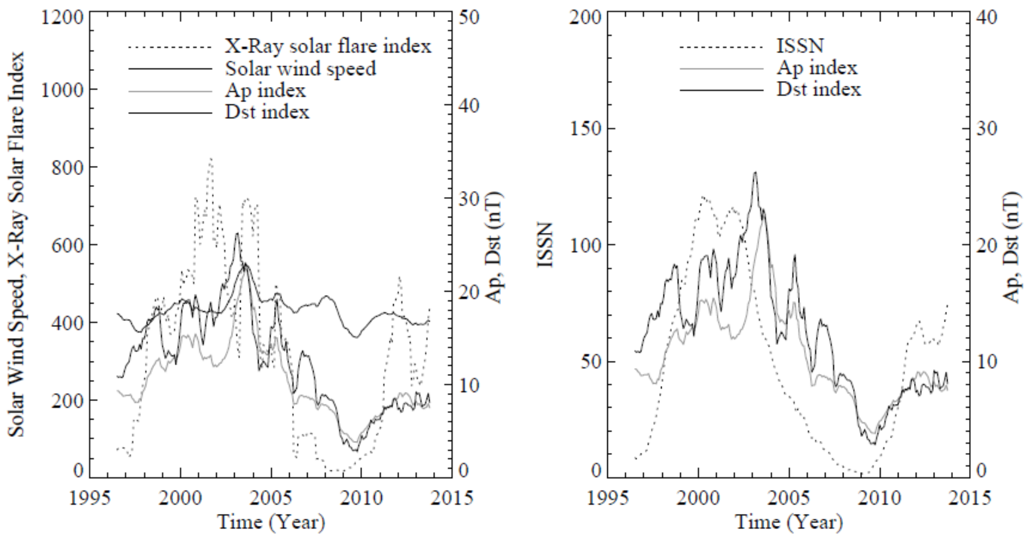

Figure 2. Temporal variations of *Ap* and *Dst* indices, the X-Ray solar flare index, the solar wind speed (left panel) and the ISSN (right panel). In this plot, dotted lines show the X-Ray solar flare index (left panel) and ISSN (right panel), the thick solid lines the *Dst* index, the gray solid lines represent the Ap index, and the thin solid line in the left panel is the solar wind speed.

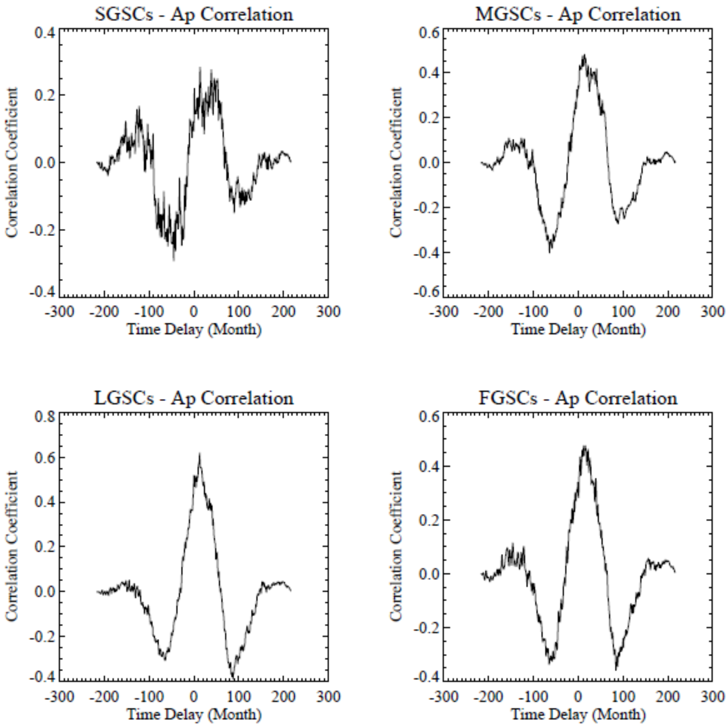

Figure 3. The cross-correlations results for sunspot counts in different categories and *Ap* index. SGSCs, MGSCs, LGSCs and FGSCs describe Small, Medium, Large, and Final Group Sunspot Counts, respectively.

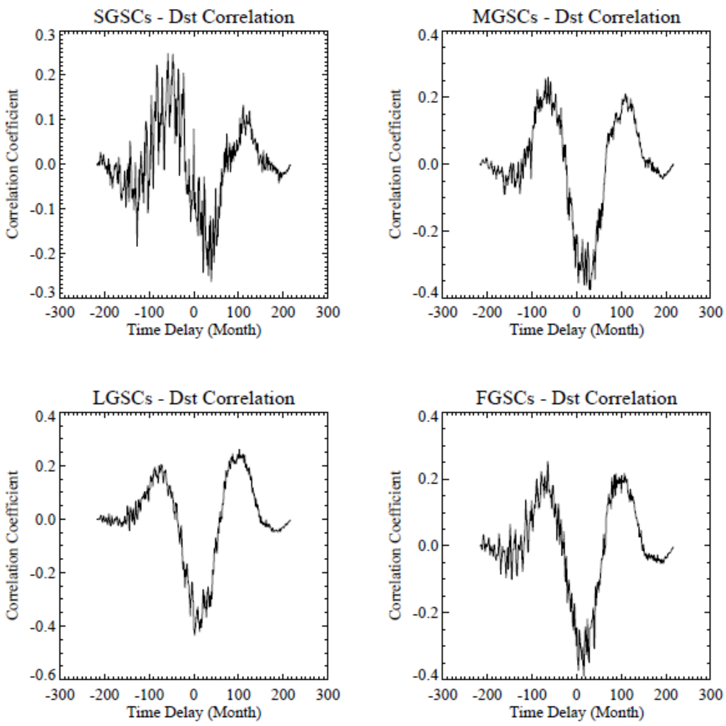

Figure 4. The cross-correlations results for sunspot in different categories and Dst index. SGSCs, MGSCs, LGSCs and FGSCs describe Small, Medium, Large, and Final Group Sunspot Counts, respectively.

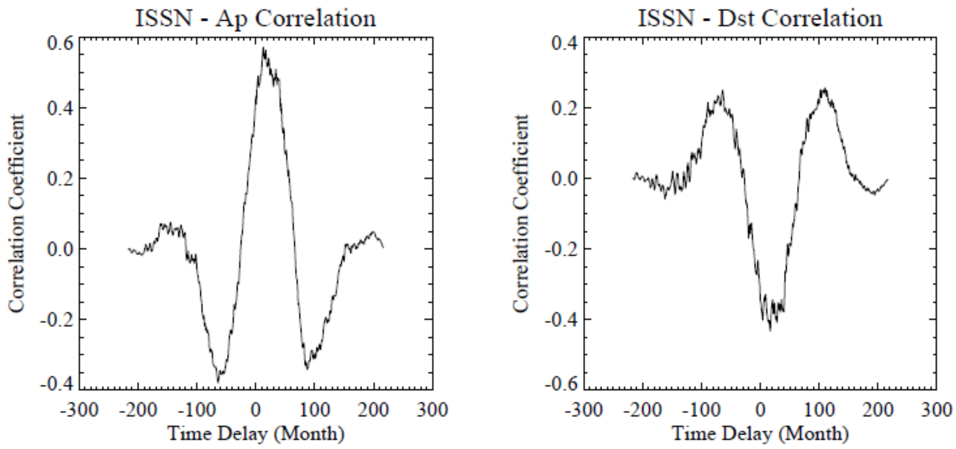

Figure 5. The cross-correlation results for the geomagnetic *Ap* (left panel) and *Dst* (right panel) indices and the ISSN data.

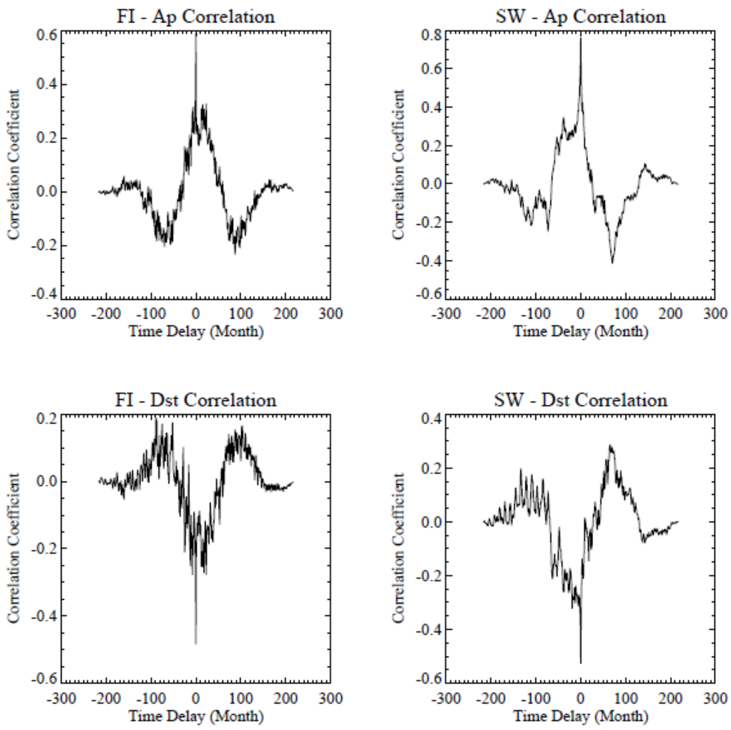

Figure 6. The cross-correlation results for the geomagnetic indices (*Ap* and *Dst*) and the solar flare index (FI) and the solar wind speed (SW).

Table 1. Cross-correlation coefficients and corresponding time delays. SGSC, MGSC, LGSC and FGSC describe Small, Medium, Large, and Final Group Sunspot Counts, respectively.

	Ap (nT)	Delay (Month)	Dst (nT)	Delay (Month)	Time of Maximum
SGSC	0.28 ± 0.13	14	-0.26 ± 0.13	39	1999.8
MGSC	0.48 ± 0.11	14	-0.38 ± 0.12	31	2000.5
LGSC	0.62 ± 0.09	13	-0.44 ± 0.11	2	2002.2
FGSC	0.48 ± 0.11	12	-0.39 ± 0.12	16	2002.0
ISSN	0.57 ± 0.10	13	-0.43 ± 0.11	17	2000.3
X-ray solar flare index	0.59 ± 0.09	0	-0.48 ± 0.11	0	2001.7
Solar Wind Speed	0.76 ± 0.06	0	-0.53 ± 0.10	0	2003.6

As evident from these figures and Table 1, the best correlation between the sunspot counts and geomagnetic indices was found for the large ARs, while, the final and medium ARs show significantly lower and nearly the same correlations. As expected, the lowest correlation is obtained for the small groups. It also is interesting to note that the geomagnetic *Ap* index lags behind all sunspot count series by about 13 months. Similarly, the best correlation between the sunspot counts and the *Dst* index was obtained for the large ARs time series, while the correlation coefficients are nearly the same for the medium and final AR categories. The *Ap* index shows higher correlation (*r = 0.57*) with *ISSN data* than with all sunspot count series, except the large ARs (*r = 0.62*) with a 13 month delay. The ISSN and the large groups show almost the same level of correlation with *Dst* index (*r = -0.43* and *r = -0.44* respectively), but the Dst index is delayed by about 17 months with respect to ISSN, while the delay is only two months in case of the large groups. The highest correlation between the solar and geomagnetic indices was obtained between the solar wind speed and the *Ap* and *Dst* indices with a zero time delay (*r = 0.76*, *r = 0. 52,* respectively). The X-Ray solar flare index data also showed good agreement with both *Ap* and *Dst* indices (*r* = 0.59, and *r* = -0.48, respectively) with a zero time delay. These correlation coefficients are a little higher than those found for the ISSN, which may reflect the fact that a large number of major flares is accompanied by CMEs affecting the Earth's space weather.

Discussion and Conclusions

In this study, we investigated the relationship between the monthly averaged solar activity indicators (i.e., sunspot counts in different categories, ISSN, solar wind speed, and X-Ray solar flare index) and the geomagnetic indices (*Ap* and *Dst*) by using the cross-correlation analysis. The main findings are as follows.

(1) The best correlation between the sunspot counts and the *Ap* index are obtained for the large AR time series, while the other categories exhibited lower (final and medium) or no correlation at all (small). It is interesting to note that *Ap* index is delayed by about 13 months relatively to all sunspot count series and ISSN data.

(2) The best correlation between the sunspot counts and the *Dst* index was obtained for the large AR time series as well. The *Dst* index delays with respect to the large AR by about 2 months.

(3) The highest correlation between the solar and geomagnetic indices were seen between the solar wind speed and *Ap* and *Dst* indices with zero time delays (*r = 0.76*, *r = 0. 52,* respectively).

(4) The correlation coefficients between the geomagnetic indices (*Ap, Dst*) and X-Ray solar flare index (*r = 0.59*, *r = -0.48*, respectively) are somewhat higher than the correlation coefficients between these geomagnetic indices and ISSN (*r = 0.57*, *r = -0.43*, respectively).

(5) The magnitude of all solar and geomagnetic indices (except the solar wind speed) has significantly decreased during the current solar cycle as compared to the same phase of the previous cycle.

Kilcik et al (2011b) analyzed sunspot group counts separated into two categories, small and large ones, and found that the number of large ARs peaked nearly two years after than the peak of the small ARs, which peaked at the same time with the ISSN (2000), while the large ARs reached their maximum simultaneously with the F10.7 flux, the facular area, and the maximum CME speed index (2002). The authors concluded that since the fast CMEs largely determine the most intense geomagnetic activity, the large AR counts may be valuable in describing the geo-effectiveness of solar activity. Later, Zhang et al. (2007), Gopalswamy et al. (2007) and Verbanac et al (2010) discussed two main sources of geomagnetic activity and concluded that the CMEs that are the principal driver of intense geomagnetic storms in the interval around the solar activity maximum, and the high speed solar wind streams, originating from the low latitude CHs, which dominate in the declining phase of the solar cycle. We used different approach and data set and further confirmed their conclusion. Major flares and CMEs most frequently occur in complex and large ARs, which explain the correlation between the monthly averaged sunspot counts of the large ARs and the *Dst* index. On the other hand, the *Ap* index is considered to be more sensitive to the high speed solar wind streams that typically emanate from CHs. The existence of correlation between large ARs and the *Ap* is an evidence that large groups contribute more to the high speed streams as compared to other types of ARs. The *Ap* index has constant time delay (about 13 months) with all categories sunspot count data sets, while the *Dst* index has variable time delay. This result show that the main sources of correlations between these geomagnetic indices and sunspot counts are different: the *Ap* index variations are more sensitive to the fluctuations observed in sunspot counts, while the *Dst* index variations are sensitive to the general trend except large groups that they have only two months delay.

Echer et al. (2004) compared the annual sunspot numbers with the *Dst* and found a 0.57 negative correlation with zero time delay. Verbenac et al. (2010) compared the annual 10.7 cm solar radio flux (F10.7) with *Ap and Dst* indices, and reported 0.57 positive correlation with a two year delay, and a 0.61 negative correlation with a zero time delay for the entire time interval between 1960 and 2001, respectively. They noted a significant difference from cycle to cycle: F10.7 and *Ap* time series show a four year delay for cycle 21, and one year delay for cycle 22, and no time delay for the ascending phase of solar cycle 23 (1996 – 2001). Later, Verbenac et al (2011) analyzed the correlation between the yearly solar and geomagnetic indices from 1960 to 2001 and reported that the Ap index is delayed by two years with respect to the analyzed solar data (sunspot number, group sunspot number, and F10.7), while the Dst has a zero time delay. Here we report similar tendency, although a slightly shorter delays: 13 and 17 month for the *Ap* and the *Dst* indices for 1996 – 2014 time interval. Note that we analyzed monthly averaged data sets, which determined the temporal resolution of the study. The difference between Verbenac et al (2010) and our results may be due to the data resolution and the analysed time intervals: while Verbenac et al (2010) analyzed the ascending phase of cycle 23, we analyzed the the entire cycle.

The X-Ray solar flare index and the geomagnetic indices show high correlation with a zero time delay. As shown in Figure 2 left panel, the main contributor of the correlation between X-Ray solar flare index and geomagnetic indices are ascending and descending phases of the solar cycle 23; at that time intervals (1997-2001, 2003-2008) these data sets follow one another quite well, while ISSN data has a very smooth temporal variation along the entire time interval (see Figure 2 right panel). Thus, we may argue that to describe the geomagnetic activity, the X-Ray Solar flare index is the better indicator compared to ISSN.

Kilcik et al. (2011a) compared *Ap* and *Dst* indices with ISSN and the maximum CME speed index (MCMESI) from 1996 to 2008. They found that the MCMESI show better correlation with geomagnetic indices (($r = 0.68$, $r = -0.53$, for *Ap* and *Dst*, respectively) than ISSN does ($r = 0.51$, $r = -0.37$, respectively). As shown in Figure 5, here, we analyzed ISSN and these geomagnetic indices (*Ap, Dst*) from January 1996 to March 2014, and found different correlations ($r = 0.57$, $r = -0.43$,*respectively*). We obtained little higher positive correlation between ISSN and geomagnetic *Ap* index ($r = 0.57$). Possibly, this small difference may arise from the difference of the investigated time intervals. For the ISSN and geomagnetic *Dst* indices, the highest correlation is also better than their previous result. On the other hand, we calculated the correlations between the geomagnetic indices (*Ap, Dst*) and solar wind speed/X-Ray solar flare index, and found that the highest correlations exist between the solar wind speed and these geomagnetic indices ($r = 0.76$, $r = -0.5$, for *Ap* and *Dst*, respectively). X-Ray solar flare index also shows a higher correlation than all sunspot counts and ISSN with the same geomagnetic indices ($r = 0.59$, $r = -0.48$, respectively).

It is known that the most of flare activities occur in large (complex) sunspot groups, they are also clearly associated with CME activities. The CME activities also affect the solar wind variations, but the main source of the solar wind is the coronal holes. As shown in Table 1 both *Ap* and *Dst* indices show higher correlations with the solar wind speed and X-Ray solar flare index compared to all sunspot counts and ISSN data with zero time delay. On the other hand, sunspot counts and ISSN data have constant time delay (13 months) with *Ap* and variable delay with *Dst*. The highest correlation between these indices is obtained in the case of large groups with 13 and 2 month time delays for *Ap* and *Dst*, respectively. Thus we may argue that solar active events such as flares and CMEs, mostly arise from complex groups, are more dominant on *Dst* variations compared to Ap variations.

We would like to emphasize that Kilpua et al. (2014) analyzed geomagnetic the *Dst* and *AE* indices as well as the interplanetary magnetic field (IMF) and plasma conditions, during two periods around the last two solar minima and rising phases (1995-1999 and 2006-2012) and reported very low geomagnetic activity during solar cycle 24. Later, Kilcik et al. (2014) compared sunspot counts in different Zurich class sunspot groups with ISSN and found that both ISSN and large ARs counts show significant decrease during the first half of the current solar cycle 24. In this study, we found that this significant decrease also exists in X-Ray solar flare index, while the situation is completely different for solar wind speed that it is almost in the same level with previous cycle. This agreement strongly supports the argument that the CME associated solar X-Ray flare activities, mostly occur on large/complex active regions, and strongly affect Earth's geomagnetic activity.

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