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Long-term correlation between solar and geomagnetic activity

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Abstract

A long-term correlation study between solar and geomagnetic activity is reported in this work using annual averages of the *aa* index and of the sunspot number R_z in the period of 1868–2000. *Dst* and *AE* geomagnetic indices and solar wind speed data are used for more recent periods. It is shown that the geomagnetic and solar activity correlation has decreased since the end of the 19th century, and the lag between them has increased. The variations of R_z and *aa* were in phase in the early period (solar cycles 11–14, around 1868–1910), and became out of phase in later periods (with a lag of 2 years in solar cycle 22, with *aa* maximum after R_z). Nevertheless, this trend is not monotonic and superposed fluctuations are seen, which does not permit determine if this correlation decrease is part or not of a long period solar activity cycle. The probable cause of the correlation decrease seems to be related to the *aa* index dual peak structure. The second *aa* peak seems to have increased relative to the first one. This second peak is more related to the high-speed streams originated from co-rotating structures whereas the first one is related to sunspot (coronal mass ejections) activity. In recent periods, since 1964, it has been observed that *aa* annual values have higher correlation with the fraction of days per year with daily solar wind speed peaks larger than 500 km/s (F_{pk}) than with R_z. The *aa* index also shows larger correlation with *AE* index than with *Dst*. Thus, it seems that average *aa* is strongly influenced by *AE* activity, which is influenced mainly by high speed streams from coronal holes. One can conclude that the decrease in correlation between *aa* and R_z occurs because the second *aa* peak has becoming stronger relative to the first one. The cause seems to be that open solar magnetic field structures have increased their activity relative to the closed (sunspot-related) solar magnetic field structures. This implies that the global solar magnetic field could have experienced a differential (between closed and open structures) large-scale variation in the last 130 years.

Keywords: Geomagnetic activity; Solar activity; Solar wind; Sunspot number

1. Introduction

The 11-year solar cycle and the associated variability in the electromagnetic environment of Earth—the geospace—has been largely studied in the last decades (Russel, 1975; Akasofu, 1981; Gorney, 1990; Gonzalez et al., 1994, 1999). However, the long-term relation between solar and geomagnetic activity is a topic of intense research and it is not very well understood at present (Crooker et al., 1977; Gorney, 1990; Thompson, 1993; Cliver et al., 1996; Kishcha et al., 1999; Richardson et al., 2000; Wang et al., 2000).

The Wolf (or Zurich) sunspot number (R_z) has been largely used to infer the long-term variability of the solar activity with annual averages available since 1700 (Eddy, 1976). The longest time series of geomagnetic activity is the 3-h antipodal *aa* activity index (*aa*), which was defined by Mayaud (1972). The *aa* is derived from the *K*-indices (Menvielle and Berthelier, 1991), which are difficult to interpret physically because they can be affected by several current systems, such as the auroral

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electrojets, magnetopause, field-aligned and ring currents (Gonzalez et al., 1994).

In this paper, the evolution of the correlation and lag of *aa* and R_z annual average series is studied for the period 1868–2000 and compared with solar wind speed data (since 1964) and *Dst–AE* indices (since 1957), in order to assess the physical mechanisms responsible by the differences in the long-term variation of geomagnetic and solar activity correlation.

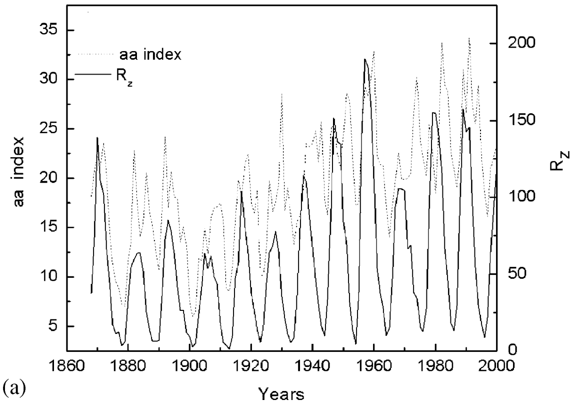
2. Indices and solar wind data

Sunspot number and *aa* index annual averages for the period of 1868–2000 were analyzed in this work. The sunspot number time series was obtained from the Sunspot Index Data Center in Brussels, Belgium. Annual averages of the 3-h *aa* index were obtained from the NGDC—National Geophysical Data Center—National Oceanic and Atmospheric Administration—NOAA, USA. Hourly values of solar wind speed were obtained from the OMNIWeb database for the period of 1964–2000. *AE* and *Dst* indices were obtained from World Data Center for Geomagnetism, WDC-2, Kyoto.

3. Results

In Fig. 1a the time series of *aa* and R_z are shown and their very well-known behavior is easily seen. The 11-year periodicity in R_z is also observed in *aa*. Sunspot number has a cyclical variation with the minimum of a cycle reaching the same level than the minimum of the preceding cycle, while *aa* shows an increasing trend in both minima and maxima values of the cycle (Gorney, 1990). A very well-known feature in the *aa* time-series is its dual-peak structure (Gonzalez et al., 1990; Gorney, 1990), with one peak close to the solar cycle maximum and the other one in the descending phase. It is believed that the first peak is caused by coronal mass ejections (CMEs) related activity, whereas the second peak is caused by geomagnetic disturbances due to co-rotating interaction regions (CIRs) between coronal hole fast solar wind streams and the lower solar wind streams, which are more frequent in this part of the solar cycle (Gosling et al., 1976; Crooker et al., 1977; Gonzalez et al., 1990; Richardson et al., 2000).

A cross-correlation analysis was applied to the *aa* and R_z series. The largest correlation coefficient ($r = 0.66$) was found for a lag of 1 year (*aa* maximum after R_z maximum). A larger correlation is obtained by using 11-year running averages. The correlation coefficient is $r = 0.94$ with lag $= 0$ years. This result indicates that on a large time scale the solar and geomagnetic activity have greater correlations because both are affected by the long-term component in the solar activity.



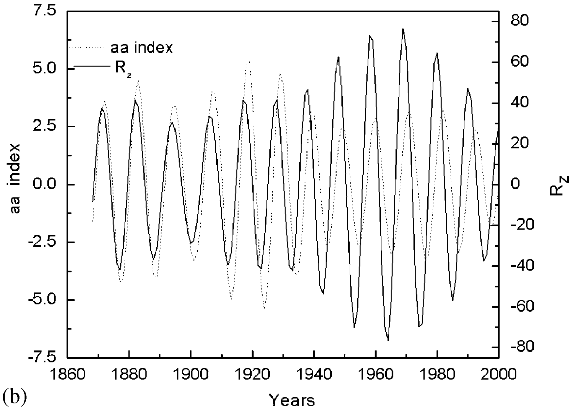


Fig. 1. (a) Annual averages of *aa* and R_z time series for the period of 1868–2000; (b) filtered data, 9–13-year band pass, of R_z and *aa* annual averages.

In order to study the correlation evolution in the spectral band of 11-year solar cycle, both *aa* and R_z series were filtered with a 9–13-year band pass filter, shown in Fig. 1b. The correlation coefficient is 0.78 and the lag = 1 year (*aa* maximum after R_z maximum). It can be seen from this figure that in the early period, both series were varying in phase. However, the variation became out-of-phase around the 1910s. Lag between *aa* and R_z seems to be increasing with time, particularly in the later studied period, when three is a larger discrepancy between the two series.

In order to determine how the lag is varying with time, cross-correlation was calculated between R_z and *aa* for every solar cycle (original and filtered data). The cycle was defined starting one year after the minimum value of R_z to the year with the next R_z minimum. Fig. 2a shows the correlation coefficient on the right and the lag on the left-axis for (a) original data and (b) filtered data. The points are plotted in the year of maximum R_z for each cycle.

In original data (Fig. 2a), the lag was close to zero year until 1910–1920s, with large correlation coefficients, and had an upward trend after that period, superposed with

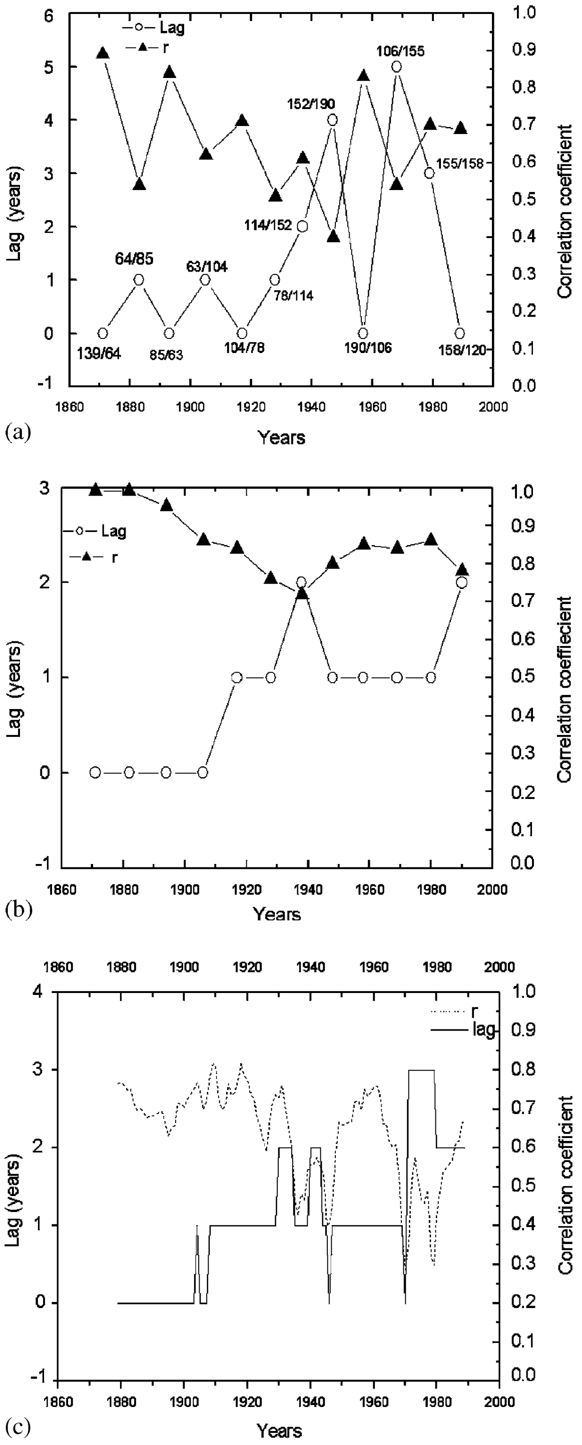


Fig. 2. Correlation coefficients and lag for each solar cycle for: (a) annual averages of *aa* and R_z, the labels for each lag point shows the amplitude of that cycle relative to the next one; (b) 9–13 year filtered data of annual averages; (c) 23-year running mean correlation.

oscillations. Lag was also close to zero for filtered series from the period between 1868 and 1912, increased to 1 year during the period 1913–1974 (with exception of 1934–1944 cycle) and 2 years in the period 1975–1985. Cross-correlation coefficients are very large in the early cycles ($r = 0.99$ for the first two cycles), and decreased after 1910, reaching $r = 0.72$ for the period 1986–1996. Thus, the aa–R_z correlation has a decrease trend, with some oscillations, result that was previously observed by Kishcha et al. (1999).

In order to improve statistics and use more data points, a 23-year running average correlation coefficients and lags were calculated, similar to the work of Kishcha et al. (1999). These results are shown in Fig. 2c. The period of 23 years was chosen because shorter intervals could cause distinction due to even and odd number cycles that could influence the long-term correlation (Kishcha et al., 1999). The 23-year running average coefficients also show a decreasing trend with time, superposed with fluctuations. Lag is seen to be zero in the beginning of series and increases after 1910s, in agreement with cycle results (panels 2a and 2b). It is important to comment that the period 1880–1930 is considered to be of a weak solar activity, especially around 1900 (Gorney, 1990), and although the correlation started to decrease during this period, it reached a minimum around 1940s, in the transition from these weaker cycles to the more recent and stronger solar cycles. Thus, it is not possible to conclude at present if the long-term decrease in solar-geomagnetic correlation has a monotonic nature or if it is part of a long solar activity periodicity.

Also shown in Fig. 2a is the ratio between solar maximum R_z values for the current and the next cycle. It is seen that cycles which exhibit a lag of zero year are cases when the amplitude of the cycle is larger than that of the next one. Since coronal holes in the descending phase are related to magnetic fields of the next solar cycle (Layden et al., 1991; Thompson, 1993), it seems that the cycles with zero lag are the ones when geomagnetic activity is stronger around solar maximum, while cycles when lag is higher than zero are years when geomagnetic activity is stronger during the descending phase, which could imply different weights of solar magnetic field between a cycle (mostly closed sunspot related structures) and the next one. This fact is well known and is the basis of the precursor method to predict solar cycle amplitudes (Thompson, 1993).

Fig. 3 shows the amplitude ratio between the two *aa* peaks, the lag among the two *aa* peaks and R_z and the lag between the first and second *aa* peaks. The first *aa* peak (aa_1) has a small difference to the R_z maxima, around 0 to −1 years, with exception of solar cycle 17 (around 1940), when the difference is of 4 years. It is expected that this first *aa* peak varies mostly in phase with R_z, because it is more related to CMEs structures. The second *aa* peak (aa_2) has a difference to the R_z maxima between 2–4 years during most of time, with values of 6 years in cycles 17 and 20. This second peak is always in the descending phase, related to

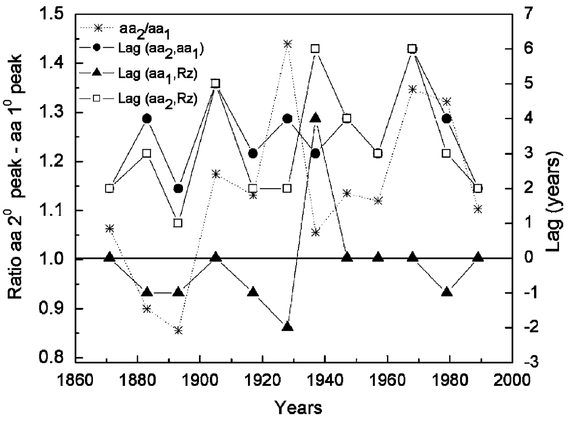


Fig. 3. Left axis, ratio between *aa* second and first peaks (dotted line with stars). Right axis, lag (years) between the two *aa* peaks (continuous line with solid circles), between the *aa* first peak and R_z (continuous line with solid triangles) and between the *aa* second peak and R_z (continuous line with open squares).

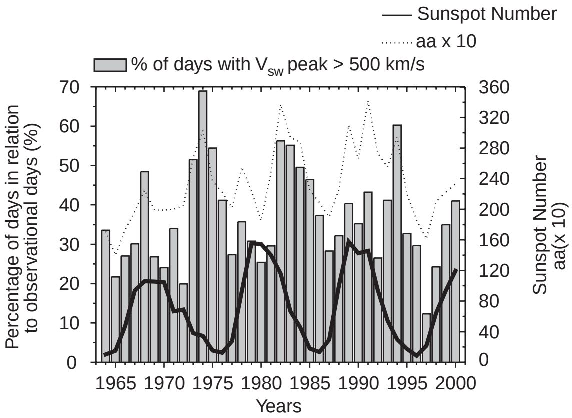


Fig. 4. Annual averages of R_z (continuous line), *aa* (dotted line, multiplied by 10× for visualization) and the fraction of days per year with solar wind speed peak higher than 500 km/s (bars) for 1964–2000.

coronal holes activity. The difference between the two *aa* peaks varies between 2 and 5 years.

It is observed that until solar cycle 13 ($\sim$ 1910) the ratio between successive *aa* peaks was most of time lower than 1, indicating the first peak was more important (a higher weight to CME-related activity on geomagnetic activity) and later the ratio is always larger than 1—the second peak became more important. This result could explain the increase in lag and decrease in correlation coefficient between *aa* and R_z, because it seems to show that solar wind structures dominant to drive average geomagnetic activity have changed from CME-related do CIR-related.

It is important to comment in addition that in some cycles (maximum around 1920, 1930, 1970 and 1990), a triple peak structure appears in *aa* annual averages. These extra peaks occur in the descending phase of solar cycle and they are probably also related to the CIR structures.

In order to assess the relative importance of solar closed and open magnetic field structures, the fraction of days per year with solar wind speed peak > 500 km/s ($F_{\rm pk}$) was determined from OMNI database, in the period of 1964–2000, and it was compared to *aa* and R_z variability (Echer et al., 2001). In Fig. 4, the R_z (continuous line), *aa* (dotted line) and $F_{\rm pk}$ (bars) series are shown. The *aa* series was multiplied by 10 for better visualization. A good correspondence is observed between $F_{\rm pk}$ and *aa*. It is seen in Fig. 4 that the maximum of $F_{\rm pk}$ occurs in the descending phase of the sunspot cycle, but a secondary peak occurs earlier in the sunspot cycle. Cross-correlation analysis between *aa* and $F_{\rm pk}$ resulted in a coefficient of 0.72 and an in-phase variation (lag = 0 year), whereas the correlation coefficient between R_z and $F_{\rm pk}$ is $r = 0.40$ at lag = 4, $F_{\rm pk}$ maximum 4 years after R_z. The correlation between R_z and *aa* in this period has a lag = 2 years and a coefficient $r = 0.50$. These results show clearly, similarly to previous works (Gosling et al., 1976) that average geomagnetic activity is much more affected by solar wind (speed) than by the sunspot cycle, in terms of annual averages. It is known that solar wind parameters measured in the last years are not varying in phase with R_z (Gorney, 1990). For instance, both dynamic and static solar wind pressures are observed to reach maximum values in the declining phase of the sunspot cycle (Nakai and Kamide, 1994).

A multiple linear regression was performed, and the coefficients found at 99% confidence level (t-test) are shown as

$$aa^* = (9.25 \pm 1.58) + (0.29 \pm 0.03)F_{\rm pk} + (0.04 \pm 0.01)R_z. \qquad (1)$$

The correlation coefficient of this regression is $r = 0.84$ ($r^2 = 0.71$), which implies that 71% of the variability in *aa* index can be explained by a multiple linear dependency both on R_z and $F_{\rm pk}$.

Fig. 5 shows the calculated aa^*, by using Eq. (1), and the measured *aa*. Also shown are the decomposed *aa* terms, as a function only of the R_z, $F_{\rm pk}$ and independent terms. It is seen that the calculated aa^* also shows the dual peak structure observed in *aa* data (Gonzalez et al., 1990). The calculated *aa* shows good agreement in some periods, particularly around 1970–1980, but it overestimates *aa* in the early period, 1964–1970 and underestimates after 1988. Stamper et al. (1999) have performed a more extensive regression of *aa* in terms of several variables: solar wind speed, density and magnetic field, Earth's magnetic dipole and have obtained a better correspondence. In spite of this, the reconstruction obtained in this work may be considered reasonable. Especially, it was shown that *aa* is strongly dependent on several solar wind parameters, such as VB^2 (Svalgaard, 1977), and the interplanetary magnetic field is an important parameter that is not fully taken into account in this simple model.

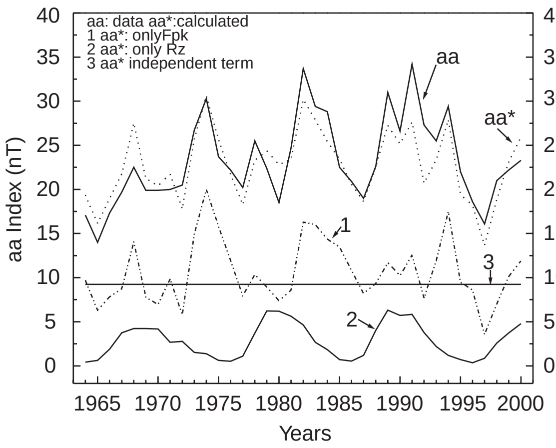


Fig. 5. Observed *aa* index (dotted line, 1) and *aa** calculated using the three terms of Eq. (1) (line, 2) and as a function only of F_{pk} (dotted–dashed line, 2), as a function only of R_z (dashed line, 3) and of the independent term (4).

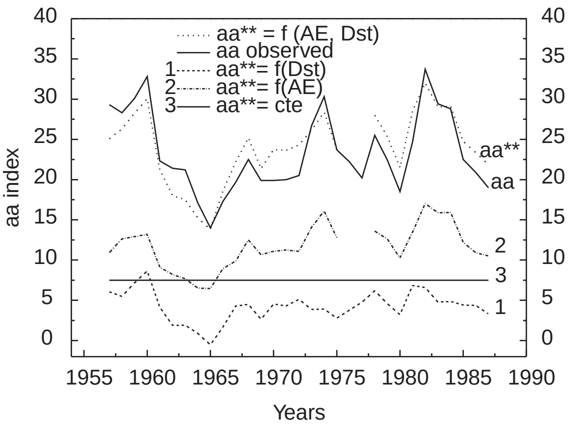


Fig. 6. Observed *aa* index (dotted line, 1) and *aa* calculated using the three terms of Eq. (1) (line, 2) and as a function only of *AE* (dotted–dashed line, 2), as a function only of *Dst* (dashed line, 3) and of the independent term (4).

It is seen that *aa* term which depends only on F_{pk} (curve 1) has variations similar to the observed *aa*, and its absolute values are larger than the R_z-dependent term (curve 2). This result confirms that high-speed streams from coronal holes are more important in modulating the *aa* variations. On the other hand, the *aa* calculated only as a function of R_z shows clearly the periodical variation associated with the solar cycle. Feynman (1982) has shown that the *aa* index can be decomposed in two parts, one dependent only on solar activity/sunspot number and the other an excess over the observed linear trend. This excess is explained by F_{pk} in this work and corresponds to recurrent activity.

It is important to comment that F_{pk} series constructed in this work should have some contribution from CMEs, but since only long-term variations are considered here, and CMEs are in general very sporadic activity having a duration of 2–3 days, the role of CMEs seems to be secondary in relation to the high-speed streams from coronal holes, which are long period phenomena. It can be considered that on an annual basis of data, such as that used in this work, the effects of coronal hole fast streams are much more predominant than the ones from CMEs. Furthermore, Richardson et al. (2000) have done an extensive study to determine by how much a long-term (more than three solar rotations) geomagnetic activity average is influenced by each one of the solar wind structures. In their work, they had determined that co-rotating high-speed streams contribute with around 70% of average *aa* activity during solar minimum and around 30% in solar maximum, while CME-related structures contributes with around 50% at solar maximum and less than 10% in solar minimum to the average *aa*.

In order to study the long-term geomagnetic activity variation from several sources, a correlative study on the annual averages of geomagnetic indices *aa*, *Dst* and *AE*, and solar activity indices, R_z and F_{pk}, was also performed. It was observed that, considering annual averages, *aa* has a zero lag with both *AE* and *Dst*, and the correlation is higher between *aa* and *AE* ($r = 0.81$) than between *aa* and *Dst* ($r = -0.73$). A lag of zero years between R_z and *Dst* ($r = -0.57$), and between F_{pk} and *AE* ($r = 0.75$) was also observed. Notice that *AE* correlation with F_{pk} is very similar to the *aa*–F_{pk} (0.72). Also similar is the correlation between *AE* and R_z ($r = 0.52$) and *aa* and R_z (0.50), both with a lag of 2 years. The correlation between F_{pk} and *Dst* is very low ($r = -0.28$) with a lag of −1 year (*Dst* maximum before F_{pk}). These results shows that *Dst* is better correlated with sunspot number, implying a larger influence of CME structures to ring current activity, while both *AE* and *aa* are correlated with F_{pk}, which implies a larger influence of CIR structures on the current systems that both indices represent.

The estimated aa^{**} index was calculated through multiple linear correlation. The coefficients are significant at 99% confidence level (t-test) and are shown as

$$aa^{**} = (7.50 \pm 2.23) + (-0.29 \pm 0.03)Dst + (0.04 \pm 0.01)AE. \qquad (2)$$

Around 75% of the variance in *aa* can be explained by this multiple linear model in relation to *AE* and *Dst*. Fig. 6 shows the *aa* observed and calculated (aa^{**}) as well the *aa* calculated only in function of *Dst* (curve 1), only as a function of *AE* (curve 2) and the independent term (curve 3). This analysis is similar to that done with *aa* dependent on R_z and F_{pk} (Fig. 5). The reconstruction describes quite well the *aa* behavior. It is also seen that *AE* represents a large fraction of the *aa* variation when compared to *Dst*. While both terms have general similar variations, *aa* variability is closer to the *AE* than to the *Dst*.

4. Discussion and summary

Long-term correlation between solar activity (R_z) and geomagnetic activity (*aa*) has been studied in this paper. It was observed that annual averages of both indices were varying in phase and with large correlation coefficients until around 1910–1920, but later they presented an increasing trend in lag (2 years) and a decrease in the correlation coefficient. Nevertheless, these trends are not monotonic, but they have superposed fluctuations. The fluctuations observed in lag are such that for cycles when lag is zero, the amplitude of a given cycle is larger than of the next, which implies that during some cycles the geomagnetic activity is stronger near sunspot maximum, implying in stronger magnetic fields of the current cycle. On other hand, in other cycles geomagnetic activity is stronger in the descending phase, implying stronger solar magnetic fields of the next cycle structures. The fluctuating character of lag and correlation coefficients could be explained by these differences in consecutive solar cycles, but a long-term trend of increase in lag and decrease in correlations is also seen. Correlations were higher and lag lower during the end of 19th and beginnings of 20th century. It is unknown presently if this is a trend or if it is part of a long-term solar activity period. The minimum in the correlation coefficient during the 1940s (Fig. 2) could be an indicative of a periodical process.

It was also observed that the second *aa* peak is more intense than the first one from 1910 onwards. This time is coincident with the upward trend in lag seen in filtered data. It seems that the lag is increasing because average geomagnetic activity during declining phase has became stronger than during solar maximum.

Using more recent data (1964 onwards), it was shown that *aa* is more dependent on high-speed streams, that are related to the open solar magnetic field structures, than to R_z (closed magnetic field structures). Also *aa* depends more on *AE* than on *Dst*, indicating that long-term (1 year) average magnetospheric activity is more influenced by auroral electrojet activity than by the ring current.

A causal scheme could then be constructed. Average (1 year) *aa* was shown to be more sensible to the *AE* activity. The variability of this last one is strongly influenced by large-amplitude Alfvén wave trains, present in CIR high-speed streams, which have a fluctuating southward enhanced component of the interplanetary magnetic field. Through magnetic reconnection with the magnetospheric field, this mechanism transmit energy from solar wind to Earth's magnetosphere, generating weak and moderate activity, such as sub-storms and high intensity, long duration continuous *AE* activity/HILDCAAS events (Tsurutani and Gonzalez, 1987; Gonzalez et al., 1995, 1999; Tsurutani et al., 1995). Furthermore, in the slow–fast stream interfaces in co-rotating interaction regions, the magnetic field is compressed and could cause mainly to weak and moderate storms (Tsurutani et al., 1995; Gonzalez et al., 1999). High-speed streams of CIRs are known to be emitted from coronal holes, open magnetic field regions in solar corona. Coronal holes are extending to low solar latitudes during the descending phase of solar cycle, when their effects on solar wind near Earth are more important (Gonzalez et al., 1996). The cause of the change in the relative importance of the two *aa* peaks could be could then be tracked to a possible Sun's magnetic field large scale variability, with coronal hole open magnetic field structures becoming more important to drive average geomagnetic activity.

A large scale solar magnetic field variation in the last 130 years has been largely discussed in recent works. Kishcha et al. (1999) have suggested that the increase in lag and the decrease in the correlation between *aa* and R_z, observed by them, are being caused by a long-term variation in the large-scale solar magnetic field stability and in the solar wind conditions. Lockwood et al. (1999) have determined that a doubling of the Sun's coronal magnetic field occurred since 1901. Wang et al. (2000) have shown that the open magnetic flux has a maximum in the sunspot cycle declining phase, with a lag of about 2 years in relation to the R_z and to the total photospheric magnetic flux. They have also shown that the interplanetary magnetic field radial B_x component has a higher correlation with the *aa* than with the sunspot number has in the period 1971–1998. Thus, it seems that solar magnetic open flux has a long-term variation different from the total photospheric flux and the sunspot number. Makarov et al. (2001) have determined that the area of the polar zone occupied by magnetic field of a single polarity has doubled over the last 120 years, indicating that magnetic flux increase could be accounted by area and not magnetic field strength increase. This result shows that open magnetic field structures has been intensified in the last century.

Based on these results, it can be concluded that correlation and lag variation between sunspot number and *aa* long-term (annual) averages are being caused probably by a stronger role of CIR-related structures in driving average magnetospheric activity. This seems to indicate an increase in open solar magnetic field structure strengths to drive geomagnetic activity in comparison to the closed ones. This last fact might mean that open and closed solar magnetic field structures have had a differential evolution with time at least during the last 130 years. Further studies are needed to assess this possible differential evolution and its implications for solar-terrestrial physics.

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