A Study of Solar-Geomagnetic Indices Correlation

E. Echer, L. E. A. Vieira, N. R. Rigozo, M. P. Souza and D. J. R. Nordemann.
Instituto Nacional de Pesquisas Espaciais, PO 515, 12201-970, São José dos Campos, SP, Brazil.
 ezequiel@dge.inpe.br

Abstract

In this paper a spectral analysis of the aa geomagnetic index (aa) and of the sunspot number (SSN) time series during the period 1868-1998 is made. The spectral method used was the multiple taper method. The main periods found were related to the 11 year solar cycle and its harmonics. The aa spectrum shows in addition a period of 4.4 years, which is caused by the dual-peak distribution of the aa time series. The cross-correlation for all the periods indicates that aa lags SSN by 1 year, however the correlation is decreasing and the lag is increasing with time. Using averages of 23 years, cross-correlations calculations show that the correlation coefficient decreases from 0.76 to 0.35 and the lag from 0 (1868-1890) to –3 (1960-1982).

Introduction

The solar modulation of geomagnetic activity and its corresponding effects on the Earth's atmosphere is a fact well known (Gorney, 1990; Kivelson and Russel, 1995; Gonzalez et al., 1999). The 11-year solar cycle and the associated variability that it causes on the eletromagnetical environment of Earth – the geospace – has been largely studied (Gorney, 1990; Kivelson and Russel, 1995; Gonzalez et al., 1999).

The sunspot number (SSN) has been largely used to infer about the long term variability of the solar activity (Kivelson and Russel, 1995; Hoyt and Schatten, 1997). The longest time series of geomagnetic activity is the 3-hour antipodal activity index aa (aa), which was defined by Mayaud (1972;1973). The available records are from the observatories of Melbourne in Australia and Greenwich in England. The slight changes that occurred in the sites of the antipodal geomagnetic observatories (Menvielle and Berthelier, 1991) have not affected the time series. The observatory locations were: Northern Hemisphere, Greenwich (1868-1925). Abinger (1926-1956) and Hartland (1957); Southern Hemisphere, Melbourne (1868-1919); Toolangui (1920-1979) and Canberra (1980). Similar to Kp determination, 3-hour values are calculated first, and a daily value is then obtained for each station. The combination of both stations results in the aa index.

The invariant magnetic latitude of the antipodal observatories is about 50°.

In this paper a spectral analysis using modern approach is made on SSN and aa time series. The correlation decrease between SSN and aa is also analyzed.

Spectral Analysis Methods

In spectral analysis, the use of a single taper in a time series reduces much of the bias due to spectral leakage in the spectral estimator, however, it also reduces the sample size and causes information to be lost (Jenkins and Watts, 1968). Thomson (1982) introduced the idea of using multiple tapers to recover the information lost while still maintaining acceptable bias. The method is known as the Multiple Taper Method – MTM. The MTM uses orthogonal windows (or tapers) to obtain approximately independent estimates of the power spectrum and then combines them to yield an estimate. This estimate exhibits more degrees of freedom and allows easier quantification of the bias and variance trade-offs, compared to conventional Fourier analysis. The MTM has the ability to detect small amplitude oscillations in a short time series without the necessity of filtering the signal. It has also an internal statistical F-test (F distribution) to obtain the significance level of the periodicity found (Thomson, 1990).

The parameter that controls the compromise between low variance and low bias is the product time*bandwidth (NW- number of windows or tapers). This is a resolution parameter directly related to the number of tapers used to compute the spectrum. As NW increases, there are more estimates of the power spectrum and the variance of the estimate decreases. However, the bandwidth of each taper is also proportional to the NW, so as NW increases, each estimate exhibits more spectral leakage (wider peaks) and the overall spectral estimate is more biased. For each data set a specific value of NW must be used (Thomson, 1982; Thomson, 1990).

Results and Discussion

In Figure 1 the time series of aa and SSN are shown; the very well known behavior is easily seen. The SSN has a cyclical variation with minimum of a cycle reaching the same levels than the minimum of the preceding cycles, while aa shows an increasing trend in both minima and maximum values of the cycle (Gorney, 1990)

Other well known feature in the aa time-series is the dual-peak structure (Gonzalez et al., 1990; Gorney, 1990), showing a peak near sunspot cycle maximum and other in the descending phase. This second peak is caused by geomagnetic disturbances due to coronal hole fast streams, which are more frequent in this part of the solar cycle (Kivelson and Russell, 1995).
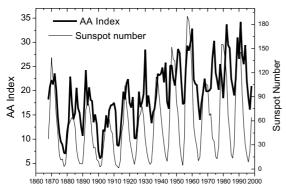
Figure 1: The Sunspot Number and the geomagnetic index aa time series – 1868 –1998.

In Figure 2 a cross-correlation spectral analysis is shown for aa and the SSN. The highest correlation coefficient (r=0.66) was found for the lag of 1 year, which means that on average, the aa maximum lags the SSN maximum by a year.
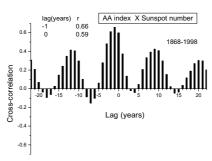

Figure 2: Cross-correlation between the aa and SSN time series, 1868-1998.

A better correlation is obtained by using the 11 year average of aa and the SSN. The 11-year running averages are shown in Figure 3 and the long-term trend in the solar and geomagnetic activity is easily seen. The correlation coefficient is 0.94 with a lag=0. This result indicates that on a large time scale the solar and geomagnetic activity have a very good correlation, because both are affected by the long-term component in the solar activity.

Spectral analysis results

In Figure 4 the aa and SSN MTM spectrum are shown. The MTM was applied with NW=5.5. Only periods at confidence level of 95% are shown in Figure 5. It is seen that the 11 year solar cycle is noticed in both series (10.92 years), with a strong amplitude and that some lower periodicities, harmonics of the 11-year signal, are also observed.
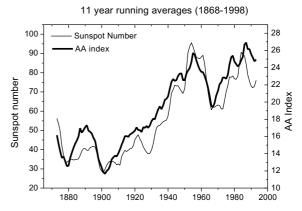

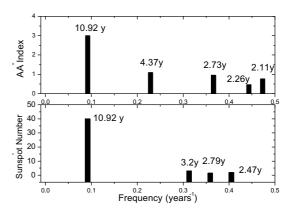Figure 3: 11-year averages of the aa and SSN.

Figure 4: Multiple Taper Spectrum for aa and SSN, 1868-1998.

The aa spectrum shows in addition a peak near 4.4 years, which is not present in the SSN spectrum; this peak is believed to be caused by the dual-peak maximum in the aa (Clua de Gonzalez et al., 1993), because the distribution of intense storms has a separation between the two peaks of 3-4 years (Gonzalez et al., 1990). These results are coherent with other works; Clua de Gonzalez et al. (1993), for example, found 10.3 years in SSN and Ap time series (1932-1982) and a period of 4.4 years only in the Ap. Longer periods in the SSN time series are found by applying spectral analysis to the full range of data, 1700-1998. Applying the same conditions, NW=5.5, 95% confidence level, to SSN in the interval 1700-1998, the most significant periods were 100, 21.4, 11.1, 10, 5.8, 3.4, 3.2, 3.1, 2.9, 2.8 and 2.2 years.

Decrease of solar-geomagnetic correlation.

In order to study the solar-geomagnetic correlation evolution, averages over a period of 23 years of aa and SSN were determined and cross-correlation was calculated. This period was chosen because shorter

intervals could cause distinction due to even and odd-number cycles (Kishcha et al., 1999). The intervals used to calculate cross-correlations were: 1868-1890, 1891-1913 ,1914-1936 ,1937-1959, 1960-1982. The period 1983-1998 was not used because it has only 16 years. The results of cross-correlations are shown in Figure 5, the lag between SSN and aa time series, the correlation coefficient (lag=0) and the correlation coefficient for the given lag of each period.
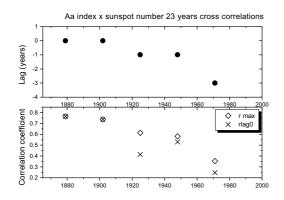

Figure 5: Evolution of correlation aa -SSN Upper panel, lag; lower panel, correlation coefficients.

It is clearly seen in Figure 5 that the correlation is decreasing with time and the lag is increasing, which indicates that aa maximum are occurring more in the descending phase than in the period of maximum of the 11 year solar cycle. The results are coherent with those found by Kishcha et al. (1999) who calculated 23-year running-window correlations. They observed a superposition of a quasi-periodical fluctuation of 40-50 years and a linear decreasing trend in the SSN-aa correlation. Their results show correlation coefficients decreasing from 0.8 in 1880 to 0.2 in 1980. In our results it is observed that the lag changes to 0 in the first period (1868-1890) to –3 years in the period (1960-1982). The correlation coefficient of lag 0 varies from 0.76 to 0.24 in the same period and correlation coefficient associated to the lag of each period changes from 0.76 to 0.35.

The physical cause of the decrease in correlation was explained by Kishcha et al. (1999) as follow: the geomagnetic activity has two components, the sporadic, associated to the sunspot cycle, and the recurrent, associated to high speed streams of solar wind, emitted by coronal holes (Gorney, 1990; Gonzalez et al., 1990; Gonzalez et al., 1999). The maximum in the recurrent component is out-of phase in relation to the sunspot number cycle maximum because the open magnetic configurations in the solar corona are more stable during the declining phase in the sunspot cycle. Thus, it was proposed by Kishcha

et al., (1999) that the decrease in correlation and increase in lag between aa and SSN would be connected to the stability of open magnetic configuration in the solar corona; a long-term variability in the large scale solar magnetic field could be causing a change in the open magnetic flux, and in the solar wind conditions.
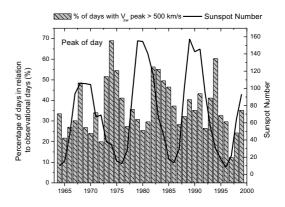

Figure 6: Fraction of days with solar wind V_{sw} peak > 500 km/s and Sunspot Number.

In order to better understand the solar wind variations and its relation to sunspot and geomagnetic activity, a study of aa, SSN and solar wind conditions was made. From Omni database, 1964-1998, the fraction of days per year with solar wind velocity peak > 500 km/s (Fpk) was determined and compared to aa and SSN variability. In Figures 6 and 7 the histograms of solar wind velocity are shown. A good correspondence is observed between Fpk and aa. The maximum number of days/year with solar wind disturbed conditions occurs in the descending phase of the sunspot cycle.

Cross-correlation analysis between aa and Fpk resulted in a lag of 0 year and a coefficient of 0.67, while the cross-correlation of Fpk and SSN resulted in a lag of –2 years (Fpk 2 years later than SSN) and a correlation of -0.48.

These results show clearly, similarly to previous works (Gosling et al., 1976), that geomagnetic activity is much more affected by solar wind than by the sunspot cycle, in terms of annual averages. The aa variation is caused by the solar wind condition variability, as may be observed in Figures 6 and 7. The solar wind variability is not in phase with the sunspot cycle. Solar wind parameters measured in the last years are not varying in phase with SSN. Both dynamic and static pressures are observed as reaching maximum values in the declining phase of the sunspot cycle (Nakai and Kamide, 1994).
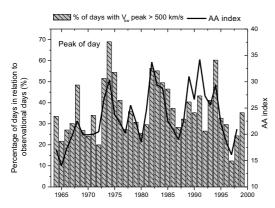
Solar-Geomagnetic Correlation

Figure 7: Fraction of days with solar wind V_{sw} peak > 500 km/s and aa index.

Conclusions

The results of applying spectral analysis to aa and SSN time series in the period 1868-1998 show that the solar 11 year cycle is a main characteristic in both time series. In addition it is observed in the aa spectrum a period of 4.4, which is caused by the dual-peak structure of the geomagnetic activity. The SSN and aa have a variation out of phase, which may be caused by predominant role of solar wind fast streams from coronal holes in the descending phase of the sunspot cycle. Thus geomagnetic activity has a peak in the solar maximum and other during the descending phase.

The decrease in the correlation of aa and SSN was confirmed in this work. It was proposed by Kishcha et al. (1999) that a long-term variability in the open magnetic field configurations, in the solar corona, could be the cause of the trend to aa and SSN become less correlated.

References

Clúa de Gonzalez, A. L., W. D. Gonzalez, S. L. G. Dutra and B. T. Tsurutani, Periodic variation in the geomagnetic activity: a study based on the Ap Index, *J. Geophys. Res.*, 98, 9215-9231, 1993.

Gonzalez, W. D., A. L. C. Gonzalez and B. T. Tsurutani, Dual-peak cycle distribution of intense geomagnetic storms, *Planet. Space Sci.*, 38, 181-187, 1990.

Gonzalez, W. D., B. T. Tsurutani and A. L. Clúa de Gonzalez, Interplanetary origin of geomagnetic storms, *Space Science Reviews*, 88, 529-562, 1999.

Gorney, D. J., Solar cycle effects on the near-Earth space environment, *Rev. Geophysics*, 28, 315-336, 1990.

Gosling, J. T, J. R. Asbridge, S. J. Barne and W. C. Feldman, Solar wind speed variations:1962-1974, *J. Geophys. Res*, 81, 5061, 1976.

Hoyt, D. V. and K. H. Schatten, *The Role of the Sun in climate change*, Oxford Univ. Press, 1997.

Jenkins, G. M. and D. G. Watts, *Spectral Analysis and Its Applications*, Holden Day, Oakland, Calif., 1968.

Kishcha, P. V., I. V. Dmitrieva and V.N. Obridko, Long-term variations of the solar-geomagnetic correlation, total solar irradiance, and northern hemispheric temperature (1868-1997), *J. Atmos. Solar-Terr. Physics,* 61, 799-808, 1999.

Kivelson, M. G., Russel, C. T., *Introduction to Space Physics*, Cambridge Univ. Press, 1995.

Mayaud, P. N. , The aa indices: A 100-year series characterizing the magnetic activity, *J. Geophys. Res.*, 77, 6870, 1972.

Mayaud, P. N. , A hundred year series of geomagnetic data, 1868-1967, indices aa, storm sudden commencements, *IAGA Bull. 33*, Int. Union of Geod. and Geophys., Publ. Off.,Paris, 1973.

Menvielle, M. and A. Berthelier, The K-derived planetary indices: description and availability, *Rev. Geophysics*, 29, 415-432, 1991.

Nakai, H. and Y. Kamide, Estimating the long-term variations of magnetotail pressure, *J. Geophys. Res.*, 99, 23747-23751, 1994.

Thomson, D. J., Spectrum estimation and harmonic analysis, *Proc. IEEE,* 70, 1055-1096, 1982.

Thomson, D. J., Quadratic-inverse spectrum estimates: applications to palaeoclimatology, *Phil. Trans. R. Soc. Lond. A*, 332, 539-597, 1990.