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Discrete wavelet analysis to assess long-term trends in geomagnetic activity

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Abstract

To assess long-term trends in geomagnetic activity, the discrete wavelet transform using the Daubechies function was applied to *aa* and D_{st} for periods 1868–2003 and 1957–2003 respectively. Among a variety of techniques available for analysing trends, wavelet analysis has emerged in the last decade as a useful statistical tool for this purpose. The wavelet order and border conditions of the transform were selected minimizing the mean relative error. A sequence of alternating trends is obtained in the case of *aa*, with the greatest minima around 1880 and 1905 followed by 1965 and 2000. Maximum values occur around 1890, 1955 and 1990. D_{st} index shows the last two minima and the maximum around 1990. Long term trends in solar wind velocity, density and pressure, IMF magnitude *B*, southward component *Bz*, sunspot number *Rz* and the coronal index were also analysed in order to identify possible causes for the observed long-term variation in geomagnetic activity. They all qualitatively agree with *aa* and D_{st} behavior pointing out a solar origin.

Keywords: Geomagnetic activity; Wavelets; Long-term trend; Solar activity

1. Introduction

As a consequence of the increasing interest in global changes and Sun-climate relations, long-term variation of geomagnetic activity has become an important subject.

There are many studies concerning geomagnetic indices variability (Rangarajan and Iyemori, 1997; Kane, 1997; Rangarajan and Barreto, 2000 to mention a few) pointing out its periodicities and links to solar activity cycle. There are also many studies regarding long-term variations. Russell (1974, 1975) analyzed the geomagnetic activity index, Ci, and found that the amplitude of the ≈22-year cycle has varied markedly since 1885, being large from 1885 to 1907, then diminishing until 1949 and being large again from 1949 to 1970. From this result he suggested that magnetic field at the solar poles has undergone long-term changes indicating that they not only reverse in sign but also change gradually in strength from solar cycle to solar cycle. Russell and Mulligan (1995) analysed the average behavior of the *aa* index and also suggest that the field in the polar regions of the sun presents long-term variations. They describe the variations of the *aa* index since 1844 to 1995 as falling since 1850 to 1900, and rising since then until the most recent solar cycles. Rangarajan and Barreto (2000) detected a long-term variation in the reconstructed solar wind velocity composed of a rise between 1902 and 1958 and a decline thereafter in agreement with trends in sunspot numbers obtained by Kane (2002). Vennerstrom (2000) found that the long-term variation of the geomagnetic activity index-*aa* on the quietest days and on the most

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disturbed days is similar. He points out that an increase in the background solar wind parameters, rather than in the number of solar wind disturbances, cause the long-term increase of geomagnetic activity. On the other hand, Richardson et al. (2002) find no evidence for an IMF strength increase after 1974 and suggest that it has been relatively constant since ~1954.

We are concerned in this work with the detection of long-term variations of time-scales longer than the 11-year solar cycle in geomagnetic activity through the analysis of *aa* and D_{st} indices, using the discrete wavelet transform. While *aa* is a global geomagnetic activity index, D_{st} monitors the disturbance of the horizontal component of the geomagnetic field (H) at the dipole equator on the Earth's surface (Mayaud, 1980) monitoring the ring current state.

2. Data analysis

Monthly *aa* and D_{st} index for periods 1868–2003 and 1957–2003, respectively, available at the World Data Center-A for Solar-Terrestrial Physics, were used. High frequency variations corresponding to periods smaller than the 11-year cycle were filtered out through the discrete wavelet analysis (DWT) using the Wavelet Toolbox for Matlab. A decomposition of the series was performed using Daubechies wavelets by estimating first the coefficients of all the components (details and approximation) up to a level J. This maximum level is that where the number of data after the last subsampling become smaller than the filter length. That is, if k is the order (or number of vanishing moments) of the Daubechies wavelet, and N is the number of data in the series, then $N/2^J = (2k - 1)$ from where $J = \log[N/(2k - 1)]/\log(2)$ (Kaiser, 1994). We used Daubechies wavelet because it is a commonly used family of wavelets (Daubechies, 1988, 1992) for discrete analysis. They are the only wavelets having a finite support (they are non-zero only over a finite range) with full scaling and translational orthogonality (Horgan, 1999).

While details contain the high frequency information of a series, the approximation reflects its slowest variations. In fact, details correspond to the reconstruction of the series after going through a high-pass filter, while the approximation corresponds to the low-pass filtered series. Since we are interested in long-term changes we just reconstructed the approximations of *aa* and D_{st} data series.

Classically the DWT is defined for series with length of some power of two. Methods for extending the signal to the needed length are: zero-padding, periodic extension, and boundary value replication or symmetrization (Misiti et al., 1997). The method of zero-padding assumes that the signal is zero outside its original support. It has the disadvantage that discontinuities are artificially created at the border. The method of symmetrization assumes that signal can be extended by symmetric boundary value replication. The disadvantage of this method is the artificially creation of discontinuities of the first derivative at the border, but this method works well in general. The method of smooth padding assumes that signal can be recovered outside its original support by a simple first order derivative extrapolation.

In order to decide on the wavelet order and border condition, the approximation of the series was estimated for every $k = 2$–45 and the three different border conditions, together with its mean relative error (ε) (Popivanov and Miller, 2002). Given a signal x of length N, let x^* denote any approximation of x, ε is assessed as

$$\varepsilon = \frac{1}{N}\sum_{i=1}^{N}\frac{|x_i^* - x_i|}{|x_i|}$$

Minimum ε values are obtained for the symmetrization border condition in every case. Under the symmetrization method, ε oscillates around 0.293 with almost stable minimum values for $k = 7, 11, 15, 19, \ldots$ In fact, for $K \geqslant 7$ the approximations are all very similar.

A common maximum level of decomposition J was used for both of the series analyzed in order to have the same scale of long-term oscillations. J was estimated from the shortest series, that is D_{st}. Since this series has more than 512 (2^9) data values, the DWT performed by Matlab completes the series until the next power of 2, that is up to 1024 (2^{10}) data values. Given a filter length of 13 ($k = 7$), we reached $J = 7$.

Fig. 1 shows the approximations of *aa* and D_{st} indices. In the case of *aa* there are two greater minima around 1880 and 1905 followed by another two minima in 1965 and 2000, while maximum values occur around 1890, 1955 and 1990. D_{st} index, due to its much shorter period, shows the last two minima and the maximum around 1990.

In order to identify possible causes for the observed trends in geomagnetic activity as shown by *aa* and D_{st}, we also analysed solar wind velocity v [km/s], solar wind proton density [cm^{-3}], flow pressure [nPa], interplanetary magnetic field (IMF) magnitude B [nT], southward component of IMF Bz [nT], sunspot number Rz and the coronal index of solar activity [10^{16} W/steradian].

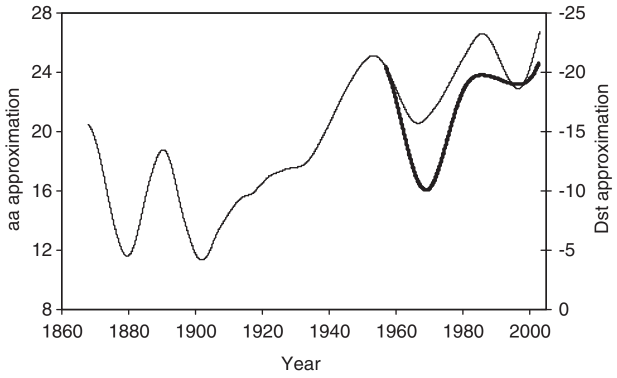

Fig. 1. Low-pass filtered *aa* (solid line) and D_{st} (enhanced line) indices assessed as the approximation at level 7 obtained with a discrete wavelet transform using Daubechies 7 and symmetrization border conditions.

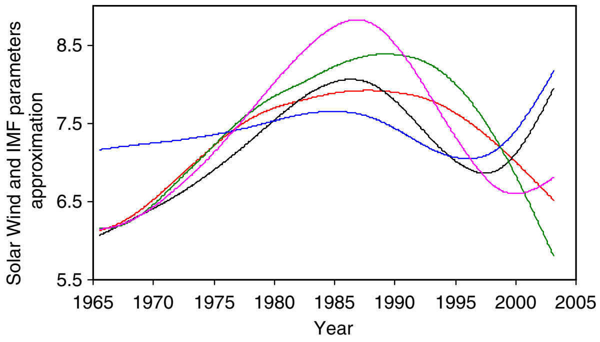

Fig. 2. Low-pass filtered solar wind velocity (blue), solar wind proton density [cm^{-3}] (green), flow pressure (violet), interplanetary magnetic field (IMF) magnitude *B* (black) and southward component of IMF *Bz* (red) assessed as the approximation at level 7 obtained with a discrete wavelet transform using Daubechies 7 and symmetrization border conditions. Only solar wind density has its real dimensions. The other parameters have been rescaled to fit in the figure. (For interpretation of the references in colour in this figure legend, the reader is referred to the web version of this article.)

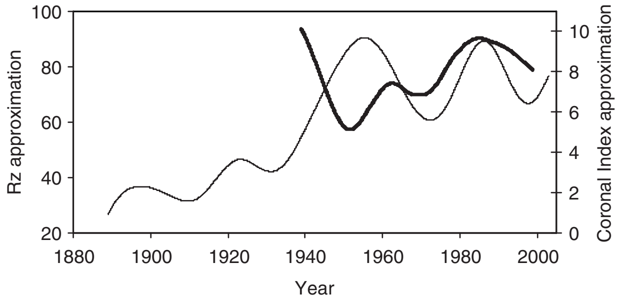

Fig. 3. Low-pass filtered coronal index (enhanced line) and sunspot number *Rz* (solid line) assessed as the approximation at level 7 obtained with a discrete wavelet transform using Daubechies 7 wavelet and symmetrization border conditions.

Solar wind and IMF data were obtained from the NSSDC OMNI data base. *Rz* and the coronal index of solar activity, which measures the total energy emitted by the sun's corona at a wavelength of 530.3 nm, are available at the National Geophysical Data Center.

The approximation of each series was estimated for different orders of the Daubechies wavelet and different border conditions. As in the case of *aa* and D_{st}, the minimum ε was obtained for the symmetrization method and for $k \geqslant 7$. The long-term variation for solar wind and IMF parameters as measured by the approximation at level 7 using Daubechies 7 and symmetrization border conditions, resulted similar to that of *aa* and D_{st}, except for small shifts in the maximum around 1985 and the minimum around 2000, as can be seen in Fig. 2. Fig. 3 presents the results of *Rz* and the coronal index. *Rz* behaves quite similar to *aa* with the only difference being that the maximum values around 1960 and 1990 are almost the same in the case of *Rz*. The coronal index present a decreasing trend until the 1950's which do not coincides with a corresponding increasing trend in *aa* and *Rz*.

3. Discussion and conclusions

The long-term trend in *aa* index is almost the same as that of *Rz*, suggesting that these variations are a result of long-term changes in the sun. Cliver and Ling (2002) also used the close correspondence between the secular variations in *aa* and *Rz* to point out the solar origin in geomagnetic activity. There are other possible sources of long-term changes in geomagnetic activity detected by *aa*, such as instrumental effects, long-term changes in the Earth magnetic field and ionospheric effects, among others, that have been ruled out by Stamper et al. (1999) and Cliverd et al. (2002).

D_{st} long-term variations in its much shorter period agree with the maximum activity level around 1990, as the solar wind and IMF data do. The solar wind velocity is the parameter with the most flat trend.

The coronal index rise since the 1950's may indicate an increase in the coronal magnetic field as indicated by Lockwood et al. (1999). Makarov et al. (2001), instead, points out an increase in area and not in magnetic field strength after determining that the area of the polar zone occupied by magnetic field of a single polarity at solar minimum has doubled over the last 120 years, between 1878 and 1999.

Assuming a solar origin then, the long-term behavior observed in *aa* may be part of the Suess cycle of solar activity (~200 year period) whose last minimum occurred in 1905–1915 (Cliverd et al., 2002). The maximum could be the 1990 maximum or it could arrive around 2010. The upward trend from the beginning of the 20th century up to 1990 may be part of this oscillation.

Some authors, as Cliver and Ling (2002), suggest that the post 1965 increase may result from a weak cycle 20 (1964–1976) lying between two strong cycles, 19 and 21. However, we suggest here that the partial minimum around 1965–1970, may be the last minimum of the Gleissberg cycle (~80–90 year period), which would be modulating the much stronger Suess cycle. The previous minimum of this cycle may have occurred around 1880.

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