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A wavelet based approach to Solar–Terrestrial Coupling

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Abstract

Transient and recurrent solar activity drive geomagnetic disturbances; these are quantified (amongst others) by D_{ST}, AE indices time-series. Transient disturbances are related to the Interplanetary Coronal Mass Ejections (ICMEs) while recurrent disturbances are related to corotating interaction regions (CIR). We study the relationship of the geomagnetic disturbances to the solar wind drivers within solar cycle 23 where the drivers are represented by ICMEs and CIRs occurrence rate and compared to the D_{ST} and AE as follows: terms with common periodicity in both the geomagnetic disturbances and the solar drivers are, firstly, detected using continuous wavelet transform (CWT). Then, common power and phase coherence of these periodic terms are calculated from the cross-wavelet spectra (XWT) and wavelet-coherence (WTC) respectively. In time-scales of ≈27 days our results indicate an anti-correlation of the effects of ICMEs and CIRs on the geomagnetic disturbances. The former modulates the D_{ST} and AE time series during the cycle maximum the latter during periods of reduced solar activity. The phase relationship of these modulation is highly non-linear. Only the annual frequency component of the ICMEs is phase-locked with D_{ST} and AE. In time-scales of ≈1.3–1.7 years the CIR seem to be the dominant driver for both geomagnetic indices throughout the whole solar cycle 23.

Keywords: Magnetosphere; Geomagnetic disturbances; Solar cycle; Solar wind; Wavelet coherence

1. Introduction

The connection of solar activity to geomagnetic disturbances, dubbed Solar–Terrestrial Coupling, remains an open field of research. The effects on Earth appear as geomagnetic disturbances driven by the solar wind–magnetosphere interaction and quantified by geomagnetic indices (see review by Akasofu, 2011).

Feynman (1982) and Du (2011), indicated that the annual values of the geomagnetic index *aa* could be the resultant of two components: one originating from solar transient (or sporadic) activity and in phase with the solar cycle; the other was related to recurrent solar drivers with peak in the declining phase (see also Richardson and Cane, 2012). Along the same line (Cliver, 1995) provides a historical review of the solar–terrestrial research since 1930, and the two basic types of geomagnetic storms: recurrent and sporadic. The studies, mentioned above, propose two classes of geomagnetic–solar drivers on a time scale of approximately a year as Feynman (1982) and Du (2011) used annual averages of *aa* in their study. The Interplanetary Coronal Mass Ejection (ICME) is the major driver of transient geomagnetic activity.The solar recurrent activity, on the other hand, is driven by High Speed Solar Wind Streams (HSSWS) and Co-rotating Interaction Regions (CIR) (Schwenn, 2006; Pulkkinen, 2007). Borovsky and Denton (2006) and Richardson and Cane (2012) indicate, also, that the different driver classes (CIR, ICME) result in distinct geomagnetic disturbances; the ICMEs, for example, induce higher ring current, manifested by a high negative peak in D_{ST}.

The solar–geomagnetic coupling, when studied in the frequency plane manifests itself with periodic terms having

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the same periodicity in the solar drivers and the geomagnetic indices time series. The basic periodicity is the 11/22 year solar cycle (sunspot and magnetic respectively), yet quasi-periodic variations on shorter time-scales have been reported.

Lou et al. (2003) found A_p index periodicities of 187, 273 and 364 days in the 1999–2003 time interval. Periodicities of about 27.5, 13.5, 9.1, and 6.8 days, due to the solar rotation have been identified in the solar wind speed and the IMF polarity (Gonzalez and Gonzalez, 1987; Clúa de Gonzalez et al., 1993; Svalgaard and Wilcox, 1975; Fenimore et al., 1978; Sabbah et al., 2011). Kudela et al. (2010) reported that a range of periodicities, 1.7–2.2 years, appear in cosmic rays during the time interval 1951–2010, while (Mavromichalaki et al., 2003) published similar results for the 1953–1996 interval. Valdés-Galicia et al. (1996), Mursula (1999) and Nayar et al. (2002) reported different periodic variations of the geomagnetic activity index A_p; 1.3–1.4 years during *even* cycles and of 1.5–1.7 years during *odd* ones.

Katsavrias et al. (2012) examined the 1966–2010 time period for periodicity in the solar activity, the solar wind speed, interplanetary magnetic field and the geomagnetic indices using wavelet analysis. Within the examined time-series time-localized common spectral peaks, between the fluctuations in the solar wind characteristics and the geomagnetic indices were detected. Certain periodicities were dominant within specified intervals which, at times, were different for different geomagnetic indices.

The interdependence between different time series requires a different wavelet based approach. In this case cross wavelet transform and wavelet coherence (XWT and WTC Grinsted et al., 2004) are used for the quantification of the interdependence. This approach has been, already, used in the study of common periodicities between two time–series and the corresponding phase relationship between them. Valdés-Galicia and Velasco (2008) studied the coherence of the sunspots with open solar magnetic fluxes. Deng et al. (2012) investigated the coronal index-sunspot numbers phase relationship finding coherent behaviour in low-frequency components corresponding to the 11-year Schwabe cycle; this coherence was absent in the high-frequency components. Deng et al. (2013) applied this method between 10.7 cm solar radio flux and sunspot numbers from 1947 February to 2012 June; the phase relationship between the time series was found both time and frequency dependent.

In this work a refinement of the Katsavrias et al. (2012) wavelet based approach is presented which aims at the detection of common and coherent periodicity and phase relationship between the ICMEs, CIRs and the D_{ST}, AE geomagnetic indices time-series by means of cross wavelet transform and wavelet coherence calculations.

2. Data selection

We used time-series of the occurrence rate of the geomagnetic drivers, ICMEs, CIR and of different geomagnetic indices, representative of the conditions in the magnetosphere, as follows:

- ICMEs per day from the Jian et al. (2006a) catalogue on line.[1] The daily rate is the duration of the ICME passage on that day, in hours, divided by 24. Two more ICME lists by Richardson and Cane (2010) and Mitsakou and Moussas, 2014 were available yet the selection does not affect our analysis as the three lists differ little from each other and exhibit the same trends in the ICME occurrence rate (Mitsakou and Moussas, 2014).
- CIRs per day from the Jian et al. (2006b) list on line.[2] The daily rate is the duration of the CIR passage on that day, in hours, divided by 24 defined similarly to the ICME rate in the previous bullet. We selected CIRs because their geomagnetic effectiveness is greater, on average, than the other stream interaction regions.
- Geomagnetic indices from the OMNIweb database: The D_{ST}, represents the strength of the Earth ring current; values below −30 nT indicate a geomagnetic storm. The AE quantifies sub-storms as it represents auroral electrojet intensity (Mayaud, 1980).

Our data-set covers solar cycle 23, from January 1st, 1997 to December 31st, 2007, and consists of daily average values.

3. Results and discussion

3.1. Wavelet analysis

The analysis of a function in time, be it F(t), into an orthonormal basis of *wavelets* is conceptually similar to the Fourier Transform. The latter however is localised in frequency (or time-scale) only while the former, being localised in frequency and time, allows the local decomposition of Non-stationary time series; a compact, two dimentional, representation may be thus obtained (see Morlet et al., 1982; Torrence et al., 1998). The *wavelets* forming the basis are derived from an integrable zero-mean *mother wavelet* $\psi(t)$ and the wavelet transform of F(t), be it W(t, f), is caculated as the convolution of this function with the *mother wavelet* duly shifted and scaled in time $\psi(f \cdot (\tau - t))$:

$$W(t,f) = \int_{-\infty}^{+\infty} F(\tau)\sqrt{f}\psi^{*}(f(\tau - t))d\tau \quad (1)$$

where * denotes complex conjugate, the scale factor f represents frequency and $\sqrt{f}$ is necessary to satisfy the normalization condition; the wavelet transform represents a mapping of F(t) on the t-f plane.

The *mother wavelet* which in our case is the *Morlet wavelet* which consists of a plane wave modulated by a

[1] http://www-ssc.igpp.ucla.edu/~jlan/STEREO/Level3/STEREO_Level3_ICME.pdf recent updates of the catalogue extend beyond 2006.

[2] www-ssc.igpp.ucla.edu/~jlan/STEREO/Level3/STEREO_Level3_SIR.xls.