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Loss of synchronization in the 27-day spectral component of geomagnetic indices and its relationship with solar activity

Elena Blanter[a,b,*], Jean-Louis Le Mouël[a], Mikhail Shnirman[a,b], Vincent Courtillot[a]

[a] IPGP, 1 rue Jussieu, 75005 Paris, France
[b] IEPT RAS, Profsoyuznaya str. 84/32, 117997 Moscow, Russia

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ABSTRACT

We investigate the "27-day" spectral component of different global (*aa* and *Dst*) and local (ζ) geomagnetic indices in two period ranges relevant to the Sun's synodic rotation, as manifested by magnetic activity: 24–28 days (short) and 28–32 days (long). Cross-correlation analysis of the respective energies of the short and long periods of the 27-day rotation signal in the same geomagnetic index reveals well-defined de-synchronization events during certain solar cycles. The largest de-synchronization in the past century occurred during solar cycle 21. De-synchronization events first occur in indices of the *Dst* (and ζ) family, and then in indices of the *aa* family. We found no evidence that the strength of the de-synchronization of the solar rotation signal in the ζ-index would depend on geomagnetic latitude. Applying the same analysis to proper solar indices (sunspot number, *F*10.7 radio flux, interplanetary magnetic field (IMF) series, solar wind speed), we find that only the Bz component of the IMF demonstrates a de-synchronization, during solar cycle 21, between the energies of the 27-day solar rotation signal in the short and long period ranges. We discuss possible implications of these results with respect to the evolution of the toroidal and poloidal components of the Sun's magnetic field and to its large-scale structures.

1. Introduction

The complex evolution of the solar dynamo can be observed and investigated using a number of solar and geomagnetic indices. Usoskin et al. (1997, 1998) found significant change in the cross correlation between sunspots and cosmic rays in the descending phase of solar cycle 20, explained by the anomalous properties of that cycle. In a previous paper (Le Mouël et al., 2012), we analyzed the cross correlation between different indices on timescales of tens of years and found that long periods of coherent evolution of various pairs of indices are interrupted by strong losses of correlation, that we called "de-correlation" or "de-synchronization" events: a major such event occurred during anomalous Cycle 20. De-synchronization events are relatively rare, coincide for pairs of indices and have durations comparable to the length of a solar cycle. The origin of these events and the mechanisms of de-synchronization are still unresolved questions, although different possible mechanisms have been suggested (e.g. Usoskin et al., 1997, 1998; Obridko and Shelting, 2009). In the present paper, we pursue our studies of the evolution of long-term correlation properties of geomagnetic indices, focusing on the correlations between the energies of two domains of periods in the 27-day range of solar rotation, namely 24–28 days (that we call "short rotation periods") and 28–32 days ("long rotation periods").

The existence of the 27-day solar rotation signal in geomagnetic activity is related to the solar forcing of the geomagnetic field and appears to be the combined result of solar rotation and non-axisymmetry of the solar dynamo (e.g. Bigazzi and Ruzmaikin, 2004). Different periodicities in the 27-day range appear to be the result of the differential rotation of the Sun (faster near the equator and slower near polar areas). The influence of heliospheric latitude on rotation periods is revealed by the properties of the 27-day signal in sunspots and coronal holes. However, various rotation periods in the heliospheric magnetic field and solar wind parameters are found to have no direct relation with solar latitude (e.g. Svalgaard and Wilcox, 1975, Fenimore et al., 1978, Mursula and Hiltula, 2004). Geomagnetic indices are influenced by both solar polar zones and the solar equatorial belt, through the fast solar wind streams and "CME-associated flows" (CME standing for coronal mass ejection events; see e.g. Richardson and Cane, 2012 and references within). These two sources of magnetic disturbances are closely related respectively to the poloidal and toroidal components of the solar magnetic field; thus, the study of the solar rotation signal in the evolution of geomagnetic indices provides information on the solar dynamo (Ruzmaikin et al., 2001). The coherence and phase difference between the toroidal and poloidal components of the solar magnetic field also contribute to the quality

* Corresponding author.

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of solar activity forecasting based on geomagnetic indices (Feynman, 1982; Hathaway, 2008). In this paper, we study the correlation between the energies of short and long 27-day rotation periods in geomagnetic series, focusing on the times of their de-synchronization.

An important application of the present study relates to the problem of backward reconstruction of the heliospheric magnetic field strength and solar wind properties (Svalgaard and Cliver, 2010). Indeed, records of direct measurements of the solar wind have been available only since the satellite era began, whereas geomagnetic observations have existed since the second half of the 19th century. The fact that there are time periods of discrepancy between different backward reconstructions may be due to problems of data recording or alternately may be related to the actual behavior of the solar magnetic field. All models of long-term solar properties assume constant relationships between solar proxies (Usoskin and Kovaltsov, 2004). This assumption may be violated due to long-term changes in solar dynamo evolution or to de-synchronization of solar indices that appear during particular solar cycles. The present study is aimed at investigating how strong and frequent the de-synchronization between short and long period rotation signals in geomagnetic indices can be.

2. Data

In the present paper we analyze the evolution of the correlation between the energies of short and long period component of the 27-day solar rotation signal in various geomagnetic series, namely the *aa*, *Dst* and ζ-indices. In the range of periods under study the geomagnetic signal is mainly governed by the Sun. In order to find the origin of de-synchronization observed in geomagnetic indices, we consider various solar indices (sunspot number, radio flux, solar wind speed and IMF series), and search for similar de-synchronizations in their series. Solar wind and IMF series are short and their early recordings are not of high quality; therefore we also consider sunspot number and radio flux as reference series, even if they are not as directly related to IMF forcing of geomagnetic indices. All series used in this paper have daily sampling.

The *aa* index reflects maximal magnetic disturbances in 3-hour sampling intervals. The *aa* index, introduced by Mayaud (1972), is based on data from the two roughly antipodal observatories of Greenwich and Melbourne and their successors. We use here daily *aa* values, which are the averages of the 8 three-hourly *aa* values for the day. The daily *aa* series for the time span 1868–2011 is available through the International Service of Geomagnetic Indices (ISGI), http://isgi.latmos.ipsl.fr/source/indices/aa/.

The *Dst* index has been calculated at the Data Analysis Center for Geomagnetism and Space magnetism, Graduate School of Science, Kyoto University, Kyoto, Japan, and maintained at the World Data Center WDC-C2. It uses the recordings of the horizontal component *H* of the geomagnetic field from four observatories at low to mid latitudes: Hermanus, Honolulu, Kakioka and San Juan. These observatories were chosen on the basis of the quality of observation and because they were far enough from the auroral and equatorial electrojets and distributed in longitude as evenly as possible (Sugiura and Kamei, 1991; Menvielle and Marchaudon, 2007). The *Dst* index was devised to study the temporal development and intensity of magnetic storms and the ring current. The derivation of the *Dst* index comprises two basic steps: the removal of the secular variation of the main internal geomagnetic field and the removal of the quiet day variation, both of which are calculated using the five quietest days of each month. We use daily D_{st} series available for the time span 1957–2011 through ISGI, gateway http://isgi.latmos.ipsl.fr/source/indices/Dst/.

The D_{st} series is relatively short (it starts only in 1957). In order to extend the index in the past we have introduced the ζ indices (Le Mouël et al., 2004) that are local indices determined at each geomagnetic observatory, correlate well with D_{st} and cover much longer time spans (Shnirman et al., 2010; Le Mouël et al., 2012).

The ζ index is defined as the absolute value of the 3-day slope of the horizontal component *H* of the geomagnetic field at a geomagnetic observatory. When daily data of the *H* component are used, the index is simply expressed as $\zeta(t) = |H(t+1) - H(t-1)|$. The daily ζ index may be directly obtained from hourly or minute records of the *H* component by taking the absolute value of the slope of its linear approximation in the 3-day centered running window. The resulting ζ index does not significantly depend on the sampling (day, hour or minute) of initial geomagnetic data.

The ζ index reflects the high-frequency content of geomagnetic series and reduces the low-frequency content by construction. Although the ζ series depends on the latitude of the geomagnetic station, its evolution and spectral properties are very similar for all mid-latitude stations (e.g. Shnirman et al., 2010; Le Mouël et al., 2012). In the present study we consider eight observatories that provide long and homogeneous geomagnetic series without large (annual) gaps: Alibag (1925–2011), Eskdalemuir (1911–2010), Honolulu (1902–2010), Kakioka (1924–2010), Lerwick (1926–2010), Sitka (1902–2010), San Juan (1926–2010) and Tucson (1909–2010). These data are available through the World Data Centre for Geomagnetism (WDC) in Edinburgh http://www.wdc.bgs.ac.uk/catalog/master.html.

As far as long solar index series are concerned, we use the International Sunspot number series (R_I), available as a daily series without any gap (1850–2011) at ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS/INTERNATIONAL, and the 10.7 cm radio flux $F_{10.7}$ index recorded at Penticton Observatory, and available for 1947–2011 at ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_RADIO/FLUX/Penticton_Adjusted.

The solar wind speed and Interplanetary Magnetic Field (IMF) series are relatively short (1965–2011) and unfortunately have a large number of gaps until 1995. Data are available through the OMNI database http://omniweb.gsfc.nasa.gov/form/dx1.html. We consider IMF components B_x, B_y, B_z, magnitude $|B|$, and solar wind speed v that are known to be closely related with geomagnetic indices (e.g. Lockwood et al., 2009; Rouillard et al., 2007). Although the "geo-effectiveness" of solar wind streams and CMEs has been extensively studied and related to different combinations of IMF and solar wind speed parameters (e.g. Richardson et al., 2002; Verbanac et al., 2011), there is no simple relationship between geomagnetic and solar indices, due to solar cycle variability and complexity. We note however that the southward component of IMF represented by B_z is a particularly essential measure of the solar forcing of geomagnetic disturbances (Feynman and Crooker, 1978; Yermolaev et al., 2005).

3. Methods

The power spectra of geomagnetic and solar activity series display a clear signal in the 27-day period range of solar rotation (Fig. 1). This signal corresponds to the time characteristics of solar rotation and does not reduce to a single spectral line. For each index $G(t)$, we consider the cumulative power of all orthogonal frequencies relevant to short and long periods of solar rotation in a sliding window W as two new series $E_1(t)$ and $E_2(t)$. The evolution of their running correlation $C_T(t) = C(E_1(t), E_2(t))$ computed over a sliding window T is the subject of our investigation.

3.1. Two domains of periods.

Two domains of periods can readily be distinguished in the 27-day power spectrum of the geomagnetic indices and IMF component B_z