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Response of the geomagnetic activity to solar wind turbulence during solar cycle 23

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ABSTRACT

The solar wind–magnetosphere coupled system is characterized by dynamical processes. Recent works have shown that nonlinear couplings and turbulence might play a key role in the study of solar wind–magnetosphere interaction processes.

Within this framework, this study presents a statistical analysis aimed to investigate the relationship between solar wind MHD turbulence and geomagnetic activity at high and low latitudes as measured by the AE and SYM-H indices, respectively. This analysis has been performed for different phases of solar cycle 23. The state of turbulence was characterized by means of 2-D histograms of the normalized cross-helicity and the normalized residual energy. The geomagnetic response was then studied in relation to those histograms.

The results found clearly show that, from a statistical point of view, solar cycle 23 is somewhat peculiar. Indeed, good Alfvénic correlations are found unexpectedly even during solar activity maximum. This fact has implications on the geomagnetic response as well since a statistical relationship is found between Alfvénic fluctuations and auroral activity. Conversely, solar wind turbulence does not seem to play a relevant role in the geomagnetic response at low latitudes.

1. Introduction

The Sun–Earth coupled system includes a variety of dynamical processes extending from the solar corona into the magnetosphere. Reconnection processes during periods of southward interplanetary magnetic field allow exchanges of mass, energy and momentum between solar wind and magnetosphere plasmas, causing geomagnetic storms and substorms.

It has been shown that turbulence might play a key role in the study of solar wind–magnetosphere interaction processes as both the solar wind and the magnetosphere are characterized by high Reynolds numbers (Borovsky and Funsten, 2003; Matthaeus et al., 2005).

The solar wind is a magnetofluid pervaded by fluctuations over a wide range of scales which are strongly modified by the effects of the dynamics during the expansion into the interplanetary medium. Recent studies have shown that solar wind fluctuations can be seen mainly as a mixture of Alfvénic fluctuations which propagate and structures advected by the wind, as widely reported in literature. The reader is advised to refer to e.g. Tu and Marsch (1995) and Bruno and Carbone (2005) and references therein for a complete treatment on solar wind turbulence.

Furthermore, the magnetosphere behaves as an out-of-equilibrium system due to the continuous coupling with the solar wind and the Earth's ionosphere. As a matter of fact, evidences of a nonlinear behavior (Tsurutani et al., 1990), scale-invariant dynamics and multifractal behavior (Consolini and De Michelis, 1998, 2002) of the magnetosphere have been found in analyzing the auroral electrojet (AE) indices (Davis and Sugiura, 1966) that are a rough estimate of the energy release by the magnetosphere into the ionosphere during the magnetospheric activity. On the other hand, several studies have been carried out on the study of the multifractal properties of geomagnetic indices such as the Dst and the SYM-H indices (which measure the horizontal magnetic field fluctuations near the geomagnetic equator), finding for both indices scale-free fractal and multifractal properties (Wanliss, 2004, 2005; Wanliss et al., 2005; Wanliss and Dobias, 2007; Wanliss and Uritsky, 2010).

Recent studies (Gonzalez et al., 1999; Diego et al., 2005; Chian et al., 2006) have observed a close correlation between interplanetary Alfvén waves and AE index, as originally found by Tsurutani and Gonzalez (1987) during periods of High-Intensity Long-Duration Continuous AE Activity (HILDCAA). Moreover, D'Amicis et al. (2007) showed that Alfvénic fluctuations are geoeffective in driving the geomagnetic response at high latitudes during the minimum of solar activity. At low latitudes this link has not been established.

In order to gain a deeper understanding of the phenomenology characterizing Sun–Earth connections, the present study focuses

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on the role played by Alfvénic turbulence in the solar wind–magnetosphere coupled system considering the geomagnetic response as monitored by the AE and SYM-H indices, at high and mid-low latitudes, respectively. In this study, we consider as an indicator of the geomagnetic activity at mid-low latitudes the SYM-H index (Iyemori and Rao, 1996) instead of the Dst index for its cadence of 1 min (the same as for the solar wind, magnetic field and AE index), knowing that the two indices are effectively interchangeable in an operational sense (Wanliss and Showalter, 2006), although they slightly differ for a different convolution of the station data.

This paper is organized as follows. Section 2 provides a brief outline of the method used to characterize the state of solar wind turbulence. Section 3 presents results regarding solar wind turbulence at solar minimum and maximum of solar activity 23. Sections 4 and 5 focus on the geomagnetic response at high and mid-low latitudes, respectively. At the end of the paper, we briefly summarize our findings and give a possible interpretation.

2. Method of analysis

This analysis was performed using two of the three invariants for the ideal equations of motion: the total energy and the cross-helicity, respectively. In particular, following Tu and Marsch (1995) the normalized cross-helicity

$$\sigma_C = \frac{e^+ - e^-}{e^+ + e^-} \tag{1}$$

and the normalized residual energy

$$\sigma_R = \frac{e^v - e^b}{e^v + e^b}, \tag{2}$$

were used as a tool to characterize the state of turbulence.

Eq. (1) is written in terms of e^+ and e^- which are the energy per unit mass associated to z^+ and z^- modes (the Elsässer variables), respectively. The Elsässer variables are defined in the following way: $\mathbf{z}^\pm = \mathbf{v} \pm \mathbf{b}$ where $\mathbf{b}$ is the magnetic field expressed in Alfvén units ($\mathbf{b} = \mathbf{B}/(4\pi\rho)^{1/2}$, where ρ is the mass density). The sign in front of b is given by sign($-\mathbf{k}\cdot\mathbf{B}_0$), where $\mathbf{k}$ is the wave vector and $\mathbf{B}_0$ is the ambient magnetic field. In fact, for a field directed outward (with respect to the Sun), a negative correlation indicates a mode propagating away from the Sun, while a positive one represents a mode directed towards the Sun. In case the field is directed towards the Sun, the correlation sign reverses with respect to the previous cases. The scientific community has agreed to define Elsässer variables in such a way that z^+ is always referred to outward modes while z^- to inward modes. To do this, one has to rotate the magnetic field by 180°, every time that it is directed towards the Sun (Roberts et al., 1987; Bruno and Bavassano, 1991; Grappin et al., 1991). In this analysis, the magnetic field direction was evaluated with respect to Parker's spiral, averaging B_0 over 12 h (Tu and Marsch, 1995) being this scale appropriate to describe the large scale configuration.

Eq. (2) is written in terms of e^v and e^b which are the kinetic and magnetic energy per unit mass, respectively. σ_C and σ_R were computed at 1 h scale as solar wind fluctuations show a strong Alfvénic character at this scale (Tu and Marsch, 1995; Bavassano et al., 1998).

The normalized cross-helicity, studied for the first time in the solar wind framework by Matthaeus and Goldstein (1982), depends on the correlation between v and b. The value of σ_C is 1 (-1) when only an outward (inward) mode is present. Absolute values of σ_C below 1 correspond to the presence of non-Alfvénic fluctuations in the solar wind parameters.

The normalized residual energy, first used with solar wind data by Roberts et al. (1987), gives the balance between kinetic and magnetic energy (in Alfvén units), normalized to the total energy. The absence of magnetic (kinetic) fluctuations corresponds to σ_R equal to +1 (-1), while equipartition gives $\sigma_R = 0$, as for Alfvénic fluctuations.

A thorough explanation on that topic is given in Bavassano et al. (1998).

3. Cross-helicity and residual energy during solar activity cycle

The present analysis is based on data from the OMNI dataset (details of the documentation can be found in http://omniweb.gsfc.nasa.gov/ow.html) from the solar wind plasma and magnetic field experiments. Both solar wind data, i.e. velocity components and proton density and magnetic field measurements are 1 min-averages.

For this study, six months of data were selected, both at solar minimum and maximum of solar cycle 23 as shown in Fig. 1. The selected time intervals span in the range [1–181] of 2001 and 2007 for solar maximum and minimum, respectively.

The turbulence state of solar wind data can be characterized by means of 2-D histograms of σ_C and σ_R, allowing to examine the role played by Alfvénic fluctuations for different phases of the solar cycle. This representation was first introduced by Bavassano et al. (1998) while studying the radial evolution and latitudinal dependence of the cross-helicity and the residual energy in the solar wind turbulence.

Bruno et al. (2007), using 2-D histograms, focused on the radial dependence of the turbulent population within fast and slow streams in terms of σ_C and σ_R. They analyzed the same corotating stream using Helios' data and found that at short heliocentric distances (0.3 AU) the turbulent population is largely dominated by Alfvénic fluctuations characterized by high values of σ_C and $\sigma_R \sim 0$. However, as the wind expands, a new-born population, characterized by lower values of Alfvénicity (intended as the correlation between field δb and velocity δv fluctuations), and a clear imbalance in favor of magnetic energy becomes visible and clearly distinguishable from the Alfvénic population. Slow wind, on the contrary, does not show any radial evolution.

D'Amicis et al. (2007) performed a statistical study aimed to evaluate the importance of Alfvénic fluctuations for different

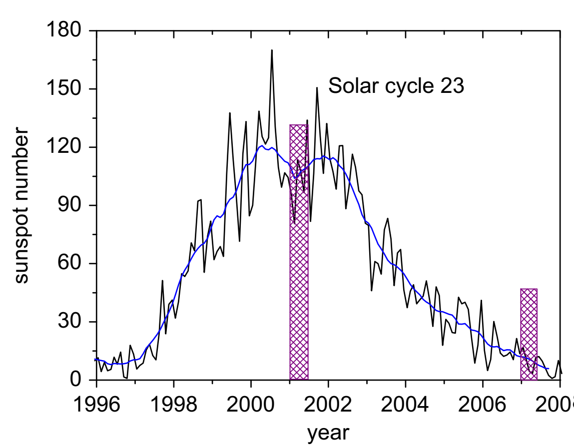

Fig. 1. Daily sunspot number as a function of time and monthly average (smoothed curve). The boxes correspond to the selected time intervals: six months 1 min-averaged data from OMNI dataset, both at solar minimum (year 2007) and maximum (year 2001), respectively; AE and SYM-H indices data were selected for the same time intervals.