Statistical Study of Solar Wind Parameters and Evolution of Dst Variations during 19-23 Solar Cycles in Relation with Cosmic Ray Variations

L. Biktash

Institute of terrestrial magnetism, ionosphere and radio wave propagation, 142190 Moscow Region, Troitsk, Russia

E mail: lsizova@izmiran.ru

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Abstract. We have studied the long-term variations of equatorial Dst index in 19-23 solar cycles to display favorable conditions in interplanetary space, which can have an influence on cosmic ray variation and climate change. In this connection the solar wind and interplanetary magnetic field parameters obtained from the OMNI and Ulysses databases, geomagnetic activity represented by Dst index from beginning 1957 to the end 2010 were used in our study. Yearly and 27-day average variations of Dst index and the solar wind parameters were compared with cosmic ray data from IZMIRAN and Oulu neutron monitors during the 19-23 solar cycles. During the descending phases of these solar cycles the long-lasting solar wind high speed streams occurred frequently and were the primary contributors to the recurrent Dst variations. We study cosmic ray (CR) variations in connection with evolution of Dst variations as the final product of solar wind – magnetosphere interaction because the important drivers of geomagnetic storms as CMEs (coronal mass ejections) and CIRs (corotating interaction regions) undergo very strong changes during their propagation to the Earth. Since Forbush observed decreases in the CR count rate it was shown good correlation between CR and Dst index during individual geomagnetic storms. For long-term variations of CR in a number of papers a good correlation between CR and sunspot numbers was shown but these results do not adequately reflect CR intensity variations and peculiarities concerned with the solar wind arrival to 1 AU. We show that long-term Dst variations in these solar cycles were correlated with cosmic ray count rate and can be used for prediction of CR variations. Climate change in connection with evolution of Dst variations is discussed

Keywords: Dst index, solar activity, solar wind, cosmic rays

Introduction

The ring and magnetopause currents are the major current systems of the magnetosphere and they are the dominant cause of Dst variations. In contrast to Kp, AE, etc the Dst index is free of ionospheric currents influence. The conditions in the solar wind that lead to the generation of extreme and severe geomagnetic storms are relatively rare and depend on the phase and level of solar activity (SA). The Earthwards directed coronal mass ejections (CMEs) are the major cause of the severe geomagnetic storms. Primary factors determining CME geoeffectivity are the direction of propagation of CME, its speed, size, density, and orientation and strength of the magnetic field at the near-Earth space (Gosling et al., 1991; Gopalswamy, 2010). Corotating interaction regions (CIRs) are the main cause of the moderate geomagnetic storms (Tsurutani et al., 2006). These important drivers of geomagnetic storms have very strong evolution during their propagation to the Earth's magnetosphere due to their interaction with the ambient solar wind. The first reason of studying the long-term Dst variations is the fact that Dst index shows the final result of these phenomena. The second reason is that since Forbush observed decreases in the cosmic rays (CRs) count rate (Forbush Decreases – FDs) a good correlation between CR and Dst index during individual geomagnetic storms was shown. The solar sunspot numbers (SSN) do not adequately reflect the CR intensity variations and the peculiarities concerned with the solar wind reaching to 1 AU. The aim of our paper is to clear up the peculiarities of the long-term variations in Dst during descending phases of SA and its possible effect on climate by means of cosmic rays. Yearly and 27-day average variations of Dst index and the solar wind parameters obtained from the OMNI database are used in our study. We also used catalog of the Dst index (Sugiura and Poros, 1971) to examine its behavior in solar cycle (SC) 19. Cosmic ray data were taken from IZMIRAN and Oulu neutron monitors.

Analysis of the experimental data

Let us examine Figure 1 where 27-day average variations of sunspot numbers (SSN) (a), the solar wind plasma density (b), the solar wind velocity (c), Dst index (d) and cosmic ray variations from Oulu neutron monitor (e) for the period from 1964 to 2010 are shown. It is observed that the 27-day average of solar wind density variations was in antiphases with SSN. The solar wind velocity variations had maxima during the descending phases of the solar cycles. 27-day average of Dst (min) = - 80 nT was observed in the 22 SC. This result is an average of the severe geomagnetic storm in March 1989, which was associated with CME. As seen in Dst, the high speed streams with low density during descending phases of solar activity in SCs 20-23 were geoeffective and produced a lot of moderate storms. They are shown in Figure 1 by the ovals. These high speed solar wind streams are result of averaging and can be caused by large, long-lasting low latitude solar coronal holes. SOHO's extreme ultraviolet imaging telescope EIT (http://cdaw.gsfc.nasa.gov/) shows large coronal holes during descending phases and minima of the solar activity. We can see the intervals nearly 1-1.5 years of high speed streams in 27-day average data in Fig. 1c with low solar wind density – Fig. 1b during 20-23 SCs. The Ulysses observations have a good quantitative agreement in the trends and values with ACE measurements of solar wind velocity, density and dynamic pressure when Ulysses was at low latitudes. The Ulysses and ACE 27-day average data show the long-lasting high speed solar wind streams between of 2003-2004. This long-lasting high speed solar wind stream in Figure 2 is denoted by the oval (Mc Comas et al., 2008). Cosmic ray variations from Oulu neutron monitor (e) in Figure 1 show sizeable decreases of count rate related to the high speed solar wind streams.

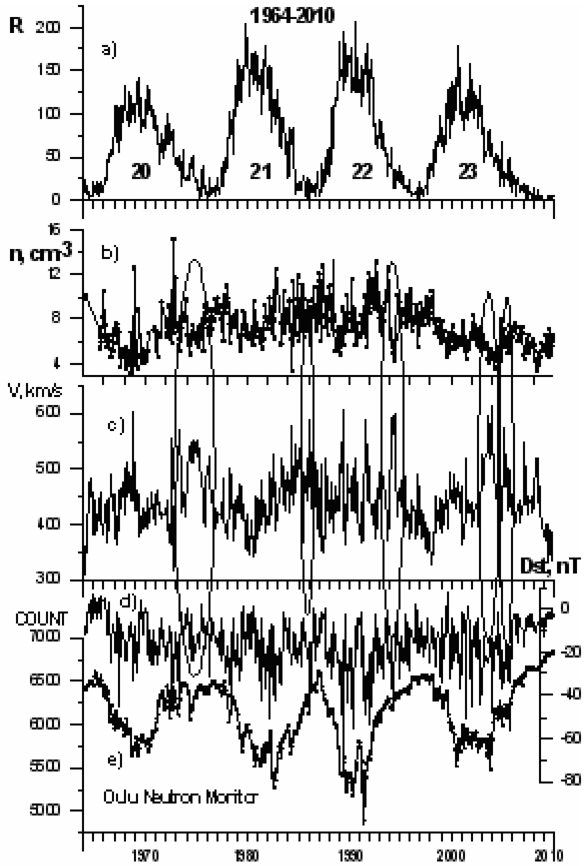

Figure 1. Plots of 27- day average data in SCs 19-23: a) R - sunspot number, b) solar wind density n in cm-3, c) solar wind velocity v in km s-1, d) Dst index in nT, e) cosmic ray count rate of Oulu neutron monitor. The ovals encompass the solar wind velocity and density variations during declining and minimum phases of the solar cycles.

We calculated 27-day average Dst variations for SC19. For 1957-1965 years we have used Sugiura's catalog of Dst index (Sugiura and Poros, 1971). Plots of the sunspot numbers and Dst index for SC19 are presented in Figure 3. We can see that in general Dst variations in SC19 were correlated with the solar activity and the most pronounced minima of Dst variations were coincided with sunspot numbers maxima. Dst variations reached -60 nT and it was similar to SC22. The SC19 in descending phase had 27- day average Dst variations like in SCs 20-23 and shows geomagnetic storms, most probably associated with high speed solar wind streams from coronal holes. Furthermore, unusual solar minimum with average Dst near +5 nT was observed during two years. For comparison, in minimum of SC23 average Dst was around -5 nT during four years. We do not see solar spots on the solar maps (for example, see Sacramento Peak Observatory images) which can be connected to geomagnetic variations during descending phase of SC19. So, the moderate geomagnetic storms of this SC could be associated with corotating interaction regions and could make one's contribution to Dst and CR variations.

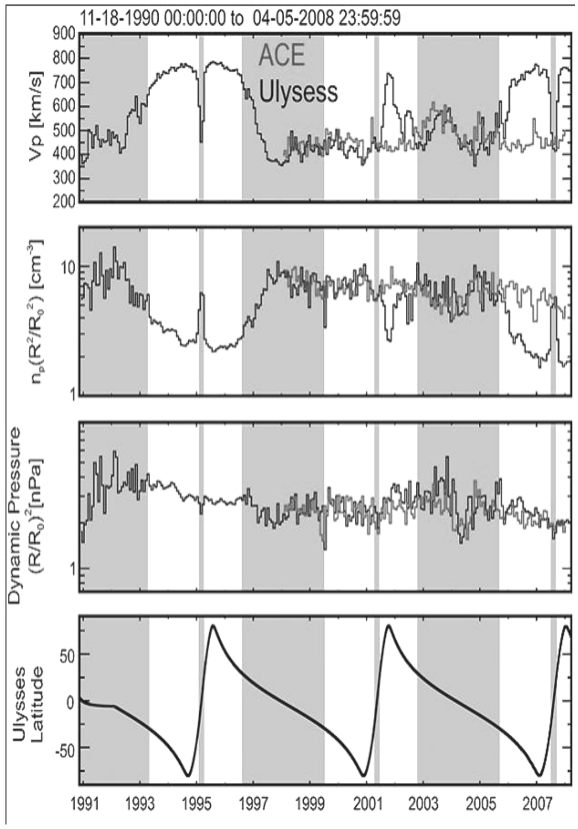

Figure 2. Solar wind parameters from Ulysses - black line (McComas et al. 2008) compared to ACE (grey line). Intervals when Ulysses was within ±30o of the ecliptic plane (shaded area) match very closely in speed, density and dynamic pressure. Dynamic pressure continues to match quantitatively even over Ulysses' high latitude excursions.

Dst and cosmic ray variations in relation of climate change

Since Forbush (1937) observed decrease in the in the cosmic rays count rate during the geomagnetic storm, scientists tried to understand their origin and influence on the Earth. Simpson (1954) suggested that the origin of these decreases was probably in the interplanetary medium. Relations with geomagnetic storms and their drivers CMEs, magnetic clouds, as well as corotating regions were found (Cane, 2000). Many authors have considered the influence of

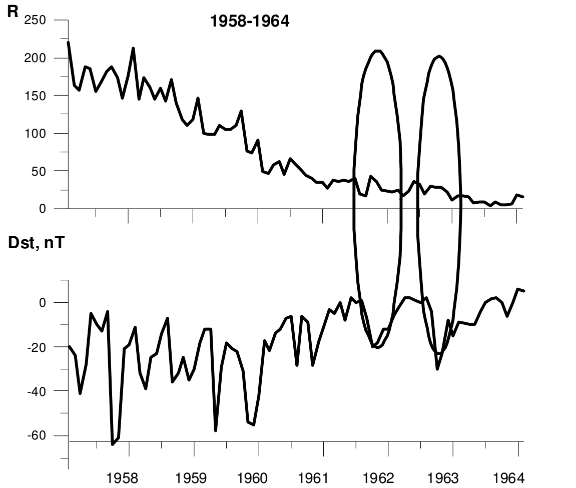

Figure 3. 27-day averages of SSN and Dst index during SC19. Dst index during the descending phase shows geomagnetic storms (ovals), most probably associated with CIRs.

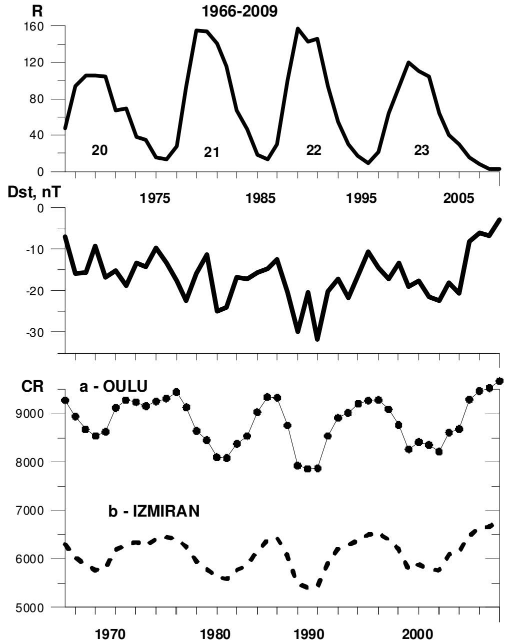

Figure 4. Monthly averages of SSN, Dst index and count rate of CRs at Oulu and IZMIRAN.

galactic and solar cosmic rays on the Earth's climate. At present cosmic ray activity as possible mechanism of climate change is the subject of wide speculation. Recent researches have shown that the Earth's cloud coverage is strongly influenced by cosmic ray intensity (Pudovkin and Raspopov, 1992; Pudovkin and Veretenenko, 1995; Tinsley 2000; Swensmark, 2000). Clouds influence the irradiative properties of the atmosphere by both cooling through reflection of incoming short wave solar radiation, and heating through trapping of outgoing long wave radiation (the greenhouse effect). It is shown that cosmic radiation is the main source of air ionization below 40-35 km (Belov et al., 2005; Dorman, 2010; Kane, 2010). Kane (2010) reexamined the severe Dst events for their relationships with Forbush decreases and interplanetary parameters for SCs 19-23. The time evolutions of Dst and FDs were very different and sometimes the correlation between events was almost zero. Basically, negative Dst and FDs are uncorrelated, indicating altogether different mechanism. Kane (2010) used data for one location (Climax are used for cosmic ray FDs) and he concluded that it should be kept in mind that using cosmic ray data at only one location may involve uncertainties. CRs bend in magnetic fields and have trajectories depending upon the cut-off rigidities at any geographical location (lesser the cut-off rigidity, larger the FD, because more low energy particles are received). Moreover the trajectories at different longitudes may sample different part of the interplanetary shocks, which may not be uniform. In a rigorous analysis, the trajectories of data at different locations need to be examined. On the other hand, using Climax data, Dorman (2010) holds the opinion that the action of space factors on the Earth's climate is realized mostly through cosmic rays and space dust. He supposes that the influence of these factors on clouds formation controlles the total energy input from the Sun into the Earth's atmosphere. He shows good correlations between CRs and different phenomena right up to wheat prices.

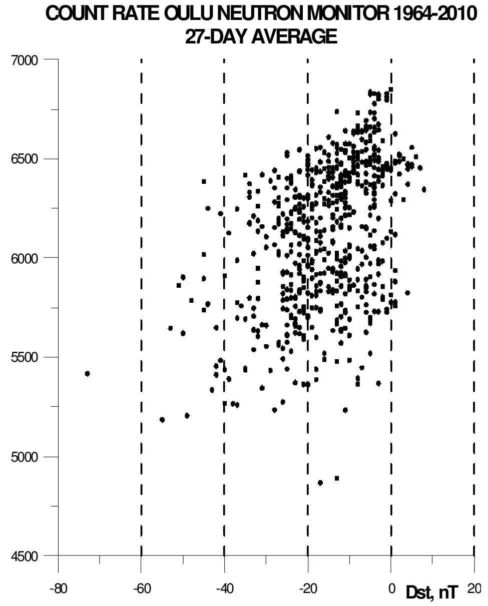

Figure 5. 27-day average of count rate of CRs at Oulu vs Dst-index during SCs 20-23.

Munakata et al. (2010) have analyzed the temporal variations of the diurnal anisotropy of sub-TeV cosmic-ray intensity observed with the Matsushiro (Japan) underground muon detector over two full solar activity cycles during 1985–2008. Their results didn't show any clear correlation with either the solar activity or magnetic cycles. They show significant time lag between the temporal variations of the CRs amplitude and the sunspot number obtaining the best correlation coefficient of +0.74 with the SSN delayed for 26 months. It was suggested that this anisotropy might be interpreted in terms of energy change due to the solar-wind-induced electric field expected for galactic cosmic rays crossing the wavy neutral sheet. The wavy heliospheric current sheet is associated with solar rotation and neither the solar rotation axis nor the effective dipole axes are perpendicular to the ecliptic plane. Accordingly, the Sun's rotation causes the heliospheric current sheet to move up and down at a fixed observer's position, with associated changes in the plasma density and the direction (towards/away) of the magnetic field. This wavy pattern of the current sheet is sometimes referred to as the ``ballerina skirt'' effect (Alfven, 1981; Mursula and Hiltula, 2003). Localized coronal magnetic configurations can also be expected to modify the position and properties of the heliospheric current sheet.

In this study we have tried to understand what causes the discrepancies between the foregoing results using 27-day average Dst-index and CR evolution during of 20-23 SCs. Figure 1 shows a general agreement between Dst and CR variations in Oulu. After this conclusion we calculated yearly averages of Dst-index for 1966-2009 years and correlated it with cosmic ray neutron monitors data from Oulu (http://cosmicrays.oulu.fi) and IZMIRAN (http://www.izmiran.ru) stations. A good correlation between SSN, Dst and count rate of cosmic rays at Oulu and IZMIRAN is shown in Figure 4. We can calculate yearly average count rate of cosmic rays (Y) using Dst index and SSN without time lag from the equations:

$$Y = 41.5 * Dst + 6788.4\,, \quad R = 0.5, \;\; \sigma = \pm 249.8 \qquad (1)$$

$$Y = -8.3 * SSN + 9400.4\,, \quad R = 0.67, \;\; \sigma = \pm 282.3 \qquad (2)$$

where R is correlation coefficient, σ is standard deviation. Correlation coefficient between CR and SSN is 0.67 in (2) but σ is a little better for CR - Dst correlation (1). Monthly averages of count rate of neutron monitors in Oulu and IZMIRAN (Figure 5) show that CR intensity is better modulated by Dst variations in SCs 20-23 than by SSN. Cosmic ray variations (increasing of count rate with Dst-index maxima) during 1964-1965 years and after 2006 as seen in Figure 1 could have partial effect on climate change.

Conclusion

Solar wind parameters and geomagnetic activity represented by Dst index from beginning of 1957 to end of 2010 were used in our study. Yearly and 27-day average variations of Dst index and 27-day averages of solar wind parameters were calculated and compared with cosmic ray variations during 19-23 solar cycles. Superposed epoch results show that Dst variations were most intensive in 19 and 22 solar cycles. During the descending phases of SA the solar wind high speed streams with low density occurred frequently and were the primary contributor to the recurrent Dst variations. The maximum in monthly Dst variations was observed in the minimum of solar cycle 19 in spite of the fact that this solar cycle was the strongest among SCs 19-23. It is shown that CIRs had effects on cosmic ray variations during descending phases of SCs 19-23. Evolution of Dst index from point of view of solar variability and cosmic rays during SCs 19-23 show that the long-term variations of the Dst index can be used together with other solar and interplanetary parameters for climate change studies. The geoeffectiveness of the solar wind evaluated using the Dst index and correlation with cosmic rays radiation confirms that one of the main sources of air ionization and climate change will depend on the solar wind parameters and the magnetospheric current intensity. Taking into account cut-off rigidities of CRs at any geographical location and other factors requires a more detailed investigations of CR-Dst relationship.

Acknowledgments

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