Journal of Atmospheric and Solar-Terrestrial Physics 73 (2011) 796–804

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

A multivariate study of Forbush decrease simultaneity

O. Okike [a,b,*], A.B. Collier [a,b]

[a] School of Physics, University of KwaZulu-Natal, Westville Campus, Durban 4000, South Africa
[b] Hermanus Magnetic Observatory, P.O. Box 32, Hermanus 7200, South Africa

ARTICLE INFO

Article history:
Received 15 July 2010
Received in revised form
5 January 2011
Accepted 17 January 2011
Available online 25 February 2011

Keywords:
Cosmic rays
Solar wind
Magnetic field
Cosmic ray modulation
Forbush decreases
Multivariate analysis

ABSTRACT

The distribution of the cosmic ray flux over the Earth is not uniform, but the result of complex phenomena within the Sun–Earth environment. A Forbush decrease (Fd) is a rapid decrease in the intensity of cosmic rays. A given Fd can appear in different forms at different locations of the Earth. An investigation of simultaneous observations of Fd events by a selection of cosmic ray stations remains a subject of interest among researchers and numerous methods of analysis can be found in literature. Although these studies have contributed significantly to our knowledge, the variability in the manifestations of Fds demonstrates that there are still open questions in this field. The present work suggests that multivariate analysis is a simple method that can be used to discriminate between globally simultaneous and non-simultaneous Fds.

1. Introduction

It has long been known that the intensity as well as the energy spectrum of galactic cosmic rays (GCRs) are modulated on various time scales. The first observations of the temporal changes in GCR intensity at Earth were made by Forbush (1938). It was originally assumed that the variations were produced, either directly or indirectly, by geomagnetic disturbances such as perturbations of the Earth's magnetic field during geomagnetic storms. As a result the variations were taken to be of Earth's origin. Simpson et al. (1953), however, found that such variations cannot be ascribed to the effects of a ring current or other phenomena associated with geomagnetic field perturbations.

Studies on GCR modulation have played a significant role in our understanding of the nature of the Sun–Earth environment (Lockwood, 1971; Belov et al., 2006). The variability in the GCR flux has, for example, been successfully correlated with a number of space weather phenomena such as coronal mass ejections (CMEs), solar flares and geomagnetic storms. It has been hypothesized that changes in cloudiness, atmospheric electricity, temperature, thunderstorm, lightning activity and depletion of the ozone layer might be associated with GCR intensity variation (Svensmark and Friis-Christensen, 1997; Gurevich et al., 1999; Palle Bago and Butler, 2000; Marsh and Svemsmark, 2000; Fedulina and Lastovicka, 2001; Stozhkov, 2003; Usoskin et al., 2004; Dorman and Dorman, 2005; Pierce and Adams, 2009). GCRs are deflected by magnetic fields and their trajectories depend on cutoff rigidities of different locations on the Earth. The flux of GCRs incident on the Earth's atmosphere is modulated mainly by the interactions between solar wind and geomagnetic field (Geranions and Mavromichalaki, 1982; Firoz et al., 2010). The solar modulation of GCR intensity is generally divided into different types according to the time scales and the periodicity of the variation. The dominant periodic variations occur over 22- and 11-year, 27-day and diurnal time scales. Non-periodic decreases in the GCR count rate, generally referred to as Forbush decreases (Fds), last typically for about a week, and were initially observed by Forbush (1937) and Hess and Demmelmair (1937) using ionization chambers. Every Fd consists of two major parts: a main phase and a recovery phase. The onset of the main phase occurs in less than half a day while the recovery phase lasts several days. Some authors (Cane, 2000; Lockwood, 1971; Chilingarian and Bostanjyan, 2010) assert that Fds are of two types: recurrent and non-recurrent decreases. Recurrent Fds have more gradual onsets, are more symmetric in profile, and are associated with corotating high-speed solar wind streams. Non-recurrent Fds are caused by transient interplanetary events, which are related to CMEs. They are usually larger than recurrent Fds and represent the so-called classical Forbush decreases (Venkatesan and Ananth, 1991). They have a sudden onset, reach maximum depression within a day and are characterized by a more gradual recovery. All short-term decreases in the intensity of GCR have been historically called Forbush decreases.

---

[*] Corresponding author at: School of Physics, University of KwaZulu-Natal, Westville Campus, Durban 4000, South Africa. Tel.: +27 31 2602775.
E-mail addresses: ogbos.okike@gmail.com (O. Okike), collier@ukzn.ac.za (A.B. Collier).

1364-6826/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jastp.2011.01.015

Some authors (e.g. Cane, 2000), however, use the term only for the non-recurrent events with a sudden onset and gradual recovery. Belov (2009) noted that the solar wind disturbances that could generate the two types of Fd events are the result of complex interactions and are associated with both sporadic and recurrent phenomena.

Prior to the development of a worldwide network of GCR detectors, Fds were thought to happen simultaneously around the world. Such simultaneity was observed in sudden commencement geomagnetic storms formerly believed to have a definite correlation with Fds (Forbush, 1938). Early workers studied the onset times of large Fds and found that they were not simultaneous but dependent on the asymptotic cones of acceptance of different stations (Lockwood, 1971). The onset time for such large events were believed to vary by 2–4 h. Ahluwalia et al. (1968) redefined the onset time of the Fd main phase as the time of minimum intensity of the pre-increase phase. They investigated GCR intensity increases after the minimum intensity in the recovery phase of Fds and concluded that such short-term increases in the recovery phase of Fds are dependent on local time. Hofer and Fluckiger (2000) analyzed the pre-increase in GCR intensity prior to the onset time of large Fds. They agreed that the increase before the main phase onset time is dependent on local time. Recently, Oh et al. (2008) and Oh and Yi (2009) investigated the global simultaneity of Fds by comparing the main phase of large and small Fds observed by three neutron monitors. Their definition of a simultaneous event was not based on the onset time or the time of maximum decrease in cosmic ray intensity. Instead, they considered an event to be globally simultaneous if the main phases overlapped at the three stations. They found that large events were simultaneously observed in universal time while small events are generally non-simultaneous.

Belov et al. (2001) found that observations of Fds at a few locations on the Earth may give an incomplete picture since the spatial scale of some Fds is tens of astronomical units (AU). Fds are so variable in their manifestations that an event may appear in various forms at different locations of the Earth. What looks like a Forbush decrease at a given position and time may reveal itself to be a small variation in the cosmic ray anisotropy or as an increase in density at another position and time. It has also been noted that whether a given neutron monitor observes an increasing or decreasing GCR flux is a function of its asymptotic cone of acceptance and geomagnetic cutoff rigidity (Smart and Shea, 2003; D'Andrea et al., 2009). This is because the distribution of GCR flux over the Earth is not uniform, but the result of the complex relationship between the interplanetary magnetic field (IMF) and the geomagnetic field at a particular location on Earth. During perturbations of the IMF, its directions can undergo significant changes, which could influence the GCR trajectories. CMEs that overtake the Earth may also modify the cutoff rigidities and asymptotic cones of neutron monitors and might produce varieties of Fds at different stations (McCracken et al., 2008).

The Chree method (Chree, 1912, 1913) of Superposed Epoch Analysis (SEA) dominates literature documenting the relationships of Fds with geomagnetic disturbance indexes (Kane, 2010), IMF parameters (Pankaj and Shukla, 1994), magnetic clouds (Badruddin et al., 1991; Ananth and Venkatesan, 1993), terrestrial clouds (Pudovkin and Veretenenko, 1995; Svensmark et al., 2009), marine aerosols (Bondo et al., 2010), atmospheric electricity (Marcz, 1997), solar flares (Belov et al., 2008) and CMEs (Pankaj and Singh, 2005). Some researchers (see, for example, Pankaj and Shukla (1994) and Kane (2010)) base the use of SEA on the assumption of global simultaneity of Fds at one or more stations. The use of SEA might also be based on the similarities or differences of effects of these parameters before or after the time of Fds. These are important studies that depend on the exact time when a Fd event is globally observed. The epoch time is generally taken as the time of maximum decrease in GCR intensity or as the onset time of the Fd events. Kane (2010) doubted the conclusions drawn from such studies since data from one location may not fully represent the global effects of cosmic rays. There is thus a need to study the global simultaneity of Fds using all possible cosmic ray data from the neutron monitors at all locations of the Earth rather than from a single specific station.

2. Data and analysis

2.1. Data source and selection of Fd events

The World-Wide Neutron Monitor Network (http://cr0.izmiran.rssi.ru/common/links.htm) provides on-line data for a large number of stations at a variety of locations. However, availability of data for a particular Fd event is limited by the operational dates of different stations. The dates of Fds were taken from literature. The periods in which multiple stations had complete data for the Fd event dates were selected. The stations that did not have complete data for the periods of interest were not included. The number of stations with data varied as a result of data gaps. On average, the number of stations with data was about 30, covering a wide range of geomagnetic latitudes and longitudes. A broad spatial distribution of cosmic ray stations is well suited to the study of global Fd simultaneity.

The magnitude of Fds remains a subject of controversy among researchers and forms the basis of event selection for this study. Some argue that relatively large Fds are caused by magnetic clouds that are preceded by shocks while small Fds are caused by magnetic clouds that are not preceded by shocks (Venkatesan et al., 1992). Cane (2000) proposed a model in which the different magnitudes of CME-related Fds are grouped into three; those caused by an interplanetary (IP) shock and ejecta, those caused by IP shock only and those caused by ejecta only. The magnitude of Fds generated by shocks will be larger whereas those caused by the passage of ejecta over the Earth will be relatively small. Krittinatham and Ruffolo (2009) reported that magnitudes of GCR intensity decreases can also be associated with one of the interplanetary signatures of ejecta called flux ropes (Marubashi, 2000). Recently, Kubo and Shimazu (2010) argued that the intensity of GCRs inside flux ropes is determined by the ratio (L_o) of the Larmor radius of the GCRs at the flux rope axis to the flux rope radius. Their work indicated that near Earth (large values of L_o), GCRs could easily penetrate the flux rope through gyration, resulting to small Fd events. Belov et al. (2005) successfully linked the changes in magnitude of Fds with changes in cutoff rigidities as well as cosmic ray asymptotic directions arising from disturbances in the Earth's magnetic field during magnetic storms. Others conclude that the magnitude of Fds depends on the speed of the solar wind and the intensity of IMF overtaking the Earth (Cane et al., 1993). It is suspected that a 1 nT increase in IMF magnitude leads to about 0.2% decrease in cosmic ray intensity (Belov et al., 2003; Firoz et al., 2010). Fds of the order of -4% are associated with strong geomagnetic activity while stronger Fds of the order of -8% are thought to result from severe space weather events (Belov et al., 2001). It has also been speculated that the severity of space weather events could be connected with the strength and simultaneity of the associated Fds. Large Fds are thought to occur simultaneously and are connected with strong IMF passing over the Earth, while small Fds are generally non-simultaneous and occur when weak IMF encounters the Earth (Oh and Yi, 2009).

The magnitude of Fds, usually expressed as a percentage, is a relative quantity, which cannot be assigned a unique global value using count rates from separate detectors since it varies from one station to another. Fd magnitudes depend on the type of cosmic ray monitor, the vertical geomagnetic cutoff rigidity and the atmospheric depth at which the detector is located. Ahluwalia et al. (2009) found that the magnitude of a particular Fd event could vary with geographical locations of detectors. This underlines the difficulties in the study of Fds with isolated stations. For instance, Shea et al. (1993) found that the magnitude of the 13 June 1991 event was 3% for Socorro muon telescope detector (cutoff rigidity: 45 GV) and 17% for Inuvik neutron monitor (cutoff rigidity: 1 GV). For this event, Gurnett and Kurth (1995) and Ahluwalia et al. (2009) used data from the same cosmic ray station but calculated 30% and 7% decreases, respectively. This indicates that Fd magnitude also depends on different workers. Ahluwalia et al. (2009) define the amplitude of the event as the difference in the counting rate of detectors near onset of Fd (19 UT) on 12 June and 7 UT on 13 June while Shea et al. (1993) take the cosmic ray intensity values at 19–21 UT on 12 June 1991 as baseline. Van Allen (1993a) criterion for a Fd is a 10% decrease in GCR intensity, whereas some (Belov, 2009; Oh and Yi, 2009; Kane, 2010) chose a smaller threshold. Belov (2009) considered a 0.5–1.0% decrease in GCR intensity as a Fd if a significant solar wind disturbance was observed at the same time. Oh and Yi (2009) used a threshold of 3% for three high latitude stations, arguing that there was no exact criterion for a Fd event.

Instead of deciding the strength of an event based on values from a few isolated stations, the simultaneous detection of Fds at various points on the Earth might be a better criterion to distinguish between strong and weak Fds. A number of investigators (Belov et al., 1995; Ahluwalia et al., 2009; D'Andrea et al., 2009; Kane, 2010) agree that the Fd events of August 1972, June 1991 and October 2003 are among the strongest events ever recorded since continuous monitoring began. These events are good candidates to study the simultaneity of large Fds. Such large events have been selected in order to study their observation at various points on Earth. Some Fds whose magnitudes are relatively small were also selected for a comparative study of global simultaneity of strong and weak Fds. Following the indications of Belov (2009) that a decrease in cosmic ray intensity is considered as a Fd if a significant solar wind disturbance is observed at the time of the Fd, solar wind velocities as well as maximum IMF intensity associated with the Fd events were also searched for. The list of the Fds and their details are displayed in Table 1.

2.2. Method of analysis

Principal Component Analysis (PCA) is a non-parametric technique used to identify structural similarities in multidimensional signals (Green and Carroll, 1978; Bruce, 1981). It reduces the dimensionality of a data set consisting of multiple interrelated variables while retaining as much of the variation present in the original data as possible. This is done by transforming the original data to a new set of mutually orthogonal dimensions with sequentially maximal variance. These new dimensions, called principal components (PCs), are linear combinations of the original data. The first component, PC1, is computed such that it accounts for the greatest possible variance in the data followed by the subsequent components with the condition of orthogonality among the axes. Usually, the bulk of the variance is associated with the first few PCs, making it possible to reduce the dimensionality of the transformed coordinate system by discarding the higher dimensions that are associated with the smallest variance in point projections.

The central objective of PCA coordinate system transformations is to reduce the dimensionality of multivariate data without the loss of too much information. A number of rules have been proposed for determining a suitable dimension for the reduced data. In some circumstances the last few, rather than the first few, PCs are of interest. In the present study, however, the idea of replacing the number of variables in the original data by the first few PCs is adopted while the possible information of the latter PCs is neglected. The criteria for choosing the reduced dimension varied between simultaneous and non-simultaneous Fds. It is selected in such a way that PC1 will contribute over 80% of the total GCR intensity variations at all the locations of the Earth for simultaneous events. Much less is assigned for non-simultaneous Fds.

Interpretation of PCs could be somewhat ambiguous with a complex data set. However, PCA relies on correlation across the original data, making it possible to interpret components by examining the correlations between the initial raw signals and each of the PCs. It is easier, in the case of non-simultaneous Fds, to interpret each component as a combination of a small number of the original variables with which they are most highly correlated. Pearson's product–moment correlation is used to verify the significance of the correlation matrix obtained in our analysis.

2.3. Illustration of global Fd event simultaneity

This section illustrates the concept of global simultaneity of Fds and the reason why PCA is considered as a good tool for studying such events. Data for 4–5 August 1972 as observed by three stations, Inuvik (68.35°N, 133.72°W), Climax (39.37°N, 106.18°W) and McMurdo (77.85°S, 166.72°E), are shown in Fig. 1. Here a Fd event is said to be globally simultaneous if the maximum intensity decrease is observed at the same universal time by all detectors regardless of their location. It is evident from Fig. 1 that the three stations, though widely spaced in latitude and longitude, observed a maximum decrease in GCR intensity at the same universal time. There are also considerable similarities in the structures of the main phase and recovery phase of this event at the three stations. Such structural similarities suggest a common origin of a Fd event and are the main driver of correlation coefficients associated with PCA results. The effects of some small local structural differences observed before

Table 1
Details of the selected Fds. V is the solar wind speed, B is maximum IMF intensity and Fd is the maximum GCR intensity decrease on separate neutron monitors.

Dates	V (km/s)	B (nT)	Fd (%)	References
4–5 August 1972	?	108	−28	Kane (2010)
31 July–01 August 1973	740	9	−3	IZMIRAN database
12–13 June 1991	>800	>25	−30	Ahluwalia et al. (2009), Gurnett and Kurth (1995)
23–24 October 1998	564	9.44	−4	Oh et al. (2008)
21–22 October 1999	529	35.6	−2	Kane (2010)
6–7 April 2000	516	30	−3	Kane (2010), Oh et al. (2008)
8–9 April 2001	650	11.77	−6	Oh et al. (2008)
11–12 April 2001	730	33.1	−11	Kane (2010)
31 October–01 November 2003	1300	37.8	−21	Kane (2010), Kristjansson et al. (2008)

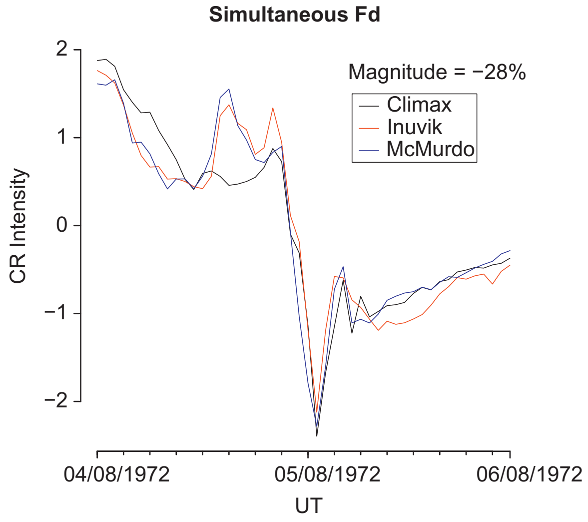

Fig. 1. GCR intensity profiles of simultaneous Fd event that occurred on 4–5 August 1972.

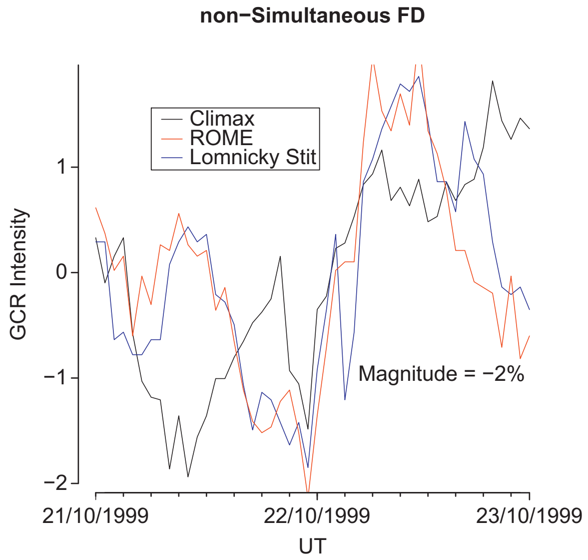

Fig. 2. GCR intensity profiles of non-simultaneous event that occurred on 21–22 October 1999.

the main phase or after the recovery phase cancel out and have little or no influence on the average time of maximum decrease as seen by all the stations.

Fig. 2 shows the time profile of a non-simultaneous Fd that happened on 21–22 October 1999. In order to illustrate the simultaneity of this event with regard to different locations on the Earth, two additional stations that are close in longitude are selected: Rome (41.86°N, 12.47°E) and Lomnicky Stit (49.20°N, 20.22°E). Fig. 2 indicates that Rome and Lomnicky Stit see the maximum decrease for this event at the same time whereas Climax sees the Fd event at a different time. It is interesting to note that Climax station was observing a decrease in GCR intensity at the time when Rome and Lomnicky Stit were recording increases. The magnitudes of the events plotted in Figs. 1 and 2 are, respectively, −28% and −2% (Kane, 2010). The results thus indicate that the simultaneity of Fds is related to their magnitudes. It is also important to note that the magnitudes of both strong and weak Fds are generally highly variable at different cosmic ray stations. Cane et al. (1996) and Jamsen et al. (2007) found that they vary between several to a couple of tens percent for neutron monitor observation. Our method of analysis accounts for the variable magnitudes by normalization.

When analyzing Fd simultaneity at a few locations on Earth it is easy to plot the data as in Figs. 1 and 2 and visually assess the correlation between the GCR intensity variations. However, it is difficult to draw a conclusion with respect to global simultaneity of Fd events based on a few isolated neutron monitor stations. Qualitative identification of patterns in data from a number of globally distributed stations becomes intractable.

3. Results and discussion

Fig. 3 reflects the PCA results of the Fd event of 4–5 August 1972 for 30 cosmic ray stations. Data for the same event were previously presented in Fig. 1. There are striking similarities between Figs. 1 and 3b. The time of minimum flux is exactly the same in both cases, suggesting that all the stations detect the event at the same universal time. Fig. 1 shows that there are minor fluctuations in cosmic ray intensity before the onset of the Fd main phase. Such fluctuations are not the same at all stations. Thus, while some observe an increase in intensity, others see a decrease. Hofer and Fluckiger (2000) found that such intensity variations prior to the onset time of the main phase are local time dependent and are attributable to anisotropic flux of GCRs. Fig. 3b shows that PCA smooths out those irregularities and depicts the average global intensity fluctuations. Fig. 3a represents the correlation of the GCR flux at all the stations with the PC1 scores. The minimum and maximum correlation coefficients are 0.90 and 0.98, respectively. Their *p*-values are in the order of 2.2×10^{-16}, implying that the correlations have high statistical significance. This strong positive correlation is an indication of an overlap of the form of the event at all stations. It is evident from the high correlation coefficients of the raw data with PC1 loadings that the PC1 signal accounts for this Fd signal at all stations. The percentage variance associated with PC1 is 93.3%. The variances of the remaining components are small (0–3.5%) and are ignored as they do not account for significant GCR intensity variation during the time of this event. The fact that it is detected all over the Earth within an hour might be an indication of the high speed of the associated solar wind or the IMF structures. The CME responsible for this event is classified as one of the fastest CMEs on record. It had a record transit time from the Sun to the Earth of 14.6 h and average velocity of 2850 km/s compared to the average CME velocity of ~483 km/s (Kane, 2005; Gopalswamy, 2006).

The result of another strong event is shown for completeness. Fig. 4 presents the event of 12–13 June 1991. Fig. 4b represents the PC1 signal. It shows that the Fd is observed everywhere on the globe at exactly 7:00 on 13 June. The minimum and maximum correlation coefficients of the original data from 33 stations with PC1 signal are, respectively, 0.96 and 0.99 ($p\sim2.2\times10^{-16}$). This strong positive correlation of the original data with the PC1 suggests that PC1 reflects the GCR intensity variations at all stations. The percentage variance of PC1 is 95.6% while the variance of the successive PCs is small (less than 2.2%). Ahluwalia et al. (2009) attempted to represent this event graphically using data from 8 neutron monitors and two underground muon telescopes. Their results showed that the neutron monitors as well as the muon detectors also recorded a maximum decrease at 7:00 on 13 June 1991. There were also good structural similarities in the main phase and recovery phase observed by both types of detectors. They observed, however, that the onset time varied between stations. Although the magnitude of Fds may vary between detectors and locations, the relative structure of a large Fd is the same irrespective of detector or location on the Earth. In addition to detectors on Earth, six spacecraft located at various points in the heliosphere also observed this event (Van Allen, 1993b).

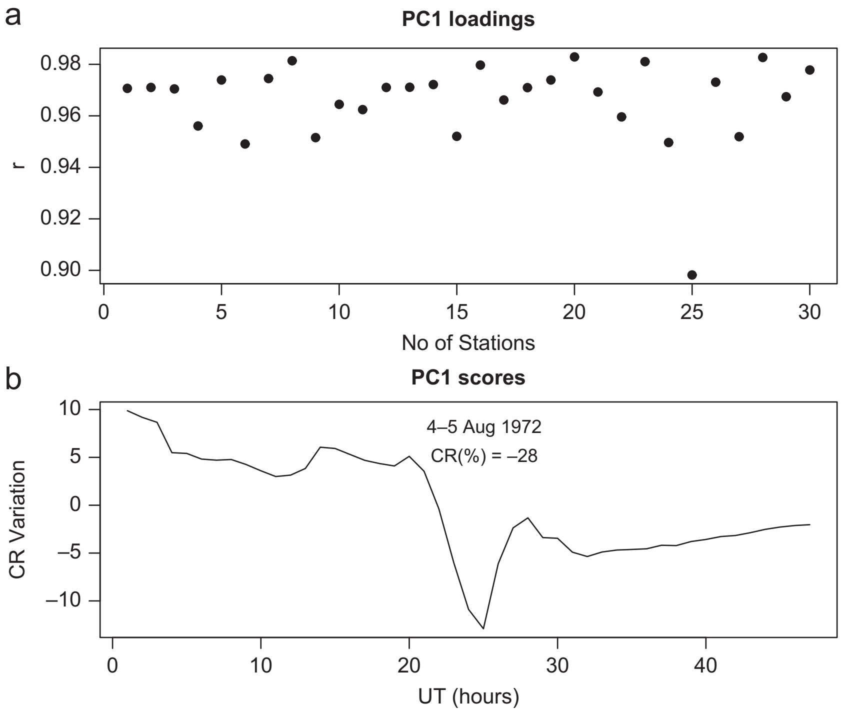

Fig. 3. (a) Correlation between the stations' signal variation and the PC1 loadings and (b) PC1 scores for 4–5 August 1972 event.

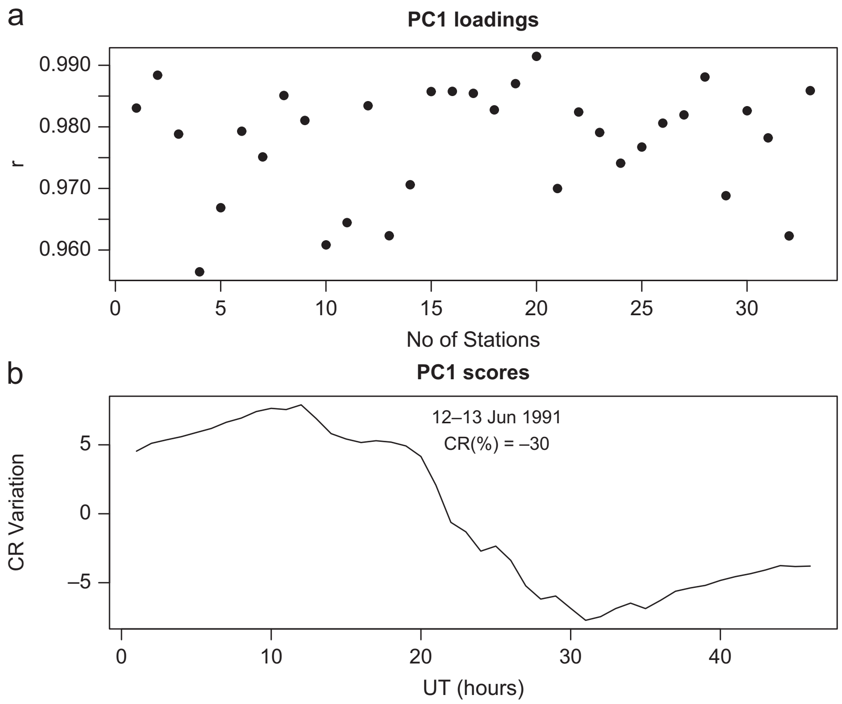

Fig. 4. Same as Fig. 3 for 12–13 June 1991 event.

The decreases recorded by the spacecraft were of similar magnitudes ($\sim -20\%$) to those of neutron monitors. Van Allen (1993b), however, found that the time of observation varied with heliocentric longitude and over a radial range 1.0–53 AU. While the detectors on the Earth see the minimum at 7:00 on 13 June 1991, spacecraft located at 53 AU observed the Fd on September 30. This event is linked with flare of X12/3B importance that occurred on 11 June 1991, leading to a fast CME. Though in situ measurements of interplanetary structures are patchy for the duration of the Fd, a strong interplanetary shock above 25 nT and solar wind speed exceeding 800 km/s were observed (Ahluwalia et al., 2009). The simultaneous detection of this event at all points on the Earth within an hour could be explained if the high-speed strong interplanetary shock generated by the fast CME encounters the Earth's magnetosphere.

Fig. 5 is the PC1 results of the Fd event of 21–22 October 1999 previously plotted in Fig. 2. As already noted, the minimum GCR flux was observed at different times by various stations and as such, PC1 scores do not reflect the Fd as seen at all stations.

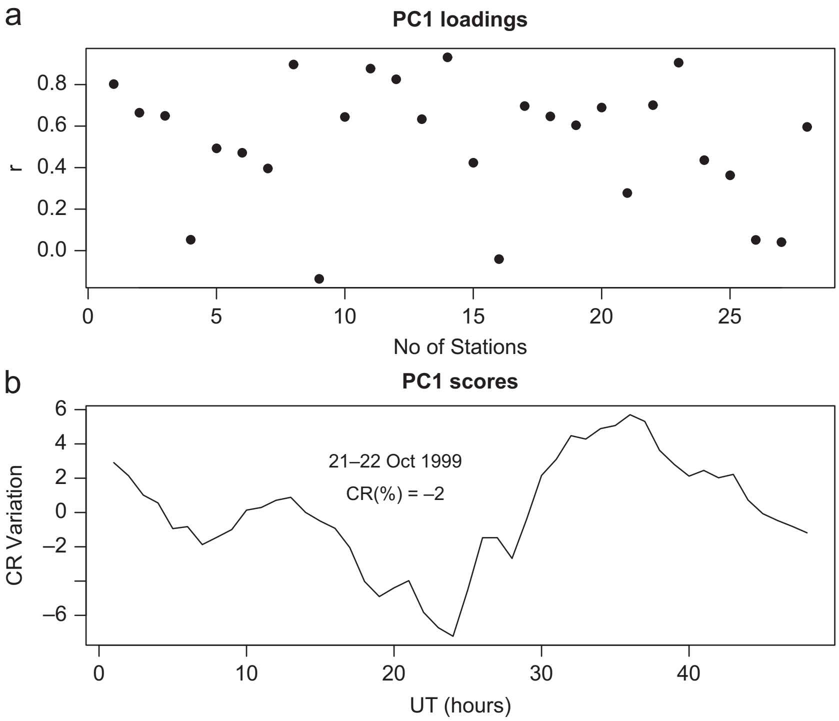

Fig. 5. Same as Fig. 3 for 21–22 October 1999 event.

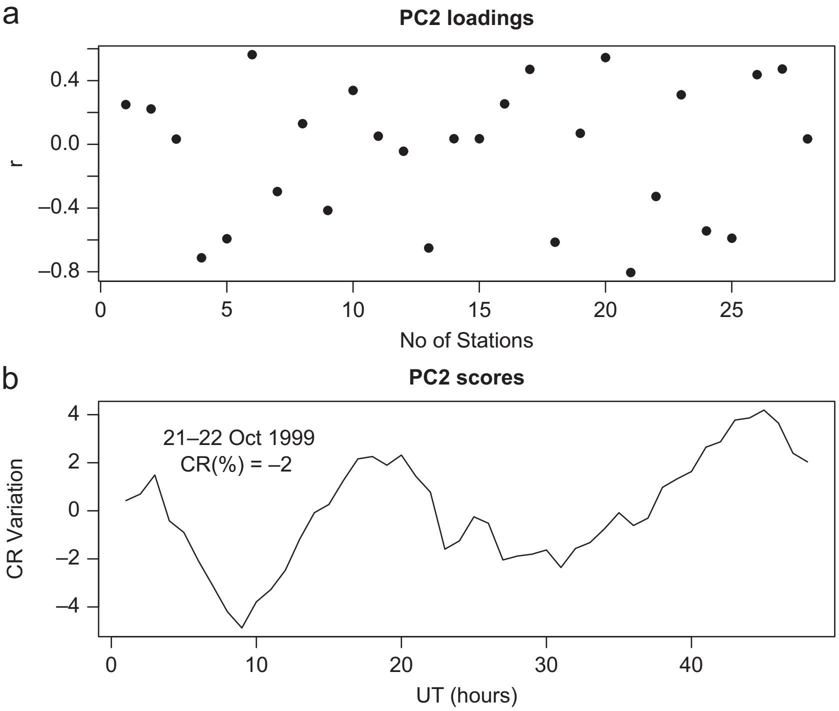

Fig. 6. Same as Fig. 5 for (a) PC2 loadings and (b) PC2 scores for 21–22 October 1999 event.

As a result, PC1 loadings show that some of the stations have no correlation with PC1 scores. A comparison of PC1 scores with Fig. 2 suggests that the PC1 signal represents stations such as Rome and Lomnicky Stit that observe the event at about 24:00 of the first day, while other stations, Climax for example, observed the event at about 9:00 of the first day and are not accounted for by PC1. The GCR intensity variations seen at other stations during this event are represented by other PCs. Figs. 6 and 7 are the PC2 and PC3 results, respectively, that indicate the stations that observed the event at about 9:00 of 21 October and those that observed it at about 6:00 of 22 October. This result highlights the error in deciding global Fd events simultaneity based on a few locations. Using Climax data, Kane (2010) studied the relationship between this Fd event and IMF/solar wind data. They show, in agreement with our results, that Climax observed the minimum at about 9:00 (Fig. 6) on the first day. It is evident from Figs. 5 and 7 that some stations see the minimum at 24:00 of the same day while others observe it at 6:00 on the next day. Their results

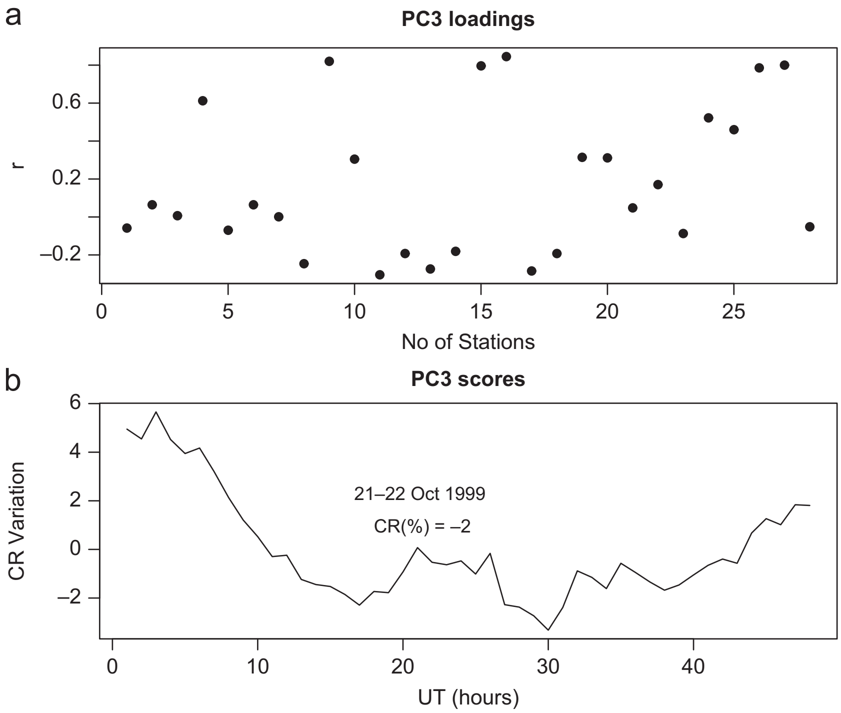

Fig. 7. Same as Fig. 5 for (a) PC3 loadings and (b) PC3 scores for 21–22 October 1999 event.

(see Figure 2 of Kane (2010)) show no relationship between Fd and IMF/solar wind velocity for this event. Instead, Figure 2 in Kane (2010) shows that maximum IMF and minimum Dst occurred at 6:00 on 22 October. Some stations such as Magadan and Inuvik observed this event at this time. The implication of this is that another investigator using cosmic ray data from any of the stations that observed the event at 6:00 will obtain a positive result while another who chose to work with stations such as Oulu and Lomnicky Stit that detected the event at 24:00 will have a different result.

A solar wind speed of 529 km/s was observed at the time of October 1999 event. This is above the average solar wind speed of about 400 km/s (Feldman et al., 2005). It is, however, far below those observed at the time of large Fds. A geomagnetic field disturbance of $D_{st}=-231$ nT was also recorded at time of the Fd. A D_{st} of such magnitude could be attributed to severe space weather events since Firoz et al. (2010) and the references therein classified a D_{st} of -100 nT as a strong storm. Though there are differences in the evolution of Fds and terrestrial magnetic field, Cane (2000) suggested that they have some commonality in their interplanetary sources. It should be noticed from Table 1 that maximum intensity B of the IMF associated with this event ($B=35.6$ nT) is comparable, and in some cases, larger than those of the simultaneous events. Such increase in the IMF magnitude should have resulted in a large depression in GCR intensity (Belov et al., 2003; Kane, 2010; Firoz et al., 2010) instead of a paltry 2% decrease. It is, however, evident from Table 1 that there is no one to one correspondence between the magnitudes of Fds and the associated maximum intensity of IMF B (see Barnden, 1973; Belov and Ivanov, 1997; Cane, 1995). A Fd event of small magnitude could be generated by ejecta that encounters the Earth (Cane, 2000). It is equally speculated that since the intensity of GCRs inside flux ropes is dependent on Larmor radius (Kubo and Shimazu, 2010), the number of GCRs that could penetrate the flux ropes at one Larmor radius might be so high that the flux ropes produce only a small Fd at Earth. The slow-speed solar wind and the large geomagnetic field perturbation could also impact on GCR intensity modulation.

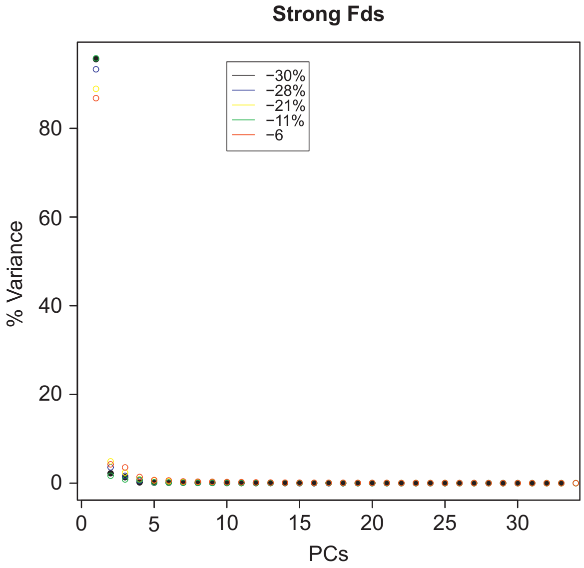

Fig. 8. Percentage variance associated with the PCs of strong Fds.

Figs. 8 and 9 are the summary of the percentage variance of the strong and weak Fds considered in this study. As noted for the two strong Fds (Figs. 3 and 4), there are no set rules for determining the number of PCs that should be retained as a reflection of the general pattern of the original data. However, a common criterion (Jolliffe, 2004) is to investigate only the PCs that explain over 80% of the variance. It is apparent from Fig. 8 that PC1 satisfies this criterion for each of the strong events and is therefore the only component that can be accepted as a true representation of the Fds at all of the stations. The variances due to other components are small and are safely discarded as noise. Usually the variance of a component is an indication of its correlation matrix. The statistical significance of the correlation between the original data (PC1 loadings) and the PC1 signal will

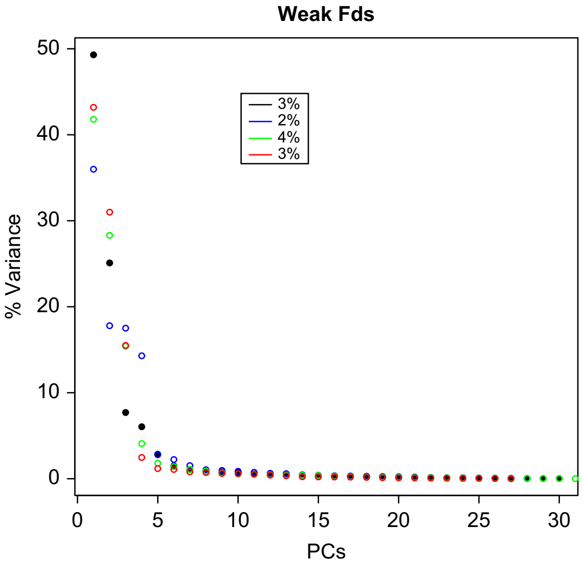

Fig. 9. Percentage variance associated with the PCs of weak Fds.

be high if the variance associated with PC1 is about 80%. Consequently, the implication of the large variance associated with PC1 of the large Fds is that there is a strong correlation between the PC1 scores and the original data. The PC1 scores represent the global GCR intensity variation, suggesting that these Fd events are simultaneously observed at the same universal time at all parts of the Earth. The two large Fds were related to fast CMEs, solar flare, strong IMF shock and high-speed solar wind. It is speculated that the space weather condition that generated other simultaneous Fds might be similar. Interestingly, Table 1 shows that all the simultaneous Fds occurred at the time of higher speed solar wind. The Earth's magnetic field disturbance that happened at the time of some of the strong Fds might be less than those of the weak Fds. A geomagnetic field disturbance of $D_{st} = -108$ nT, for example, was associated with the large event of 4–5 August 1972. Apparently, the impact of a high-speed solar wind on GCR intensity will outweigh that of a slow varying geomagnetic field. This is consistent with the result of Oh and Yi (2009) who believed that simultaneous Fds are connected with solar wind of higher speed and stronger IMF.

Fig. 9 presents a different scenario. The correlation plots of one of these events were presented in Figs. 5–7. It was observed that PC1 scores do not represent all the Fds at all stations since some of the raw data have zero correlation. The summary of the percentage variance of all the weak events corroborates the results. PC1 contributes 50% or even less of the variance implying that two or more PCs are required to account for the Fds at all stations. The fact that PC1 alone cannot account for all the Fds is an indication that they are observed at different universal times at different locations on the Earth. These are the non-simultaneous Fds. Table 1 indicates that these Fds are generally associated with solar wind of relatively slower speed. A significant increase in the IMF strength was also observed at the time of these events suggesting that the decreases might be generated by the complex interaction between the IMF disturbances and the background solar wind (Watari et al., 2004).

The same color code in Fig. 10 represents the stations that detect the event of 21–22 October 1999 at the same universal times. It is apparent that the time of detection of this event is location dependent. Stations that are close in longitudes tend to see the event at the same time. The difference in time of maximum decrease between stations represented by the same color code is about 1–3 h while the difference in time of detection between different color codes might be as long as a day. This indicates, as noted by Oh et al. (2008), that globally non-simultaneous Fds could be simultaneous at similar local times. It is believed that the differences in the time of observation could be attributed to changes in the directions of IMF passing over the Earth. Weak Fds as well as asymptotic cones of GCR stations are supposed to respond to the IMF direction. Neutron monitors that have similar asymptotic cones of acceptance are expected to see an event simultaneously.

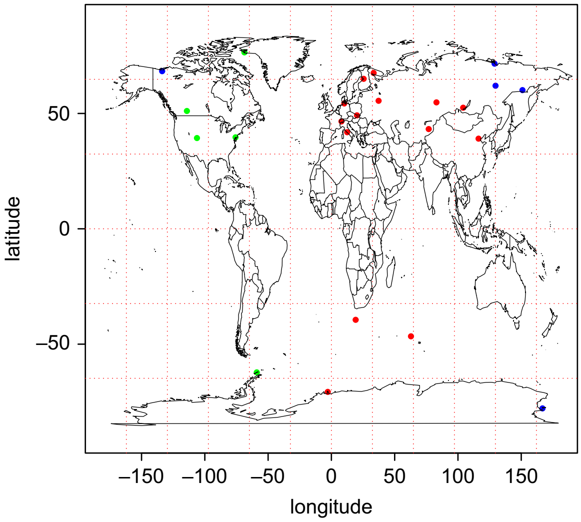

Fig. 10. Stations that see the Fd on 21–22 October 1999 simultaneously are represented by the same color. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Conclusions

We have shown that PCA is a simple method that can be used to discriminate between globally simultaneous and non-simultaneous Fd events. An event that is simultaneously observed all over the Earth will be completely represented by PC1 unlike non-simultaneous events where two or more PCs are required to account for the variations at all locations. An event is said to be simultaneous when the variance associated with PC1 is over 80%. The PC1 of a non-simultaneous event is much less. The global average time of maximum cosmic ray intensity decrease is relevant when comparing the variation in Fds with other global parameters and can easily be determined through this method of analysis. Our results show that strong Fds are simultaneous while weak Fds are generally non-simultaneous. The strong positive correlations between raw data and PC1 signals suggest that there might be structural similarities in the intensity time profiles of the main and recovery phases of simultaneous Fds at all locations, while those of non-simultaneous events may vary at different stations. Some Fds are location dependent, and it is thus thought that observation of Fds at a single location on Earth may give an incomplete description of the event since observatories at different points may see only a small part of a larger scale phenomenon.

References

Ahluwalia, H., Ygbuhay, R., Duldig, M., 2009. Two intense Forbush decreases of solar activity cycle 22. Advances in Space Research 44, 58–63.

Ahluwalia, H., Zubieta, M., Schreier, M., 1968. The physical significance of the worldwide fluctuations of cosmic-ray intensity on july 14–15, 1961. Solar Physics 4, 453–473.

Ananth, A.G., Venkatesan, D., 1993. Effect of interplanetary shocks and magnetic clouds on onset cosmic-ray decreases. Solar Physics 143, 373–383.

Badruddin, Venkatesan, D., Zhu, B.Y., 1991. Study and effect of magnetic clouds on the transient modulation of cosmic-ray intensity. Solar Physics 134, 203–209.

Barnden, L.R., 1973. The large-scale magnetic field configuration associated with Forbush decreases. Proceedings of the 13th International Cosmic Ray Conference, vol. 2, p. 1277.

Belov, A., 2009. Universal heliophysical processes. In: Proceedings of the International Astronomical Union, IAU Symposium 257, pp. 439–450.

Belov, A., Baisultanova, L., Eroshenko, E., Mavromichalaki, H., Yanke, V., Pchelkin, V., Plainaki, C., Mariatos, G., 2005. Magnetospheric effects in cosmic rays during the unique magnetic storm on November 2003. Journal of Geophysical Research, 110.

Belov, A.V., Butikofer, R., Eroshenko, E.A., Fluckiger, E.O., Oleneva, V.A., Yanke, V.G., 2003. Interplanetary magnetic field disturbances with particularly high cosmic ray modulation efficiency. In: Proceedings of the 28th International Cosmic Ray Conference, pp. 3581–3584.

Belov, A.V., Eroshenko, E.A., Oleneva, V.A., Struminsky, A.B., Yanke, V.G., 2001. What determines the magnitude of Forbush decreases? Advances in Space Research 27, 625–630.

Belov, A.V., Eroshenko, E.A., Oleneva, V.A., Yanke, V.G., 2008. Connection of Forbush effects to the X-ray flares. Journal of Atmospheric and Solar-Terrestrial Physics 70, 342–350.

Belov, A.V., Gushchina, R.T., Obridko, V.N., Shelting, B.D., Yanke, V.G., 2006. Long-term variations of galactic cosmic rays in the past and future from observations of various solar activity characteristics. Journal of Atmospheric and Solar–Terrestrial Physics 68, 1161–1166.

Belov, A.V., Ivanov, K.G., 1997. Forbush-effects in 1977–1979. In: Proceedings of the 25th International Cosmic Ray Conference, Durban 1, p. 421.

Belov, E.A., Dorman, L.I., Eroshenko, E.A., Iucci, N., Villoresi, G., Yanke, V.G., 1995. Anistropy of cosmic rays and Forbush decreases in 1991. In: Proceedings of the 1995 International Cosmic Ray Conference, Rome 4.

Bondo, T., Enghoff, M.B., Svensmark, H., 2010. Model of optical response of marine aerosols to Forbush decreases. Atmospheric Chemistry and Physics 10, 2765–2776.

Bruce, C.M., 1981. Principal component analysis in linear systems: controllability, observability, and modal reduction. IEEE Transactions on Automatic Control 26, 17–31.

Cane, H., 1995. Cosmic ray decreases and magnetic clouds. Journal of Geophysical Research 98, 509–3512.

Cane, H., 2000. Coronal mass ejections and Forbush decreases. Space Science Reviews 93, 55–77.

Cane, H.V., Richardson, I.G., von Rosenvinge, T.T., 1993. Cosmic ray decreases and particle acceleration in 1978–1982 and the associated solar wind structures. Journal of Geophysical Research 98, 13,295–13,302.

Cane, H.V., Richardson, I.G., von Rosenvinge, T.T., 1996. Cosmic ray decreases: 1964–1994. Journal of Geophysical Research 101, 21561–21572.

Chilingarian, A., Bostanjyan, N., 2010. On the relation of the Forbush decreases detected by asec monitors during the 23rd solar activity cycle with icme parameters. Advances in Space Research 45, 614–621.

Chree, C., 1912. Some phenomena of sunspots and of terrestial magnetism, at kew observatory. Philosophical Transactions Royal Society London Series, A212.

Chree, C., 1913. Some phenomena of sunspots and of terrestrial magnetism. Philosophical Transactions Royal Society London Series A, 213.

D'Andrea, C., Poirier, J., Balsara, D.S., 2009. Experimental data and analysis of the October 2003 Forbush decrease. Advances in Space Research 44, 1247–1251.

Dorman, L.I., Dorman, I.V., 2005. Possible influence of cosmic rays on climate through thunderstorm clouds. Advances in Space Research 35, 476–483.

Fedulina, I., Lastovicka, J., 2001. Effect of Forbush decreases of cosmic ray flux on ozone at higher middle latitudes. Advances in Space Research 27, 2003–2006.

Feldman, U., Landi, E., Schwadron, N.A., 2005. On the sources of fast and slow solar wind. Journal of Geophysical Research, 110.

Firoz, K.A., Phani Kumar, D.V., Cho, K.S., 2010. On the relationship of cosmic ray intensity with solar wind, interplanetary, and geophysical parameters. Astrophysics and Space Science 325, 185–193.

Forbush, S.E., 1937. On the effects in the cosmic-ray intensity observed during the recent magnetic storm. Physical Review 51, 1108–1109.

Forbush, S.E., 1938. On world-wide changes in cosmic-ray intensity. Physical Review 54, 899–975.

Geranions, A., Mavromichalaki, H., 1982. Cosmic-ray variations related to solar, geomagnetic and interplanetary disturbances (23 March–7 April, 1976). Astrophysics and Space Science 82, 33–148.

Gopalswamy, N., 2006. Coronal mass ejections of solar cycle 23. Journal of Astrophysics and Astronomy 27, 243–254.

Green, P.E., Carroll, J.D., 1978. Analyzing Multivariate Data. Dreyden Press.

Gurevich, A.V., Zybin, K.P., Roussel-Dupre, R.A., 1999. Lightning initiation by simultaneous effect of runaway breakdown and cosmic ray showers. Physics Letters A 254, 79–87.

Gurnett, D.A., Kurth, W.S., 1995. Heliospheric 2–3 kHz radio emissions and their relationship to large Forbush decreases. Advances in Space Research 16, 279–290.

Hess, V.F., Demmelmair, A., 1937. World-wide effect in cosmic ray intensity, as observed during a recent geomagnetic storm. Nature 140, 316–317.

Hofer, M.Y., Fluckiger, E.O., 2000. Cosmic ray spectral variations and anisotropy near earth during the march 24, 1991, Forbush decrease. Journal of Geophysical Research 105, 23,085–23,097.

Jamsen, T., Usoskin, I.G., Raiha, T., Sarkamo, J., Kovaltsov, G., 2007. Case study of Forbush decreases: energy depandance of the recovery. Advances in Space Research 40, 342–347.

Jolliffe, I.T., 2004. Principal Component Analysis. Springer.

Kane, R.P., 2005. How good is the relationship of solar and interplanetary plasma parameters with geomagnetic storms? Journal of Geophysical Research, 110.

Kane, R.P., 2010. Severe geomagnetic storms and Forbush decreases: interplanetary relationships re-examined. Ann. Geophys. 28, 479–489.

Kristjansson, J.E., Stjern, C., Stordal, F., Fjaraa, A.M., Myrhre, G., Jonasson, K., 2008. Cosmic rays, cloud condensation nuclei and clouds – a reassessment using modis data. Atmospheric Chemistry and Physics Discussion 8, 13265–13299.

Krittinatham, W., Ruffolo, D., 2009. Drift orbits of energetic particles in an interplanetary magnetic flux rope. The Astrophysical Journal 704, 831–841.

Kubo, Y., Shimazu, H., 2010. Effect of finite larmor radius on cosmic-ray penetration into an interplanetary magnetic flux rope. The Astrophysical Journal 720, 853–861.

Lockwood, J., 1971. Forbush decreases in the cosmic radiation. Space Science Reviews 12, 658–6715.

Marcz, F., 1997. Short-term changes in atmospheric electricity associated with Forbush decreases. Journal of Atmospheric and Solar–Terrestrial Physics 59, 957–982.

Marsh, D.N., Svemsmark, H., 2000. Low cloud properties influenced by cosmic rays. Physics Review Letters 85, 5004–5007.

Marubashi, K., 2000. Physics of interplanetary magnetic flux ropes: toward prediction of geomagnetic storms. Advances in Space Research 26, 55–66.

McCracken, K.G., Moraal, H., Stoker, P.H., 2008. Investigation of the multiple-component structure of the 20 january 2005 cosmic ray ground level enhancement. Journal of Geophysical Research, 113.

Oh, S., Yi, Y., 2009. Statistical reality of globally nonsimultanous Forbush decrease events. Journal of Geophysical Research, 114.

Oh, S., Yi, Y., Kim, H.Y., 2008. Globally simultaneous Forbush decrease events and their implications. Journal of Geophysical Research, 113.

Palle Bago, E., Butler, C.J., 2000. The influence of cosmic rays on terrestial clouds and global warming. Astronomy and Astrophysics 41, 18–22.

Pankaj, K.S., Shukla, R.P., 1994. High-speed solar wind stream of two different origins and cosmic-ray variations during 1980–1986. Solar Physics 154, 177–185.

Pankaj, K.S., Singh, N., 2005. Latitude and distribution of solar flares and their association with coronal mass ejection. Chinese Journal of Astronomy and Astrophysics 5, 198–202.

Pierce, J.R., Adams, P.J., 2009. Can cosmic rays affect cloud condensation nuclei by altering new particle formation rates? Geophysical Research Letters, 36.

Pudovkin, M.I., Veretenenko, S.V., 1995. Cloudiness decreases associated with Forbush-decreases of galactic cosmic rays. Journal of Atmospheric and Solar–Terrestrial Physics 57, 1349–1355.

Shea, M.A., Smart, D.F., Swinson, D.B., Wilson, M.D., 1993. High energy cosmic ray modulation in march–june 1991. In: Proceedings of 23rd International Cosmic Ray Conference, Calgary vol. 3, pp. 735–738.

Simpson, J.A., Fonger, W., Treiman, S.B., 1953. Cosmic radiation intensity–time variations and their origin. i. neutron intensity variation method and meteorological factors. Physical Review 90, 934–950.

Smart, D.F., Shea, M.A., 2003. The local time dependence of the anisotropic solar cosmic ray flux. Advances in Space Research 32, 109–114.

Stozhkov, Y.I., 2003. The role of cosmic rays in the atmospheric processes. Journal of Physics G: Nuclear and Particle Physics 29, 913–923.

Svensmark, H., Bondo, T., Svensmark, J., 2009. Cosmic ray decreases affect atmospheric aerosols and clouds. Geophysical Research Letters, 36.

Svensmark, H., Friis-Christensen, E., 1997. Variation of cosmic ray fluxes and global cloud coverage – a missing link in solar-climate relationship. Journal of Atmospheric and Solar–Terrestrial Physics 59, 1225–1232.

Usoskin, I.G., Gladysheva, O.G., Kovaltsov, G.A., 2004. Cosmic ray-induced ionization in the atmosphere: spatial and temporal changes. Journal of Atmospheric and Solar–Terrestrial Physics 66, 1791–1796.

Van Allen, J., 1993a. Recovery of interplanetary cosmic ray intensity following the great Forbush decrease of mid-1991. Geophysical Research Letters 20, 2797–2800.

Van Allen, J.A., 1993b. Recovery of interplanetary cosmic ray intensity following the great Forbush decrease of mid-1991. Geophysical Research Letters 20, 2798–2800.

Venkatesan, D., Ananth, A.G., 1991. Forbush decreases in cosmic rays. Bulletin of the Astronomical Society of India 19, 1–8.

Venkatesan, D., Badruddin, Ananth, A.G., Pillai, S., 1992. Significance of the turbulent sheath following the interplanetary shocks in producing Forbush decreases. Solar Physics 137, 345–353.

Watari, S., Vandas, M., Watanabe, T., 2004. Formation of a strong southward imf near the solar maximum of cycle 23. Annales Geophysicae 22, 673–687.