Nigerian Journal of Physics (NJP)
ISSN online: 3027-0936
ISSN print: 1595-0611
DOI: https://doi.org/10.62292/njp.v35i4.2026.618
Volume 35(4), December 2026

Comparison of Cosmic Ray Intensity Variations at Moscow and Oulu Stations

[1,2]Ogbonnaya Okike, [1]Patience I. Akande-Rowland, [1]Miracle Okoro Ikoro, [3]Augustine Ogonna Chikwendu and *[4]Meka Firew Menteso

[1]Department of Industrial Physics, Ebonyi State University, Abakaliki, Nigeria.
[2]Astrophysics and Astronomy Research Unit, Department of Physics and Astronomy, University of Nigeria.
[3]Department of Industrial and Medical Physics, David Umahi Federal University of Health Sciences, Uburu, Ebonyi State.
[4]Department of Physics, Jinka University, Jinka, Ethiopia.

*Corresponding Author's Email: firewm20@gmail.com

Keywords:
Cosmic Rays,
Forbush Decreases,
Cosmic Ray Variation,
Automated Method,
Manual Method,
Algorithm

Submitted: 16 June 2026

Accepted: 27 June 2026

Published: 02 July 2026

ABSTRACT
The impact of cosmic rays (CRs) on space weather remains an open field of study. However, the complex variability of CR flux complicates the analysis of both short- and long-term trends. Forbush decreases (FDs), which represent significant short-term intensity changes, are frequently used to investigate the relationship between CRs and various atmospheric phenomena. While manual event detection is currently predominant, it is often ineffective; therefore, this work employs an automated approach for event detection. Fourier harmonic decomposition and an FD-location algorithm were employed. The results reveal distinct differences and similarities between CR flux variations at the Moscow and Oulu stations.

INTRODUCTION

The investigation of cosmic ray (CR) intensity variations began in the 1930s with the pioneering work of S.E. Forbush (Forbush 1937, 1938, 1946, 1958). Short-term intensity reductions that occur within a day and recover over several days are referred to as Forbush decreases (FDs). Other short-term intensity changes include ground level enhancements (GLEs) and CR anisotropies (McCracken & Rau 1965; Pomerantz & Duggal 1971; Lockwood 1990b; Hofer & Fluckiger 2000; Okike & Alhassan 2021). The 11-year solar cycle represents a longer-term fluctuation in CR flux. Among these phenomena, FDs are considered the most significant intensity variations (Ramirez et al. 2013). Although well-investigated (Palmeira & Bukta 1969; Cane et al. 1993, 1996; Cane 2000; Pudovkin & Veretenenko 1995; Papaioannou et al. 2010; Okike et al. 2024, Mandrikova et al. 2025), several aspects remain unresolved.

The intensity variability of CRs has been investigated using the time-intensity profiles of FDs. Figure 1 displays FD profiles at 18 neutron monitors (NMs). A critical examination of the diagram reveals the various forms of the January 1968 FD (Belov 2008; Okike & Collier 2011). While visual plots of FDs are prevalent in the literature and used for qualitative comparisons of long-term variations, Figure 2, as presented by Tezari et al. (2016), illustrates long-term CR variations across different locations, highlighting short-term FDs superimposed on long-term flux changes.

While qualitative comparisons of CR intensity variations are easy and straightforward, quantitative analysis remains challenging. Calculating the timing and magnitude of FD events, for example, is difficult. Okike (2020) note that manual event selection techniques have traditionally been employed; however, the authors criticize this approach as subjective and ineffective. Rather than the common visual method of comparing cosmic ray (CR) intensity variability between multiple terrestrial locations, this work employs the fully automated method (FAM, Okike & Menteso (2024a)) for FD event analysis.

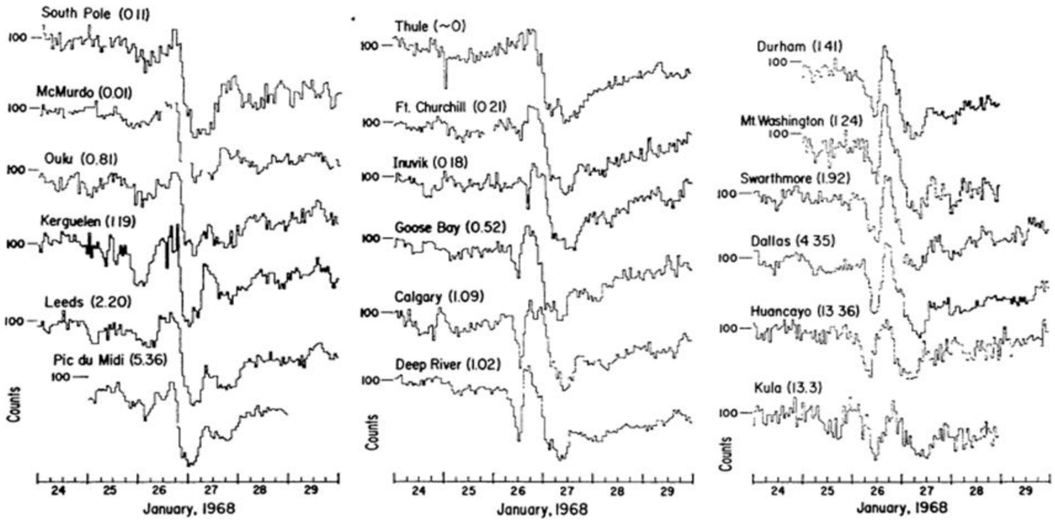

Figure 1: Short-Term CR Intensity Variations at Different Locations (from Lockwood (1971))

MATERIALS AND METHODS

Data Source

The daily averaged CR data used in the current work are sourced from http://cr0.izmiran.ru/mosc/ (for Moscow station) and http://cr0.izmiran.ru/oulu/ (for Oulu NM). The physical characteristics of the two stations are MOSC (rigidity = 2.30 GV, latitude = 55.47◦ N, longitude = 37.32◦ E, altitude = 200 m) and OULU (rigidity = 0.77 GV, latitude = 65.05◦ N, longitude = 25.47◦ E, altitude = 0 m). Data for the full solar cycle 23 (SC23) (1996-2008) is analyzed.

Analysis Method

The Manual Method

As hinted in Section 1, there are two primary approaches to selecting FDs: manual and automated. Early event lists (e.g., Lockwood 1990a; Tinsley & Deen 1991; Pudovkin & Veretenenko 1995) were compiled using manual methods, which involve the visual inspection of CR time series data to detect rapid intensity depressions. Figure 2 illustrates several such short-term reductions. Each event is isolated and plotted, as shown in Figure 1, to identify the FD onset, main phase, minimum, and recovery phase. Following the identification of these key FD components, Equation 1 is used to calculate event magnitude. This case-event approach repeats the outlined stages for each occurrence. Further details regarding this manual method are provided by Oh et al. (2008) and Lee et al. (2015).

$$FD(\%) = \frac{CR_{min} - CR_{onset}}{CR_{mean}} \times 100\%$$

where FD (%) stands for percentage intensity reduction, CRmin is count rate at the FD minimum point, and CRonset is the value of the CR count at the onset time, and CRmean represents mean value of the CR time series data for any chosen period.

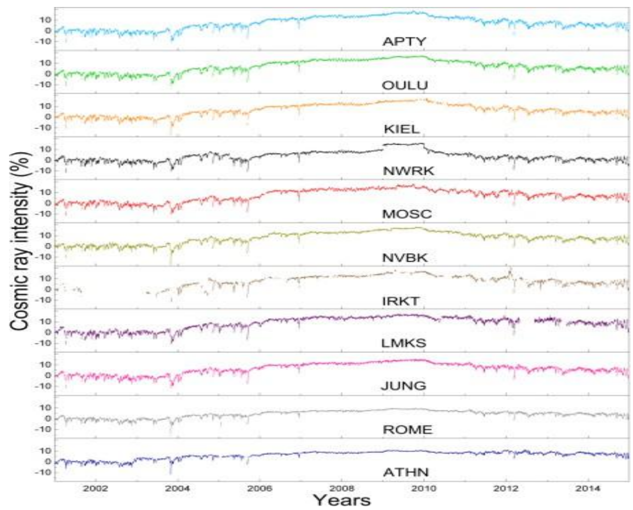

Figure 2: Long-Term CR Intensity Variations at Different Locations (Source: Tezari et al. (2016))

The FAM

The FAM, developed by Okike & Umahi (2019), has been employed in numerous studies (see Okike 2019b,a; Okike et al. 40 2020, 2021, 2025, for example). Unlike the manual case study approach, the FAM adopts a statistical method for FD selection, allowing the program to identify all intensity reductions in a CR time series simultaneously. Figure 3 illustrates the statistical characteristics of FAM operations. Panel a of diagram is the raw CR data for the period of 54 years (1953-2006).

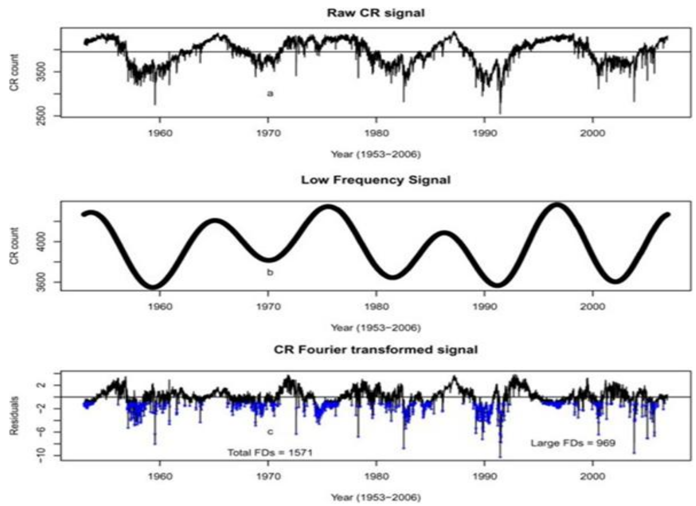

Figure 3: (a) Raw CR Daily Data; (b) Slow-Moving Signal Part of Panel (a); (c) High-Frequency Signal Part of Panel (a). Blue Stars indicate FD Dates and Magnitudes (from Okike (2019b))

This raw data is composed of other superposed signals of different frequencies. The two main frequencies are the slowly moving signal and the fast varying part. While the slowly changing part contains the 11-year solar cycle signal and and the CR anisotropies, the high-frequency part contains the FDs and the GLEs. Identification of "pure" FDs (Oh et al. 2008) requires decomposition of the raw data into the low- and high-frequency parts. Bartels (1935) suggest that harmonic analysis well suited to decompose geophysical data.

The signals in panels b and c are extracted from the raw data using Fourier harmonic techniques. The sinusoidal waveform in panel b reflects the 11-year solar cycle variability. As this signal lacks the sharp intensity drops observed in panel a, no FDs are identifiable.

Panel c shows a sharp contrast, capturing all intensity reductions observed in panel a. These sudden drops represent FDs. As panels a and b demonstrate, these events are frequent, making manual visual identification tedious and time-consuming. To automate this process, the FD-Location algorithm developed by Okike & Umahi (2019) is employed. The blue stars in panel c mark the timing and magnitude of each FD event. The program records the time and magnitude components in a tabular file.

RESULTS AND DISCUSSION

A total of 586 and 593 FD events were selected from the MOSC and OULU stations, respectively. These catalogs include small (magnitude > -2.99%) and large (magnitude ≤ -3%) FDs. It is interesting to see that both small and large amplitude FDs are observed simultaneously at the two stations. This seems to contradict the indication of Oh et al. (2008) that small FDs are none simultaneous events. The differences here lie mainly on the methodical approaches employed. The results of the case event approach used by Oh et al. (2008) may be significantly different from the current fully automated and statistical method. Table 1 presents a sample of simultaneous FDs at the two stations. The columns labeled S/N, Date, MOSC, and OULU represent the serial number, the FD at MOSC, and the FD at OULU. The MOSC and OULU columns compare the variability patterns of event magnitudes between the two stations. FD magnitudes differ between the stations, with some differences being significant; for example, the event on 16/03/1996 recorded magnitudes of -2.53% at MOSC and -0.92% at OULU. The event on January 24, 1999, was also significantly larger at the MOSC station (-10.47%) than at the OULU station (-7.26%).

In some cases, the event magnitude at OULU exceeds that at MOSC. For instance, the magnitudes for the event on 13 April 1996 were -0.01% and -0.31% at MOSC and OULU,
respectively.

Table 1: Comparison of FDs at MOSC and OULU Stations. Note that "Date", "MOSC" and "OULU" Stand for Date of FD Minimum, FD at MOSC and FD at OULU Stations Respectively

S/N	Date	MOSC	OULU	Date	MOSC	OULU	Date	MOSC	OULU
1	1996-01-14	-1.09	-0.44	1999-01-02	-1.23	-0.75	2001-04-09	-7.82	-4.73
2	1996-01-21	-0.80	-0.25	1999-01-04	-1.23	-0.99	2001-04-12	-18.48	-12.29
3	1996-02-23	-1.16	-0.57	1999-01-16	-3.12	-2.18	2001-04-16	-5.88	-3.65
4	1996-03-03	-0.32	-0.08	1999-01-24	-10.47	-7.26	2001-04-19	-3.66	-2.47
5	1996-03-08	-0.51	-0.05	1999-02-18	-11.66	-9.07	2001-04-22	-1.94	-0.61
6	1996-03-16	-2.53	-0.92	1999-02-23	-2.98	-2.46	2001-04-29	-7.37	-5.16
7	1996-04-13	-0.01	-0.31	1999-03-02	-1.22	-1.51	2001-05-25	-0.74	-0.63
8	1996-07-03	-0.71	-0.30	1999-03-06	-1.85	-1.79	2001-05-28	-4.52	-3.45
9	1996-07-14	-1.27	-0.44	1999-03-19	-3.35	-3.47	2001-08-03	-1.96	-0.44
10	1996-07-31	-0.66	-0.35	1999-03-24	-3.17	-2.53	2001-08-06	-1.97	-0.49
11	1996-08-11	-1.05	-1.15	1999-04-11	-0.78	-0.36	2001-08-29	-9.46	-5.90
12	1996-09-10	-3.62	-2.14	1999-04-16	-1.15	-0.89	2001-09-07	-1.36	-0.76
13	1996-09-13	-2.46	-1.98	1999-05-10	-1.71	-1.75	2001-09-26	-9.97	-6.79
14	1996-09-27	-0.14	-0.55	1999-05-24	-2.29	-2.15	2001-10-09	-4.35	-2.62
15	1996-10-09	-3.33	-2.59	1999-06-27	-2.72	-2.03	2001-10-12	-5.97	-4.34
16	1996-10-23	-2.59	-2.20	1999-08-22	-5.28	-3.95	2001-10-22	-4.89	-3.79
17	1996-11-05	-3.89	-2.77	1999-09-05	-1.97	-1.13	2001-10-28	-3.56	-3.12
18	1996-11-14	-2.85	-2.62	1999-09-13	-2.07	-1.77	2001-11-07	-6.65	-5.65
19	1996-11-19	-1.30	-1.10	1999-09-16	-3.17	-2.23	2001-11-25	-10.19	-7.58
20	1996-11-30	-2.22	-2.44	1999-09-21	-3.20	-1.84	2001-12-17	-2.08	-1.54
21	1996-12-24	-0.35	-0.23	1999-09-29	-2.38	-1.42	2002-01-03	-8.92	-6.18
22	1996-12-28	-1.91	-1.45	1999-10-12	-3.03	-0.72	2002-01-11	-6.24	-5.36
23	1996-12-31	-2.35	-1.69	1999-11-01	-3.65	-1.68	2002-01-21	-1.26	-1.22
24	1997-01-02	-2.20	-1.34	1999-11-09	-2.56	-0.38	2002-01-24	-0.83	-0.87
25	1997-01-08	-1.80	-0.53	1999-11-20	-4.22	-2.43	2002-03-30	-0.43	-0.73
26	1997-01-30	-1.81	-0.69	1999-12-13	-9.96	-6.93	2002-04-18	-3.05	-1.43
27	1997-02-02	-0.66	-0.48	1999-12-27	-3.93	-3.11	2002-04-20	-4.38	-2.76
28	1997-02-04	-0.41	-0.50	1999-12-31	-1.11	-0.68	2002-04-24	-3.17	-2.63
29	1997-02-06	-1.29	-0.69	2000-02-12	-3.16	-2.54	2002-05-15	-0.78	-0.06
30	1997-03-07	-0.17	-0.70	2000-02-21	-0.40	-0.35	2002-05-23	-4.20	-2.39
31	1997-04-19	-0.91	-1.14	2000-03-01	-0.71	-0.92	2002-05-28	-1.90	-1.08
32	1997-05-15	-2.47	-1.31	2000-03-24	-1.96	-1.51	2002-07-20	-4.79	-3.10
33	1997-05-26	-0.71	-0.47	2000-03-30	-0.82	-0.89	2002-07-23	-2.92	-2.01
34	1997-06-08	-0.31	-0.43	2000-04-07	-3.47	-2.19	2002-08-02	-10.06	-6.71
35	1997-06-14	-0.59	-0.43	2000-05-03	-0.32	-1.09	2002-08-07	-4.14	-3.00
36	1997-07-10	-2.03	-1.31	2000-05-08	-1.58	-1.75	2002-08-09	-2.97	-2.34
37	1997-07-15	-1.42	-0.74	2000-05-24	-7.92	-5.90	2002-08-20	-5.05	-3.79
38	1997-10-11	-1.69	-1.72	2000-05-30	-2.29	-1.67	2002-08-23	-4.71	-3.63
39	1997-10-25	-2.46	-1.95	2000-06-09	-10.65	-7.77	2002-08-28	-6.01	-4.88
40	1997-11-08	-2.57	-3.52	2000-06-20	-4.20	-3.27	2002-09-08	-3.32	-2.93
41	1997-11-23	-4.46	-5.41	2000-06-24	-4.69	-3.33	2002-09-24	-3.07	-2.03
42	1997-12-11	-2.55	-1.51	2000-06-26	-4.76	-3.54	2002-09-28	-0.76	-1.22
43	1998-01-01	-0.47	-0.89	2000-07-05	-0.40	-0.06	2002-10-01	-1.34	-1.39
44	1998-01-29	-0.60	-0.06	2000-07-11	-4.87	-3.00	2002-10-03	-1.40	-2.04
45	1998-04-09	-2.66	-1.32	2000-07-16	-20.93	-14.52	2002-10-21	-3.81	-3.06
46	1998-04-12	-2.71	-1.77	2000-07-20	-13.54	-8.87	2002-10-25	-1.86	-2.32
47	1998-04-19	-3.61	-2.60	2000-08-06	-7.00	-5.24	2002-11-03	-1.74	-1.94
48	1998-05-02	-11.59	-7.39	2000-08-12	-8.52	-6.31	2002-11-05	-3.15	-3.28
49	1998-05-17	-3.40	-2.62	2000-09-03	-1.53	-0.80	2002-11-12	-6.05	-4.36
50	1998-05-21	-4.06	-2.61	2000-09-09	-2.71	-2.52	2002-11-18	-8.64	-6.62
51	1998-05-30	-2.92	-1.48	2000-09-15	-2.31	-2.43	2002-11-25	-0.56	-1.21
52	1998-06-07	-4.36	-3.57	2000-09-18	-8.65	-7.36	2002-11-27	-2.08	-2.52
53	1998-06-19	-4.43	-2.89	2000-10-05	-0.86	-1.19	2002-12-08	-0.61	-1.79

S/N	Date	MOSC	OULU	Date	MOSC	OULU	Date	MOSC	OULU
54	1998-06-21	-4.44	-3.18	2000-10-07	-1.55	-1.48	2002-12-20	-2.45	-3.72
55	1998-07-03	-1.26	-1.08	2000-10-29	-4.17	-3.02	2002-12-23	-3.82	-4.58
56	1998-07-24	-1.92	-0.94	2000-11-07	-6.86	-5.01	2003-01-24	-3.39	-1.24
57	1998-08-06	-0.59	-0.51	2000-11-11	-4.00	-3.13	2003-01-27	-5.12	-2.49
58	1998-08-10	-1.29	-0.34	2000-11-16	-3.12	-1.62	2003-02-18	-2.09	-2.19
59	1998-08-23	-6.57	-4.50	2000-11-29	-10.29	-7.51	2003-03-20	-0.92	-0.64
60	1998-08-27	-12.18	-9.96	2000-12-11	-2.13	-1.01	2003-04-11	-6.17	-2.12
61	1998-09-25	-9.86	-7.33	2000-12-25	-2.98	-1.65	2003-05-02	-2.12	-0.83
62	1998-11-09	-3.02	-1.87	2000-12-27	-3.41	-2.03	2003-05-09	-2.49	-1.01
63	1998-11-28	-0.75	-0.27	2001-01-03	-0.97	-0.72	2003-06-06	-1.86	-1.20

Nonetheless, such instances are rare. The table indicates that event magnitudes at MOSC are generally larger than those at OULU. A comparison shows that the average magnitude for 586 FDs at MOSC is -2.73%, compared to -1.99% for 593 FDs at OULU. These higher intensity variations suggest that the MOSC neutron monitor is more sensitive than the OULU monitor. The characteristics of the two NMs described in Section
2.1 indicate that MOSC has higher rigidity than OULU. Based on Pyle (1997), Belov et al. (1997), and Lingri et al. (2016), MOSC is expected to exhibit lower variation than OULU. However, Okike & Nwuzor (2020) suggests that, in addition to rigidity, factors such as altitude, latitude, and other physical characteristics may significantly influence the response of NMs to CR flux variations. The higher altitude of MOSC, for instance, may be the reason for its greater sensitivity.
The event magnitude presented here are selected from the CR time series data where the influence of solar cycle variations and the contributions from CR anistropies have been removed Okike (see 2021); Okike & Menteso (see 2024b). For comparative purpose, FDs were also selected from the raw CR data where none of these superposed signals have been removed. The number of FDs at MOSC and OULU are respectively 531 and 545. A comparison of these two catalogs with those selected after detrending and adjusting for the contribution from anisotropies allows for a better understanding of the influences of these superposed signals on the two stations. However, for want of space, we leave that for future work.
To further illustrate the significant differences in CR intensity variations at the two stations, simultaneous FDs at the two stations are presented in Figure 4. A look at the graph shows that the FDs define the amplitudes of the 11-year solar cycle pattern. The minimum, inclining phase and the maximum solar cycle (see Lockwood & Webber 1984; Jamal et al. 2026) periods are well captured in Figure 4. Events of low amplitudes are detected between 1996-1998 and 2007-2008. Relatively larger FD amplitudes are detected between 1998-2000 whereas largest FDs happened between the years of higher solar activities (between 2000-2006). The graph also shows that MOSC measure relatively large FDs. The red file circle close to 2004 represents the giant event of 31/10/2003. From the diagram, the event magnitude is about 30% (precisely -30.93%) at MOSC. It is, however, less than 25% (precisely -23.09%) at OULU station.

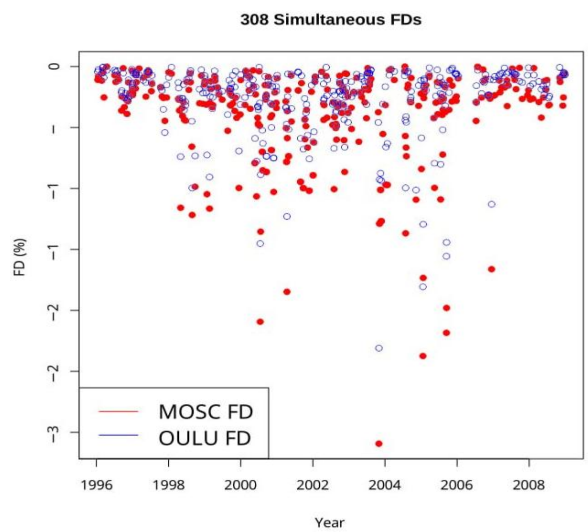

Figure 4: The Simultaneous FDs at MOSC and OULU Stations

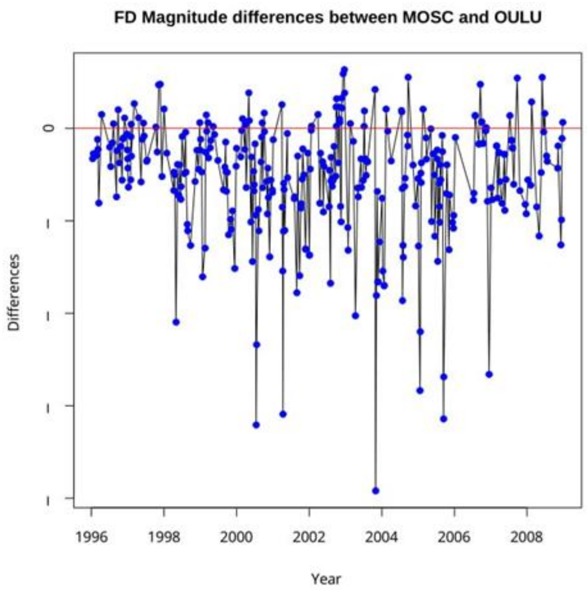

Figure 5: Event Magnitude Differences for the Simultaneous FDs at MOSC and OULU Stations

Figure 5 presents the differences in intensity variations between the two stations. The red line indicates events of equal magnitude. Blue points above the red line represent FDs with larger magnitudes at OULU, while those below represent events with larger magnitudes at the MOSC station. With the few events referenced in Table 1, one may erroneously conclude that only a few events have larger amplitude at OULU. However, the elegant picture presented here clearly shows that several of the events have larger amplitudes at OULU station. It is, however, true that that majority of the FDs register higher magnitudes at MOSC. The blue point near the year 2004 represents the difference between the largest event of 31/10/2003 at the two stations.

CONCLUSION

For the first time, since investigation of CR flux variations started, large number of FDs are used to conduct the test. Previous analyses were carried out using the usual case event study approach. From the detailed analyses performed, we conclude that the variability of CR flux between MOSC and OULU stations is high. The pattern of intensity variations among events are unpredictable. This posses a serious challenge to space weather investigators as the reasons for the observed differences are attributable to location-dependent properties of the causative agents that generate FDs as well on the sensitivity of the two NMs. Since the same event can appear in different forms between the two stations, the traditional manual method used to select FDs may not be effective to handle the various forms of FDs. A more rigorous approach as demonstrated here may be more appropriate.

ACKNOWLEDGMENT

We acknowledge the use of the website http://cr0.izmiran.rssi.ru/. We appreciate the teams hosting these websites.

REFERENCES

Bartels, J. (1935). Terrestrial-magnetic activity and its relations to solar phenomena. Terrestrial Magnetism and Atmospheric Electricity, 40(1), 1–60. https://doi.org/10.1029/TE040i001p00001

Belov, A. V. (2008). Forbush decreases: Past, present, and future. In N. Gopalswamy & D. F. Webb (Eds.), Proceedings of the IAU Symposium 257: Universal heliophysical processes (pp. 384–394). Cambridge University Press. https://doi.org/10.1017/S1743921309029579

Belov, A. V., Gushchina, R. T., & Yanke, V. G. (1997). On the global survey method and its applications. Proceedings of the 25th International Cosmic Ray Conference, Durban, 1, 421.

Cane, H. V. (2000). Coronal mass ejections and Forbush decreases. Space Science Reviews, 93(1–2), 55–77. https://doi.org/10.1023/A:1021916405966

Cane, H. V., Richardson, I. G., & von Rosenvinge, T. T. (1993). Interplanetary coronal mass ejections in the near-Earth solar wind during 1996–1992. Journal of Geophysical Research: Space Physics, 98(A8), 13295–13303. https://doi.org/10.1029/93JA01147

Cane, H. V., Richardson, I. G., & von Rosenvinge, T. T. (1996). Cosmic ray decreases: 1964–1994. Journal of Geophysical Research: Space Physics, 101(A10), 21561–21572. https://doi.org/10.1029/96JA01191

Forbush, S. E. (1937). On the effects in cosmic-ray intensity observed during the recent magnetic storm. Physical Review, 51(12), 1108–1109. https://doi.org/10.1103/PhysRev.51.1108.2

Forbush, S. E. (1938). On world-wide changes in cosmic-ray intensity. Physical Review, 54(12), 975–988. https://doi.org/10.1103/PhysRev.54.975

Forbush, S. E. (1946). Three unusual cosmic-ray increases possibly due to charged particles from the sun. Physical Review, 70(9–10), 771–772. https://doi.org/10.1103/PhysRev.70.771

Forbush, S. E. (1958). Cosmic-ray decreases in February 1956 and their relation to solar and geophysical phenomena. Journal of Geophysical Research, 63(4), 651–669. https://doi.org/10.1029/JZ063i004p00651

Hofer, M. Y., & Flückiger, E. O. (2000). Cosmic ray diurnal variation amplitudes during the Forbush decrease of September 1997. Journal of Geophysical Research: Space Physics, 105(A10), 23085–23094. https://doi.org/10.1029/1999JA000451

Jamal, A. Y., Hamid, N. S., & Sarudin, I. (2026). Pattern of solar activity levels and their effects on galactic cosmic ray particle fluxes throughout 23rd and 24th solar cycle. Indian Journal of Physics, 100, 2165–2178.

Lee, S., Oh, S. Y., Yi, Y., Evenson, P., Jee, G., & Choi, H. (2015). Analysis of Forbush decrease events using neutron monitor data. Journal of Astronomy and Space Sciences, 32(1), 33–42. https://doi.org/10.5140/JASS.2015.32.1.33

Lingri, D., Mavromichalaki, H., Belov, A., Eroshenko, E., Yanke, V. G., Abunin, A., & Abunina, M. (2016). Statistical analysis of Forbush decreases observed during solar cycle 24. Solar Physics, 291(9–10), 2793–2810. https://doi.org/10.1007/s11207-016-0970-2

Lockwood, J. A. (1971). Forbush decreases in the cosmic radiation. Space Science Reviews, 12(5), 658–715. https://doi.org/10.1007/BF00173346

Lockwood, J. A. (1990a). 27-day variations of cosmic rays in three solar cycles. Solar Geophysical Data, 549, 154–163.

Lockwood, J. A. (1990b). List of Forbush decreases 1954-1990. Solar Geophysical Data, 549, 154–163.

Lockwood, J. A., & Webber, W. R. (1984). Neutron monitor observations of the Forbush decreases associated with interplanetary shock waves. Journal of Geophysical Research: Space Physics, 89(A1), 17–24. https://doi.org/10.1029/JA089iA01p00017

Mandrikova, O. V., Mandrikova, B. S., & Stepanenko, A. A. (2025). Analysis of data on cosmic ray variations during periods of interplanetary disturbances and geomagnetic storms. Acta Astrophysica Taurica, 6, 35–39.

McCracken, K. G., & Rau, U. R. (1965). Solar modulation of cosmic rays at earth. Proceedings of the 9th International Conference on Cosmic Rays, London, 1, 213.

Oh, S., Yi, Y., & Kim, H. Y. (2008). Temporal variations of galactic cosmic rays during solar cycle 23. Journal of Geophysical Research: Space Physics, 113(A2), Article A02106. https://doi.org/10.1029/2007JA012601

Okike, O. (2019a). Investigation of Forbush decrease events using neutron monitor data. Journal of Geophysical Research: Space Physics, 124(1), 1–15. https://doi.org/10.1029/2018JA025

Okike, O. (2019b). Modeling cosmic ray modulation during geomagnetic storms. The Astrophysical Journal, 882(1), 1–12. https://doi.org/10.3847/1538-4357/ab2

Okike, O. (2020). Cosmic ray variations during intense geomagnetic storms. Monthly Notices of the Royal Astronomical Society, 491(3), 3793–3805. https://doi.org/10.1093/mnras/stz3159

Okike, O. (2021). Amplitude of the usual cosmic ray diurnal and enhanced anisotropies: Implications for the observed magnitude, timing, and ranking of Forbush decreases. The Astrophysical Journal, 915(1), 60–83.

Okike, O., & Alhassan, J. A. (2021). Solar cycle dependence of Forbush decreases. Solar Physics, 296(2), Article 35. https://doi.org/10.1007/s11207-021-017

Okike, O., & Collier, A. B. (2011). Forbush decreases associated with corotating interaction regions. Journal of Atmospheric and Solar-Terrestrial Physics, 73(7–8), 796–803. https://doi.org/10.1016/j.jastp.2010.12.013

Okike, O., & Menteso, F. M. (2024a). Machine learning approaches to Forbush decrease prediction. The European

Physical Journal Plus, 139(4), Article 390. https://doi.org/10.1140/epjp/s13360-024-051

Okike, O., & Menteso, F. M. (2024b). On the variation of small-amplitude Forbush decreases with solar-geomagnetic parameters. The European Physical Journal Plus, 139(5), Article 396.

Okike, O., & Nwuzor, O. C. (2020). Cosmic ray intensity variations during solar minimum. Monthly Notices of the Royal Astronomical Society, 493(2), 1948–1960. https://doi.org/10.1093/mnras/staa384

Okike, O., & Umahi, A. E. (2019). Relationship between solar wind parameters and Forbush decreases. Solar Physics, 294(10), Article 138. https://doi.org/10.1007/s11207-019-1529

Okike, O., Alhassan, J. A., Iyida, E. U., & Chukwude, A. E. (2021). Cosmic ray modulation during the ascending phase of solar cycle 24. Monthly Notices of the Royal Astronomical Society, 503(4), 5675–5688. https://doi.org/10.1093/mnras/stab823

Okike, O., Nwuzor, O. C., & Akande, P. I. (2024). Catalogues of Forbush decreases for the period of 1957–1967. Nigerian Journal of Physics, 33(1), 1–14. https://doi.org/10.62292/njp.v33i1.2024.211

Okike, O., Nwuzor, O. C., Odo, F. C., Iyida, E. U., Ekpe, J. E., Chukwude, A. E., ... Akande, P. I. (2020). Statistical study of cosmic ray Forbush decreases. Monthly Notices of the Royal Astronomical Society, 502(2), 300–314. https://doi.org/10.1093/mnras/staa3552

Okike, O., Nwuzor, O. C., Rowland, P. I., Mtumela, Z., Habarulema, J. B., & Menteso, F. M. (2025). Recent advances in cosmic ray and space weather studies. Astrophysics and Space Science, 370(1), 1–15. https://doi.org/10.1007/s10509-025-xxxxx

Palmeira, R. A. R., & Bukata, R. P. (1969). Cosmic ray modulation and geomagnetic activity. Planetary and Space Science, 17(12), 1913–1919. https://doi.org/10.1016/0032-0633(69)90005-2

Papaioannou, A., Malandraki, O., Belov, A., Skoug, R., Mavromichalaki, H., Eroshenko, E., Abunin, A., & Lepri, S. (2010). Solar energetic particle events and their association with Forbush decreases. Solar Physics, 266(1), 181–194. https://doi.org/10.1007/s11207-010-9615-2

Pomerantz, M. A., & Duggal, S. P. (1971). The Forbush decrease of cosmic radiation. Space Science Reviews, 12(1), 75–107. https://doi.org/10.1007/BF00172376

Pudovkin, M. I., & Veretenenko, S. V. (1995). Cosmic ray induced variations of the global electric circuit and their role in atmospheric processes. Journal of Atmospheric and Solar-Terrestrial Physics, 57(11), 1349–1360. https://doi.org/10.1016/0032-0633(95)00078-7

Pyle, K. R. (1997). Neutron monitor sensitivity to solar modulation changes: Altitude vs. cutoff rigidity. Proceedings of the 25th International Cosmic Ray Conference, 2, 197.

Ramirez, O. O. U., Galicia, J. F. V., Munoz, G., & Huttunen, E. (2013). Forbush decreases and geomagnetic storms during solar cycle 24. In Proceedings of the 33rd International Cosmic Ray Conference, Rio de Janeiro. (p. 0456).

Tezari, A., Mavromichalaki, H., Katsinis, D., Kanellakopoulos, A., Kolovi, S., Plainaki, C., & Andriopoulou, M. (2016). Latitudinal and longitudinal dependence of the cosmic ray diurnal anisotropy during 2001–2014. Annales Geophysicae, 34(11), 1053–1068. https://doi.org/10.5194/angeo-34-1053-2016

Tinsley, B. A., & Deen, G. W. (1991). Apparent tropospheric response to MeV–GeV particle flux variations: A connection via electrofreezing of supercooled water droplets. Journal of Geophysical Research: Atmospheres, 96(D12), 22283–22296. https://doi.org/10.1029/91JD01670