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Testing the effect of solar wind parameters and geomagnetic storm indices on Galactic cosmic ray flux variation with automatically-selected Forbush decreases

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Abstract Forbush decrease (FD), discovered by Scott E. Forbush about 80 years ago, is referred to as the non-repetitive short-term depression in Galactic cosmic ray (GCR) flux, presumed to be associated with large-scale perturbations in solar wind and interplanetary magnetic field (IMF). It is the most spectacular variability in the GCR intensity which appears to be the compass for investigators seeking solar-terrestrial relationships. The method of selection and validation of FD events is very important to cosmic ray (CR) scientists. We have deployed new computer software to determine the amplitude and timing of FDs from daily-averaged CR data at Oulu Neutron Monitor station. The code selected 230 FDs between 1998 and 2002. In an attempt to validate the new FD automated catalog, the relationship between the amplitude of FDs, and IMF, solar wind speed (SWS) and geomagnetic storm indices (Dst, kp, ap) is tested here. A two-dimensional regression analysis indicates significant linear relationship between large FDs (CR(%) ≤ -3) and solar wind data and geomagnetic storm indices in the present sample. The implications of the relationship among these parameters are discussed.

Key words: methods: data analysis — methods: statistical — Sun: coronal mass ejections (CMEs) — (Sun:) solar - terrestrial relations — (Sun:) solar wind — (ISM:) cosmic rays

1 INTRODUCTION

Forbush decrease (FD), discovered by Scott E. Forbush (Forbush 1937, 1938), is one of the outstanding transient changes in cosmic ray (CR) flux, observed by ground-based neutron detectors (Badruddin & Kumar 2015). It is referred to as a non-repetitive short-term depression in Galactic cosmic ray (GCR) intensity presumed to be associated with large-scale perturbations in solar wind and the interplanetary magnetic field (IMF). Generally, FDs can be classified as recurrent and non-recurrent in accordance with their solar sources. Whereas the recurrent FDs are induced by high-speed solar wind streams (HSSWs) from coronal holes which rotate together with the Sun, non-recurrent FDs are triggered by coronal mass ejections (CMEs) and their interplanetary extensions (ICMEs) (Richardson 2004; Richardson & Cane 2011; Belov et al. 2014). Forbush events from HSSWs are characterized by a small amplitude, gradual onset and symmetric profile while FDs caused by ICMEs have signatures of large magnitude, sudden onset and gradual recovery (Lockwood 1971; Belov et al. 2009; Melkumyan et al. 2019).

Geomagnetic storms (GMSs), which are a temporary disturbance in the Earth's magnetosphere and non-recurrent Forbush events, are both presumed to have a common solar and interplanetary origin in the form of CMEs and ICMEs (e.g., Richardson & Cane 2011; Chertok et al. 2015; Badruddin & Kumar 2015). ICMEs are conveyed from the Sun to the Earth by a stream of charged particles known as solar wind. In the course of their transportation to the Earth, CMEs and ICMEs interact with GCRs that fill interplanetary space to generate the IMF and shock waves (e.g., Richardson & Cane 2011; Lingri et al. 2016; Okike et al. 2021b). The IMF disturbances have been found to be associated with FD (Oh et al. 2008; Oh & Yi 2009). Investigations of CR intensity variations have been carried out with data recorded by ground-based and space-borne equipment for over five decades now (Fan et al. 1960; Belov 2009). Yet, association of FDs with geomagnetic activity indices and solar wind disturbances is a subject of continuous interest (e.g., Belov et al. 2005; Belov 2009; Lingri et al. 2016; Light et al. 2020). Understandably, disturbances in solar wind, magnetosphere and CRs are caused by the same

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active processes in the Sun and thus interrelated, hence the rationale for investigating them together in this work.

It has been argued that FD is the most spectacular variability in the GCR intensity which also appears to be the compass for investigators seeking solar terrestrial relationships (Okike 2020c). Understanding Sun–Earth weather connections requires FD as one of the mediator parameters to be employed. Obtaining a large dataset of an FD event is very critical before any statistically reliable investigation can be carried out. Publications from the IZMIRAN group have investigated large FDs based on a semi-automated global survey method (GSM) (e.g., Belov et al. 2001b, 2009, 2014, 2015). However, other investigators select a few FD catalogs with the manual technique for their research (e.g., Oh et al. 2008; Kristjánsson et al. 2008; Todd & Kniveton 2001, 2004; Calogovic et al. 2010; Svensmark et al. 2016). FD, being one of the superposed signals in raw CR data, is a key parameter in space weather study. Its selection requires a sophisticated computer technique rather than the manual method (Musalem-Ramirez et al. 2013). Validation of FDs, selected by a manual, semi-automated or fully automated approach, is not a very common practice among CR scientists.

In this paper, we intend to validate the algorithm selected FD list from the Oulu Neutron Monitor (NM) station between 1998 to 2002 by testing the correlation between its amplitudes, solar wind data and geomagnetic activity indices.

2 DATA

We have taken Oulu NM pressure-corrected raw CR intensity daily averaged data between 1998 to 2002 from the IZMIRAN common website: `http://cr0.izmiran.ru/common` for our investigation in this work. The site is hosted by the Pushkov Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation, Russian Academy of Sciences (IZMIRAN) team. The Oulu NM station is characterized by geomagnetic cutoff rigidity of 0.77 GV, geographic location of 25.47°E, 65.05°N and altitude = 0 m. Daily mean solar wind speed (SWS), IMF, disturbance storm-time index (Dst) and geomagnetic indices kp and ap data are obtained from the OMNI database at `https://omniweb.gsfc.nasa.gov/html/owdata.html`.

3 MANUAL FD DETECTION TECHNIQUE

CR data in raw form are fraught with superposition of several signals of similar or different magnitudes, cycles and periodicities (Okike 2019). Timing and amplitude estimation of true FDs will not be easy with the traditional manual method. In the manual technique, the time domain component is not factored into the calculation as shown in Equation (1) (e.g., Harrison & Ambaum 2010; Lee et al. 2013; Okike 2020a,b).

$$FD_{\mathrm{mag}}(\%) = \frac{FD_{\min+1} - FD_{\min-1}}{FD_{\min}} \times 100\%, \quad (1)$$

where $FD_{\mathrm{mag}}(\%)$ is the FD magnitude, $FD_{\min}$ represents CR count on the day of minimum depression, $FD_{\min+1}$, the CR count rate a day before minimum depression, and $FD_{\min-1}$, CR count rate a day after minimum depression.

The manual method involves several steps. It includes downloading CR data of preferred resolution, plotting and visually searching for pits or points of minimum depressions in CR data, identifying the onset and endtime of CR counts from the main phase profile and finally calculating the individual FD amplitude. This technique is tedious, subjective and time consuming though employed by many investigators over the years (e.g., Oh et al. 2008; Kristjánsson et al. 2008; Oh & Yi 2009; Lee et al. 2015). The absence of time domain factor is a major demerit in the manual FD selection technique. CR data being a single time-dependent series signal can only be handled by computer software.

4 AUTOMATED FD LOCATION CODE

The automated FD location code in this work is a modified version of event selection program developed by Okike & Umahi (2019). This technique takes unprocessed CR data as its input signal instead of the high frequency signal. It is designed to simultaneously search for depressions/turning points and the time of the reductions in the raw CR data. While the Okike & Umahi (2019) identification code requires several subroutines that perform a number of tasks such as Fourier transformation, data filtering and event timing, the current code is simpler. A few subprograms which compute event amplitude and timing are involved. In the manual technique (see Lee et al. 2015; Harrison & Ambaum 2010; Okike 2020b, for example), Equation (1) is utilized to calculate individual CR percentage (with reference to hourly, daily, monthly or even annual averages) reduction, whereas the equation is used for normalization of CR time series in Okike & Umahi (2019) and in the current work.

The depressions in the normalized data are indications of FD events. The two subroutines (timing and magnitude estimation routines) incorporated in the program are used to search for the depressions and the time of occurrences in the time series data.

Setting the mean as the normalization threshold, the software determines the event amplitude with the first subroutine and time of occurrence of the reductions with the second subroutine from the CR data simultaneously. The output of the present algorithm makes it possible to select FDs as low as –0.05(%). As noted in Okike & Umahi

Table 1 Correlation Results with Large FDs (CR(%) ≤ -3)

S/N	Parameter	R^2	r	p-value
1	FD-IMF	0.19	–0.44	1.98×10^{-7}
2	FD-SWS	0.19	–0.44	1.22×10^{-7}
3	FD-kp	0.08	–0.28	1.23×10^{-5}
4	FD-Dst	0.21	0.46	3.51×10^{-8}
5	FD-ap	0.08	0.29	4.95×10^{-4}
6	FD-SWS×IMF	0.34	0.58	4.65×10^{-13}

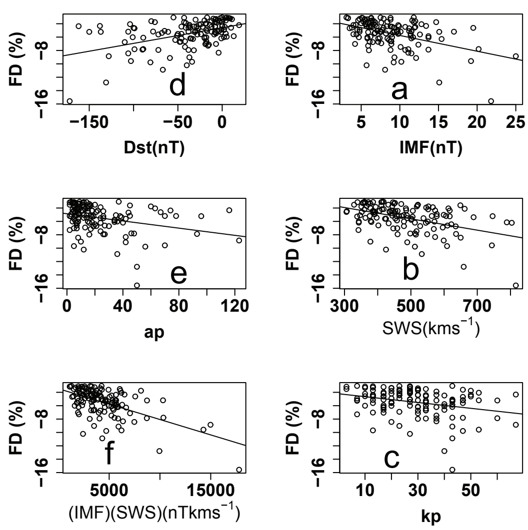

Fig. 1 Scatterplots of large FDs (CR(%) ≤ -3) and related solar wind parameters and geomagnetic activity indices.

(2019), the number of FDs detected depends on the baseline used. Using a very small baseline (CR(%) ≤ -0.01), our algorithm selected 230 FDs from the Oulu NM station covering the period 1998–2002. This result is presented in Table 3 with the associated solar wind data and GMS indices. The automated program is written in R, non-commercial software (Team 2015).

R is one of the fastest developing statistical computer programs. The software is generally referred to as R Foundation for Statistical Computing Platform. The project was initiated by Robert Gentleman and Ross Ihaka of the Department of Statistics at the University of Auckland. Readers are referred to Okike et al. (2021a) for details on the current R code.

Out of the 230 algorithm-selected FD datasets, we formed a subset of 129 large FDs (CR(%) ≤ -3) catalog. The two FD catalogs with their associated solar wind data and GMS indices are presented in Tables 2 and 3. In these tables, S/N stands for serial number, date of occurrences of both the FDs and the solar wind/geophysical activity characteristics is in Column (2), IMF stands for IMF intensity, SWS represents solar wind speed, kp, Dst and ap are GMS indices while solar wind disturbance characteristic SWS×IMF is in the last column.

5 ANALYSIS AND RESULTS

The variability of CR flux is highly unpredictable. At the moment, no method of FD selection, either semi-automated or automated, can address comprehensively the diversities of FD features. Validation of an FD data list is crucial in tackling factors that could potentially introduce feigned intensity depressions in CR flux. It also helps to check the efficiency of the computer software.

In line with the relationship that theoretically exists between FD, solar wind structure and geomagnetic activity indices as pointed out in Section 1 (e.g., Belov et al. 2005; Belov 2009; Lingri et al. 2016), we attempt to validate the current FD data by comparing the amplitudes of the FD catalog with the solar wind data and GMS indices. This was carried out with Pearson's product moment correlation statistics.

The present analysis will focus on the 129 large FD (CR(%) ≤ -3) catalog presented in Table 3. Investigations on the remaining FD data in Table 2 will be taken up in future work. FDs with (CR(%) ≤ -3) are often adopted as the common threshold to select large FDs (e.g., Kristjánsson et al. 2008; Kane 2010; Okike et al. 2021b). The matrix of correlation results for large FDs with corresponding solar wind and geomagnetic activity index data is given in Table 1. The columns of the table are explained thus: S/N stands for serial number, Parameter represents each of the two continuous variables, R^2 indicates coefficient of determination, r is the Pearson's product moment correlation coefficient and p-value is chance probability.

The scatterplot of FD magnitude and IMF intensity is displayed in panel a of Figure 1. The results of the regression and correlation analyses for the FD-IMF relation yield R^2=0.19 and r=-0.44 with p-value of 1.98×10^{-7}. The correlation is statistically significant at the 95% confidence level. R^2, which is the coefficient of determination, expresses the percentage of variation in the regressand (dependent variable) that can be attributed (Okike & Nwuzor 2020) to the regressor (independent or explanatory variable). The regression result hence implies that 19% of CR intensity variation can be accounted for by IMF intensity in the large FDs (CR(%) ≤ -3) dataset in Table 3.

The graph of FD magnitude and SWS is presented in panel b of Figure 1. The analysis of the FD-SWS relation gives R^2, r and p-value as 0.19, –0.44 and 1.22×10^{-7} respectively. The p-value indicates that the result is statistically significant at the 95% confidence level. The regression analysis suggests that 19% of GCR density changes in the sample in Table 3 is driven by high speed solar wind.

Scatterplot of FD amplitude and kp relation for the dataset of Table 3 is plotted in panel c of Figure 1. The correlation and regression analyses of FD-kp relation

Table 2 Oulu NM station FDs (All FDs) and Associated Solar Wind Data and Geomagnetic Activity Indices from 1998–2002

S/N	Date	FD (%)	IMF (nT)	SWS (km s^{-1})	kp	Dst (nT)	ap	SWS×IMF (km s^{-1}) (nT)
1	1998–08–27	–2.62	14.10	630	70	–129	144	8883.00
2	1998–09–25	–0.75	18.00	713	60	–118	117	12834.00
3	1999–01–24	–0.67	7.60	517	30	–38	17	3929.20
4	1999–02–18	–2.23	17.10	599	60	–84	80	10242.90
5	1999–08–22	–0.53	6.00	428	20	–27	12	2568.00
6	1999–10–17	–0.90	5.20	520	33	–33	21	2704.00
7	1999–10–22	–0.72	14.20	608	57	–134	91	8633.60
8	1999–10–24	–0.85	5.80	571	40	–58	26	3311.80
9	1999–11–12	–0.18	4.90	554	23	–34	10	2714.60
10	1999–11–17	–0.64	10.60	447	27	–30	12	4738.20
11	1999–11–20	–1.06	8.10	443	20	–16	9	3588.30
12	1999–11–22	–0.87	9.80	453	23	–12	11	4439.40
13	1999–12–03	–1.53	12.70	425	30	–7	16	5397.50
14	1999–12–13	–5.51	11.40	489	33	–46	26	5574.60
15	1999–12–27	–2.70	7.90	410	17	2	7	3239.00
16	1999–12–31	–0.75	10.80	653	43	–18	36	7052.40
17	2000–01–02	–0.70	5.10	679	30	–19	16	3462.90
18	2000–01–04	–0.79	5.80	577	27	–15	13	3346.60
19	2000–01–06	–0.75	6.90	533	33	–22	19	3677.70
20	2000–01–24	–0.82	10.10	366	27	–40	13	3696.60
21	2000–01–29	–0.05	5.60	722	43	–26	30	4043.20
22	2000–02–07	–0.55	5.40	629	43	–35	31	3396.60
23	2000–02–12	–3.76	14.70	553	50	–76	60	8129.10
24	2000–02–21	–2.13	14.30	423	33	–1	21	6048.90
25	2000–03–01	–2.73	7.60	480	33	–22	21	3648.00
26	2000–03–04	–1.83	5.20	361	7	0	3	1877.20
27	2000–03–06	–1.59	8.90	411	27	–8	12	3657.90
28	2000–03–09	–1.81	6.50	391	10	–14	4	2541.50
29	2000–03–13	–2.62	3.50	366	10	–13	4	1281.00
30	2000–03–19	–2.26	8.30	366	20	2	7	3037.80
31	2000–03–24	–3.59	6.60	649	23	–3	11	4283.40
32	2000–03–30	–3.15	5.20	446	27	–2	12	2319.20
33	2000–04–05	–2.99	7.30	387	20	–34	11	2825.10
34	2000–04–07	–4.36	9.90	573	50	–162	74	5672.70
35	2000–04–14	–0.79	6.60	318	3	–2	2	2098.80
36	2000–04–17	–1.76	6.20	457	23	–23	12	2833.40
37	2000–04–19	–1.98	10.10	461	23	–7	12	4656.10
38	2000–04–22	–1.79	5.50	449	13	1	5	2469.50
39	2000–04–24	–2.30	9.40	485	33	–25	21	4559.00
40	2000–05–03	–3.59	6.20	520	30	–12	17	3224.00
41	2000–05–08	–4.21	9.80	360	10	19	4	3528.00
42	2000–05–16	–3.71	8.40	444	30	-8	16	3729.60
43	2000–05–24	–7.87	13.70	636	60	–90	93	8713.20
44	2000–05–30	–4.38	6.20	617	37	–29	22	3825.40
45	2000–06–09	–9.69	10.20	609	13	–34	5	6211.80
46	2000–06–20	–5.94	6.20	379	17	5	6	2349.80
47	2000–06–24	–6.01	9.00	551	27	–20	15	4959.00
48	2000–06–26	–6.19	11.50	512	43	–36	40	5888.00
49	2000–07–02	–3.32	5.50	378	10	11	4	2079.00
50	2000–07–05	–3.34	5.80	449	20	1	9	2604.20
51	2000–07–08	–3.20	6.30	363	17	9	6	2286.90
52	2000–07–11	–5.86	13.70	458	43	13	34	6274.60
53	2000–07–13	–8.33	11.10	573	37	–4	42	6360.30
54	2000–07–16	–15.58	21.80	816	43	–172	50	17788.80
55	2000–07–20	–10.88	8.10	533	43	-67	36	4317.30
56	2000–07–22	–10.21	5.70	425	27	–40	12	2422.50
57	2000–07–29	–7.92	8.80	460	37	–38	27	4048.00
58	2000–08–06	–7.97	6.00	515	30	–32	16	3090.00
59	2000–08–12	–8.86	25.00	599	67	–128	123	14975.00
60	2000–08–26	–4.46	6.00	385	13	–8	5	2310.00
61	2000–08–31	–3.93	5.00	546	27	–18	14	2730.00
62	2000–09–03	–4.18	6.80	413	17	–14	7	2808.40
63	2000–09–09	–5.61	4.40	425	13	–9	5	1870.00
64	2000–09–15	–5.47	6.70	363	20	4	12	2432.10
65	2000–09–18	–9.59	19.20	744	53	–103	70	14284.80
66	2000–09–26	–3.89	5.90	566	37	–41	24	3339.40
67	2000–09–29	–4.01	5.50	378	17	–19	7	2079.00
68	2000–10–01	–4.16	4.30	418	27	–37	13	1797.40
69	2000–10–05	–4.33	13.40	486	67	–138	116	6512.40
70	2000–10–07	–4.58	3.80	391	10	–36	4	1485.80

Table 2 *Continued.*

S/N	Date	FD (%)	IMF (nT)	SWS (km s^{-1})	kp	Dst (nT)	ap	SWS×IMF (km s^{-1}) (nT)
71	2000–10–14	–3.61	12.00	411	47	–80	45	4932.00
72	2000–10–20	–1.81	4.90	433	7	–2	3	2121.70
73	2000–10–22	–1.71	8.70	463	27	–6	16	4028.10
74	2000–10–29	–6.09	13.70	381	40	–89	34	5219.70
75	2000–11–04	–4.48	12.00	436	40	–22	26	5232.00
76	2000–11–07	–7.79	20.20	512	43	–89	46	10342.40
77	2000–11–11	–6.21	7.20	804	30	–35	16	5788.80
78	2000–11–13	–4.90	4.50	578	23	–18	9	2601.00
79	2000–11–16	–4.92	4.80	391	7	2	3	1876.80
80	2000–11–24	–4.40	8.80	406	23	0	11	3572.80
81	2000–11–29	–9.77	9.20	512	47	–81	56	4710.40
82	2000–12–06	–6.19	5.80	343	17	–1	7	1989.40
83	2000–12–11	–4.20	4.00	552	20	0	8	2208.00
84	2000–12–15	–3.17	3.30	356	3	8	2	1174.80
85	2000–12–19	–3.29	4.80	356	13	–7	5	1708.80
86	2000–12–23	–4.58	9.20	306	33	–38	21	2815.20
87	2000–12–25	–4.60	11.90	352	17	10	6	4188.80
88	2000–12–27	–4.90	7.70	390	20	–1	8	3003.00
89	2000–12–31	–3.51	4.60	329	3	4	2	1513.40
90	2001–01–03	–3.78	6.80	351	20	–8	8	2386.80
91	2001–01–10	–3.69	5.30	367	13	0	5	1945.10
92	2001–01–14	–3.37	5.40	372	20	–8	8	2008.80
93	2001–01–19	–3.14	3.30	339	10	7	4	1118.70
94	2001–01–25	–4.67	3.50	387	13	-27	6	1354.50
95	2001–01–31	2.92	7.60	409	30	-22	18	3108.40
96	2001–02–07	–1.84	6.00	488	17	-6	6	2928.00
97	2001–02–11	–1.24	5.30	398	17	0	6	2109.40
98	2001–02–14	–2.03	5.80	513	33	–34	19	2975.40
99	2001–02–20	–1.22	6.90	315	17	5	7	2173.50
100	2001–03–04	–1.46	6.90	448	33	–17	19	3091.20
101	2001–03–21	–0.57	12.10	320	17	–65	8	3872.00
102	2001–03–28	–2.73	8.90	608	43	–53	44	5411.20
103	2001–04–01	–5.22	7.50	746	43	–137	38	5595.00
104	2001–04–05	–5.25	7.50	617	33	–31	19	4627.50
105	2001–04–09	–6.43	8.60	622	33	–53	20	5349.20
106	2001–04–12	–12.79	15.10	659	40	–131	50	9950.90
107	2001–04–16	–5.57	4.00	453	20	–24	8	1812.00
108	2001–04–19	–4.60	7.90	436	17	–41	6	3444.40
109	2001–04–22	–3.05	11.80	360	43	–55	37	4248.00
110	2001–04–26	–1.95	6.80	438	17	–6	6	2978.40
111	2001–04–29	–6.92	7.60	596	23	–18	13	4529.60
112	2001–05–08	–1.63	9.20	410	27	–20	16	3772.00
113	2001–05–12	–1.93	10.80	534	40	–35	30	5767.20
114	2001–05–16	–1.42	5.10	487	17	–9	7	2483.70
115	2001–05–20	–0.84	5.40	384	13	0	5	2073.60
116	2001–05–25	–2.95	6.60	557	17	5	7	3676.20
117	2001–05–28	–5.30	9.10	505	33	–8	18	4595.50
118	2001–06–03	–2.11	5.30	508	17	–7	6	2692.40
119	2001–06–09	–1.88	9.70	510	33	0	25	4947.00
120	2001–06–12	–1.83	5.20	433	10	–2	4	2251.60
121	2001–06–20	–1.93	5.90	700	23	–20	11	4130.00
122	2001–06–26	–1.26	6.20	464	27	–2	13	2876.80
123	2001–06–29	–1.17	3.40	347	7	11	3	1179.80
124	2001–07–05	–2.16	7.00	423	27	5	12	2961.00
125	2001–07–09	–1.58	4.10	427	17	–8	10	1750.70
126	2001–07–17	–0.27	8.90	592	30	–13	16	5268.80
127	2001–07–19	–0.53	4.80	605	17	0	7	2904.00
128	2001–07–21	–0.32	5.60	412	10	11	4	2307.20
129	2001–07–26	–1.63	4.60	552	23	–15	10	2539.20
130	2001–07–30	–1.51	6.80	312	17	10	7	2121.60
131	2001–08–03	–2.43	7.20	405	27	0	12	2916.00
132	2001–08–06	–2.50	7.00	440	30	–18	17	3080.00
133	2001–08–14	–1.56	7.80	456	23	–10	10	3556.80
134	2001–08–18	–3.76	11.80	518	27	–43	15	6112.40
135	2001–08–24	–3.05	3.10	414	7	0	3	1283.40
136	2001–08–29	–7.02	4.20	459	13	–7	5	1927.80
137	2001–09–07	–2.72	6.10	369	7	6	3	2250.90
138	2001–09–15	–1.69	7.60	541	33	–11	20	4111.60
139	2001–09–19	–1.46	6.50	422	20	–5	9	2743.00
140	2001–09–22	–0.92	5.70	327	20	1	8	1863.90

Table 2 *Continued.*

S/N	Date	FD (%)	IMF (nT)	SWS (km s^{-1})	kp	Dst (nT)	ap	SWS×IMF (km s^{-1}) (nT)
141	2001–09–26	–7.92	10.70	549	33	–72	26	5874.30
142	2001–10–01	–7.81	11.10	498	47	–99	48	5527.80
143	2001–10–09	–4.38	8.30	445	30	–37	18	3693.50
144	2001–10–12	–5.76	11.40	501	40	–51	34	5711.40
145	2001–10–22	–5.22	15.10	578	60	–150	96	8727.80
146	2001–10–28	–4.68	11.20	450	47	–99	44	5040.00
147	2001–11–07	–6.75	6.50	635	30	–110	19	4127.50
148	2001–11–15	–2.16	6.70	300	17	–5	9	2010.00
149	2001–11–22	–3.07	7.50	418	23	–17	9	3135.00
150	2001–11–25	–8.43	11.50	650	20	–106	8	7475.00
151	2001–12–01	–1.46	8.00	348	17	0	7	2784.00
152	2001–12–06	–3.51	6.40	432	27	–20	11	2764.80
153	2001–12–17	–3.39	8.80	471	30	–30	16	4144.80
154	2001–12–22	–1.02	7.70	379	20	–40	8	2918.30
155	2001–12–24	–0.67	9.00	508	37	–30	23	4572.00
156	2001–12–27	–1.29	7.30	369	17	–16	7	2693.70
157	2001–12–29	–2.25	15.40	397	27	34	11	6113.80
158	2002–01–03	–7.29	5.90	342	7	-16	2	2017.80
159	2002–01–11	–6.63	8.90	610	40	-42	27	5429.00
160	2002–01–19	–3.12	8.80	372	27	4	14	3273.60
161	2002–01–21	–3.24	7.90	452	27	–10	11	3570.80
162	2002–01–24	–2.99	5.90	360	10	–12	4	2124.00
163	2002–01–30	–5.27	5.90	338	7	–1	3	1994.20
164	2002–02–01	–5.09	11.20	347	27	–17	14	3886.40
165	2002–02–11	–0.77	8.10	491	27	–17	14	3977.10
166	2002–02–15	–0.42	6.30	371	7	–3	3	2337.30
167	2002–02–19	–0.75	7.70	401	13	–17	6	3087.70
168	2002–02–23	–1.89	6.40	362	10	–6	4	2316.80
169	2002–03–02	–2.26	9.90	386	13	–14	6	3821.40
170	2002–03–05	–1.83	9.50	646	33	–22	21	6137.00
171	2002–03–12	–1.76	7.90	453	27	–3	11	3578.70
172	2002–03–16	–1.63	6.30	310	7	13	3	1953.00
173	2002–03–22	–5.14	7.50	444	13	–4	6	3330.00
174	2002–03–25	–6.29	15.40	433	17	–33	7	6668.20
175	2002–03–30	–3.51	11.60	521	33	–5	20	6043.60
176	2002–04–05	–1.74	6.50	402	7	6	3	2613.00
177	2002–04–12	–2.72	8.70	432	30	–1	16	3758.40
178	2002–04–15	–1.58	8.80	357	13	–8	6	3141.60
179	2002–04–18	–4.06	12.80	485	53	–104	63	6208.00
180	2002–04–20	–5.19	10.10	563	53	–106	70	5686.30
181	2002–04–24	–5.10	7.10	488	17	–30	7	3464.80
182	2002–05–04	–0.69	5.10	378	13	4	4	1927.80
183	2002–05–08	–1.11	8.50	366	20	–19	8	3111.00
184	2002–05–13	–2.80	6.00	457	17	–21	8	2742.00
185	2002–05–15	–3.10	6.30	411	27	–43	12	2589.30
186	2002–05–20	–4.45	9.00	453	23	–12	10	4077.00
187	2002–05–23	–5.19	17.00	606	47	–38	78	10302.00
188	2002–05–28	–4.11	5.60	662	23	–26	9	3707.20
189	2002–06–04	–2.20	5.90	441	27	–23	13	2601.90
190	2002–06–07	–2.26	5.00	308	13	–3	5	1540.00
191	2002–06–12	–2.84	6.80	368	17	–14	6	2502.40
192	2002–06–16	–1.86	8.80	382	20	6	7	3361.60
193	2002–06–19	–2.94	10.60	468	27	–2	11	4960.80
194	2002–06–24	–1.32	7.10	474	13	–3	5	3365.40
195	2002–06–29	–0.58	5.10	344	13	6	5	1754.40
196	2002–07–03	–1.79	3.80	361	10	1	4	1371.80
197	2002–07–11	–3.10	5.10	386	13	5	5	1968.60
198	2002–07–18	–4.38	5.70	441	13	–8	5	2513.70
199	2002–07–20	–6.13	7.40	789	30	–20	18	5838.60
200	2002–07–23	–5.20	4.80	472	30	–12	17	2265.60
201	2002–08–02	–9.12	12.10	489	43	–59	42	5916.90
202	2002–08–07	–6.01	4.70	343	10	2	4	1612.10
203	2002–08–09	–5.45	8.20	397	27	–7	14	3255.40
204	2002–08–20	–6.71	7.20	479	33	–48	30	3448.80
205	2002–08–23	–6.60	8.80	402	17	–18	7	3537.60
206	2002–08–28	–7.65	8.90	447	17	–19	7	3978.30
207	2002–09–04	–5.61	12.60	422	47	–72	42	5317.20
208	2002–09–08	–6.01	11.70	479	33	–101	36	5604.30
209	2002–09–11	–5.22	9.60	458	37	–61	26	4396.80
210	2002–09–19	–4.06	6.60	613	27	–24	15	4045.80

Table 2 *Continued.*

S/N	Date	FD (%)	IMF (nT)	SWS (km s^{-1})	kp	Dst (nT)	ap	SWS×IMF (km s^{-1}) (nT)
211	2002–09–24	–5.19	9.30	376	7	–8	2	3496.80
212	2002–09–28	–4.48	10.70	307	13	3	5	3284.90
213	2002–10–01	–4.62	19.50	388	50	–100	67	7566.00
214	2002–10–03	–5.17	11.50	464	47	–78	45	5336.00
215	2002–10–09	–2.35	6.30	410	33	–60	20	2583.00
216	2002–10–13	–2.13	6.50	301	13	–30	5	1956.50
217	2002–10–21	–6.03	5.80	571	20	–18	8	3311.80
218	2002–10–25	–5.37	6.80	689	43	–68	39	4685.20
219	2002–11–03	–5.07	9.70	478	43	–65	35	4636.60
220	2002–11–05	–6.21	8.40	545	37	–46	24	4578.00
221	2002–11–12	–7.13	12.40	569	30	–15	17	7055.60
222	2002–11–18	–9.02	9.30	378	23	–37	10	3515.40
223	2002–11–25	–4.43	7.00	460	30	–46	15	3220.00
224	2002–11–27	–5.52	9.80	538	33	–50	24	5272.40
225	2002–12–01	–4.41	6.40	506	33	–32	18	3238.40
226	2002–12–06	–3.84	7.60	394	23	–6	9	2994.40
227	2002–12–08	–5.02	7.10	599	27	–28	12	4252.90
228	2002–12–15	–5.61	8.90	502	20	–28	8	4467.80
229	2002–12–20	–6.70	6.10	528	33	–47	21	3220.80
230	2002–12–23	–7.47	10.10	517	37	–42	24	5221.70

yield R^2, r and p-value of 0.08, –0.28 and 1.23×10^{-5} respectively. The p-value indicates a high level of significance. R^2 value in the dataset predicts that 8% of FD is caused by geomagnetic index (kp).

The plot of FD magnitude and Dst from Table 3 is shown in panel d of Figure 1. The regression analysis for the FD-Dst parameters gives R^2, correlation coefficient r and p-value of 0.21, 0.46 and 3.51×10^{-8} respectively. High statistical significance is implied here from the chance probability value. From the observed R^2 result, we infer that 21% of CR variation is related to Dst corresponding to data in Table 3.

We display FD magnitude and ap graph for the dataset of Table 3 in panel e of Figure 1. The corresponding R^2, r and p-value from the FD-ap relation analysis are 0.08, 0.29 and 4.95×10^{-4} respectively for data in Table 3. While the results here are statistically significant from the chance probability value, the R^2 value suggests that only 8% of the variations in FD events can be attributed to ap in the large FD data list.

In panel f of Figure 1, we present the scatterplot of FD magnitude and (SWS×IMF) for the 129 FD dataset. The result of our regression and correlation analyses gives R^2, r and p-value respectively as 0.34, 0.58 and 4.65×10^{-13}. This result is statistically significant at the 95% confidence level. The R^2 value obtained here suggests that 34% of CR variability can be accounted for by the characteristic of solar wind disturbance.

6 DISCUSSION AND CONCLUSION

6.1 Discussion

Large amplitude FDs are generally presumed to be caused by CMEs. The statistical level of significance of correlations between FDs, solar wind and geophysical parameters appears to suggest that SWS, IMF intensity and Dst are key drivers of variations in FDs, which in turn are linked to CMEs (Richardson 2004; Richardson & Cane 2011; Belov et al. 2014).

Considering a population of FDs (CR(%) $>$ 4) in magnitude that occurred between 1966 and 1972, Barnden (1973) observed that the interplanetary disturbances responsible for FDs are characterized by a region of high solar wind velocity and enhanced IMF intensity. Similarly, Barouch & Burlaga (1975) reported an association between FDs and variations in IMF intensity using Deep River NM data from 1967 to 1968. They noted that from 1967 to 1968, all the CR flux variation is associated with the passage of a region when magnetic field intensity is high. About two decades later, Ifedili (1998) found that both sudden increase in IMF and the SWS are preceded by the onset of FD at the Deep River NM station. The results of the present work in which FD-IMF and FD-SWS relations yield correlations significant at 95% confidence level are in close agreement with results in the literature referred to above. From statistical analysis of 695 events selected with GSM, Belov et al. (2001a) found that 49% of FD variation is due to the effect of solar disturbance characteristic. The result obtained here for FD-solar disturbance characteristic is in fair agreement with their finding.

Recently, Lingri et al. (2016) showed that FD amplitude does not correlate with Dst utilizing 68 large (CR(%) $>$ 2) GSM-selected FDs. They reported evidence of correlation for the FD-SWS relation from the same sample with coefficient of determination R^2 = 0.16. This result could mean that 16% of the modulation in the CR intensity is related to the effect of solar wind structure. It is interesting to note that the current statistical analysis indicates higher values of coefficient of determination. The improved relation could be a pointer to the differences in the semi-automated and the current fully automated FD event identification approaches.

Table 3 Oulu NMs Large FDs (CR(%)≤ -3)) and Associated Solar Wind parameters and Geomagnetic Activity indices from 1998-2002

S/N	Date	FD (%)	IMF (nT)	SWS (km s^{-1})	kp	Dst (nT)	ap	SWS×IMF (km s^{-1}) (nT)
1	2001–04–22	–3.05	3.10	414	7	0	3	1283.40
2	2001–08–24	–3.05	11.80	360	43	–55	37	4248.00
3	2001–11–22	–3.07	7.50	418	23	–17	9	3135.00
4	2002–05–15	–3.10	6.30	411	27	–43	12	2589.30
5	2002–07–11	–3.10	5.10	386	13	5	5	1968.60
6	2002–01–19	–3.12	8.80	372	27	4	14	3273.60
7	2001–01–19	–3.14	3.30	339	10	7	4	1118.70
8	2000–03–30	–3.15	5.20	446	27	–2	12	2319.20
9	2000–12–15	–3.17	3.30	356	3	8	2	1174.80
10	2000–07–08	–3.20	6.30	363	17	9	6	2286.90
11	2002–01–21	–3.24	7.90	452	27	–10	11	3570.80
12	2000–12–19	–3.29	4.80	356	13	–7	5	1708.80
13	2000–07–02	–3.32	5.50	378	10	11	4	2079.00
14	2000–07–05	–3.34	5.80	449	20	1	9	2604.20
15	2001–01–14	–3.37	5.40	372	20	–8	8	2008.80
16	2001–12–17	–3.39	8.80	471	30	–30	16	4144.80
17	2000–12–31	–3.51	6.40	432	27	–20	11	2764.80
18	2001–12–06	–3.51	4.60	329	3	4	2	1513.40
19	2002–03–30	–3.51	11.60	521	33	-5	20	6043.60
20	2000–03–24	–3.59	6.60	649	23	–3	11	4283.40
21	2000–05–03	–3.59	6.20	520	30	–12	17	3224.00
22	2000–10–14	–3.61	12.00	411	47	–80	45	4932.00
23	2001–01–10	–3.69	5.30	367	13	0	5	1945.10
24	2000–05–16	–3.71	8.40	444	30	–8	16	3729.60
25	2000–02–12	–3.76	14.70	553	50	–76	60	8129.10
26	2001–08–18	–3.76	11.80	518	27	–43	15	6112.40
27	2001–01–03	–3.78	6.80	351	20	–8	8	2386.80
28	2002–12–06	–3.84	7.60	394	23	–6	9	2994.40
29	2000–09–26	–3.89	5.90	566	37	–41	24	3339.40
30	2000–08–31	–3.93	5.00	546	27	–18	14	2730.00
31	2000–09–29	–4.01	5.50	378	17	–19	7	2079.00
32	2002–04–18	–4.06	6.60	613	27	–24	15	4045.80
33	2002–09–19	–4.06	12.80	485	53	–104	63	6208.00
34	2002–05–28	–4.11	5.60	662	23	–26	9	3707.20
35	2000–10–01	–4.16	4.30	418	27	–37	13	1797.40
36	2000–09–03	–4.18	6.80	413	17	–14	7	2808.40
37	2000–12–11	–4.20	4.00	552	20	0	8	2208.00
38	2000–05–08	–4.21	9.80	360	10	19	4	3528.00
39	2000–10–05	–4.33	13.40	486	67	–138	116	6512.40
40	2000–04–07	–4.36	9.90	573	50	–162	74	5672.70
41	2000–05–30	–4.38	8.30	445	30	–37	18	3693.50
42	2001–10–09	–4.38	6.20	617	37	–29	22	3825.40
43	2002–07–18	–4.38	5.70	441	13	-8	5	2513.70
44	2000–11–24	–4.40	8.80	406	23	0	11	3572.80
45	2002–12–01	–4.41	6.40	506	33	–32	18	3238.40
46	2002–11–25	–4.43	7.00	460	30	–46	15	3220.00
47	2002–05–20	–4.45	9.00	453	23	–12	10	4077.00
48	2000–08–26	–4.46	6.00	385	13	–8	5	2310.00
49	2000–11–04	–4.48	12.00	436	40	–22	26	5232.00
50	2002–09–28	–4.48	10.70	307	13	3	5	3284.90
51	2000–10–07	–4.58	9.20	306	33	–38	21	2815.20
52	2000–12–23	–4.58	3.80	391	10	–36	4	1485.80
53	2000–12–25	–4.60	7.90	436	17	–41	6	3444.40
54	2001–04–19	–4.60	11.90	352	17	10	6	4188.80
55	2002–10–01	–4.62	19.50	388	50	–100	67	7566.00
56	2001–01–25	–4.67	3.50	387	13	–27	6	1354.50
57	2001–10–28	–4.68	11.20	450	47	–99	44	5040.00
58	2000–11–13	–4.90	7.70	390	20	–1	8	3003.00
59	2000–12–27	–4.90	4.50	578	23	–18	9	2601.00
60	2000–11–16	–4.92	4.80	391	7	2	3	1876.80
61	2002–12–08	–5.02	7.10	599	27	—28	12	4252.90
62	2002–11–03	–5.07	9.70	478	43	–65	35	4636.60
63	2002–02–01	–5.09	11.20	347	27	–17	14	3886.40
64	2002–04–24	–5.10	7.10	488	17	-30	7	3464.80
65	2002–03–22	–5.14	7.50	444	13	–4	6	3330.00
66	2002–10–03	–5.17	11.50	464	47	–78	45	5336.00
67	2002–04–20	–5.19	9.30	376	7	–8	2	3496.80
68	2002–05–23	–5.19	17.00	606	47	–38	78	10302.00
69	2002–09–24	–5.19	10.10	563	53	–106	70	5686.30
70	2002–07–23	–5.20	4.80	472	30	–12	17	2265.60

Table 3 *Continued.*

S/N	Date	FD (%)	IMF (nT)	SWS (km s^{-1})	kp	Dst (nT)	ap	SWS×IMF (km s^{-1}) (nT)
71	2001–04–01	–5.22	9.60	458	37	–61	26	4396.80
72	2001–10–22	–5.22	7.50	746	43	–137	38	5595.00
73	2002–09–11	–5.22	15.10	578	60	–150	96	8727.80
74	2001–04–05	–5.25	7.50	617	33	–31	19	4627.50
75	2002–01–30	–5.27	5.90	338	7	–1	3	1994.20
76	2001–05–28	–5.30	9.10	505	33	–8	18	4595.50
77	2002–10–25	–5.37	6.80	689	43	–68	39	4685.20
78	2002–08–09	–5.45	8.20	397	27	–7	14	3255.40
79	2000–09–15	–5.47	6.70	363	20	4	12	2432.10
80	1999–12–13	–5.51	11.40	489	33	–46	26	5574.60
81	2002–11–27	–5.52	9.80	538	33	–50	24	5272.40
82	2001–04–16	–5.57	4.00	453	20	–24	8	1812.00
83	2000–09–09	–5.61	8.90	502	20	–28	8	4467.80
84	2002–09–04	–5.61	4.40	425	13	–9	5	1870.00
85	2002–12–15	–5.61	12.60	422	47	–72	42	5317.20
86	2001–10–12	–5.76	11.40	501	40	–51	34	5711.40
87	2000–07–11	–5.86	13.70	458	43	13	34	6274.60
88	2000–06–20	–5.94	6.20	379	17	5	6	2349.80
89	2000–06–24	–6.01	9.00	551	27	–20	15	4959.00
90	2002–08–07	–6.01	4.70	343	10	2	4	1612.10
91	2002–09–08	–6.01	11.70	479	33	–101	36	5604.30
92	2002–10–21	–6.03	5.80	571	20	–18	8	3311.80
93	2000–10–29	–6.09	13.70	381	40	–89	34	5219.70
94	2002–07–20	–6.13	7.40	789	30	–20	18	5838.60
95	2000–06–26	–6.19	5.80	343	17	–1	7	1989.40
96	2000–12–06	–6.19	11.50	512	43	–36	40	5888.00
97	2000–11–11	–6.21	8.40	545	37	–46	24	4578.00
98	2002–11–05	–6.21	7.20	804	30	–35	16	5788.80
99	2002–03–25	–6.29	15.40	433	17	–33	7	6668.20
100	2001–04–09	–6.43	8.60	622	33	–53	20	5349.20
101	2002–08–23	–6.60	8.80	402	17	–18	7	3537.60
102	2002–01–11	–6.63	8.90	610	40	–42	27	5429.00
103	2002–12–20	–6.70	6.10	528	33	–47	21	3220.80
104	2002–08–20	–6.71	7.20	479	33	–48	30	3448.80
105	2001–11–07	–6.75	6.50	635	30	–110	19	4127.50
106	2001–04–29	–6.92	7.60	596	23	–18	13	4529.60
107	2001–08–29	–7.02	4.20	459	13	–7	5	1927.80
108	2002–08–28	–7.65	8.90	447	17	–19	7	3978.30
109	2002–11–12	–7.13	12.40	569	30	–15	17	7055.60
110	2002–01–03	–7.29	5.90	342	7	–16	2	2017.80
111	2002–12–23	–7.47	10.10	517	37	–42	24	5221.70
112	2000–11–07	–7.79	20.20	512	43	–89	46	10342.40
113	2001–10–01	–7.81	11.10	498	47	–99	48	5527.80
114	2000–05–24	–7.87	13.70	636	60	–90	93	8713.20
115	2000–07–29	–7.92	8.80	460	37	–38	27	4048.00
116	2000–07–29	–7.92	10.70	549	33	–72	26	5874.30
117	2000–08–06	–7.97	6.00	515	30	–32	16	3090.00
118	2000–07–13	–8.33	11.10	573	37	–4	42	6360.30
119	2001–11–25	–8.43	11.50	650	20	–106	8	7475.00
120	2000–08–12	–8.86	25.00	599	67	–128	123	14975.00
121	2002–11–18	–9.02	9.30	378	23	–37	10	3515.40
122	2002–08–02	–9.12	12.10	489	43	–59	42	5916.90
123	2000–09–18	–9.59	19.20	744	53	–103	70	14284.80
124	2000–06–09	–9.69	10.20	609	13	–34	5	6211.80
125	2000–11–29	–9.77	9.20	512	47	–81	56	4710.40
126	2000–07–22	–10.21	5.70	425	27	–40	12	2422.50
127	2000–07–20	–10.88	8.10	533	43	–67	36	4317.30
128	2001–04–12	–12.79	15.10	659	40	–131	50	9950.90
129	2000–07–16	–15.58	21.80	816	43	–172	50	17788.80

Badruddin & Kumar (2015) found FD-SWS relation of r=0.58. The FD-SWS correlation r=0.44 obtained in the present investigation is in agreement with their result. Our results for FD-SWS (r=0.44) and FD-IMF (r=0.44) do not reflect the submission of Okike et al. (2021b) who obtained r=0.81 and ~ 0.34 respectively. This could be a result of the data periods. Our data period is from 1998 to 2002, while the period of the FD selection by Okike et al. (2021b) is 2003 to 2005 which included the period of high solar activity. However, from the probability values, the results obtained here are statistically significant, hence we infer that SWS and IMF might play key roles in CR intensity modulation.

Using a large FD event database with 5900 entries that span from 1957 to 2006, Belov (2009) asserted that large amplitude FDs (CR(%) < -5) are associated with strong GMSs. The results obtained here for the association between FD magnitude and GMS indices, significant at the 95% confidence level, are in agreement with their report.

6.2 Conclusion

From the study of 129 algorithm-selected large FDs (CR(%) ≤ -3) for CR intensity at Oulu NM station between 1998 and 2002, the following conclusions can be drawn:

- A new automated FD location code has been successfully developed and employed to select FD list from the daily averaged CR raw data at Oulu NM station from 1998 to 2002.
- The computer program-selected FD was validated by comparing its amplitude with the corresponding solar wind data and GMS activity indices.
- The analysis indicates that the correlations between the continuous variables are statistically significant and hence reliable. These results reveal that the selected FDs are not spurious.
- We infer that IMF intensity, SWS and GMS indices (Dst, kp and ap) are key drivers in GCR modulation.

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