



Testing the Effects of Cosmic Ray Flux Intensity Modulation on Solar Emission Characteristics

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Abstract

We investigate the relationship between the magnitudes of Forbush decreases (FDs) and solar-geomagnetic characteristics using daily-averaged galactic cosmic ray (GCR) data from Inuvick (INVK) and Magadan (MGDN) neutron monitor (NM) stations to aid in counting the case of GCR flux intensity modulation. The FDs, obtained with an automated new computer software algorithm from daily-averaged GCR data from the IZMIRAN common website: <http://cr0.izmiran.ru/common>, at INVK (224) and MGDN (229) NM stations, from 1998 to 2002, were used in the present work. The associated solar-geomagnetic parameters of the same time range were obtained from the OMNI website. A statistical analytical method was employed to test the link between FD amplitudes and solar-geomagnetic variables. We observed negative trends in FD-IMF, FD-SWS, FD-Kp, FD-SSN and FD-SI, while a positive relation was indicated in FD-Dst at both stations. All are statistically significant at a 95% confidence level. The results obtained here imply that solar emission characteristics impact the GCR flux intensity modulation.

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

1. Introduction

Galactic cosmic rays (GCRs) are high-energy (ranging from 100 MeV to 10 GeV) charged particles (Adriani et al. 2009; Yu et al. 2015; Usoskin et al. 2020) made up of 2% electrons and 98% atomic nuclei, (which in terms of number density) consisting of roughly 1% heavier nuclei, 12% helium and 87% protons (Simpson 1983). GCRs originate within the Milky Way. The movement of GCRs is isotropic in the heliosphere and in their motions, they encounter a turbulent solar wind with an embedded heliospheric magnetic field. This leads to significant global and temporal variations in their intensity and in their energy as a function of position inside the heliosphere (Potgieter 2013). Periodically and abruptly, the GCRs' flux modulations are a result of the solar wind interplanetary magnetic field (IMF) structures such as shocks, sheaths, coronal mass ejections/interplanetary coronal mass ejections (CMEs/ICMEs) and corotating interaction region (e.g., Svensmark et al. 2012; Alhassan et al. 2022a). These GCRs flux modulations can be the periodic long-term modulation of GCR intensity which includes diurnal anisotropies (Okike 2021a), 27 days, and 11 yr modulations and the non-periodic short-term variabilities such as Forbush decrease (FD) and ground-level enhancement (Oh et al. 2008; Badruddin & Kumar 2015) which can be detected using the ground-based

neutron monitors (NMs) of the global network. The geomagnetic cut-off rigidity of a particular NM detector determines the magnitude of the depressions (Burger et al. 2000). Lingri et al. (2022) suggest that the geomagnetic cut-off rigidity expresses the resistance cosmic ray (CR) particles can have in order to penetrate the terrestrial magnetic field.

There is significant information recorded from the Sun when GCRs interact with transient disturbances from the Sun concerning the incoming disturbance before reaching the Earth. These disturbances bring about an unstable situation in the magnetosphere, especially those caused by solar flares, resulting in a storm in the geomagnetic field, characterized by geomagnetic activity indices (e.g., Dst, Kp and SI). These geomagnetic storms are frequently accompanied by FDs. FDs, first investigated by Scott Forbush about eight decades ago (Forbush 1937), are transient phenomena describing the short-term abrupt reductions in the intensity of CR flux, reaching their optimum depressions in about a day and followed by a gradual recovery a few days later (Forbush 1938; Lockwood 1971; Gopalswamy et al. 2014; Menteso et al. 2023). FDs can be categorized into two classes: recurrent and non-recurrent/sporadic by the type of interplanetary medium that actuates them. Recurrent FDs are a result of high-velocity streams originating from coronal holes that are revolving

around the Sun. In contrast, non-recurrent/sporadic FDs are the ones caused by transient interplanetary events related to CMEs and their ICMEs flowing out from the Sun (see Cane 2000; Richardson 2004; Badruddin & Kumar 2015; Melkumyan et al. 2018; Menteso et al. 2023). Lockwood (1971) and Melkumyan et al. (2019) opined that recurrent FDs exhibit symmetric profiles and low amplitudes compared to their non-recurrent counterparts which show high magnitudes and an asymmetric profile in their character.

Research works on the magnitude of FDs observed by different ground-level NMs scattered globally on the Earth's surface remain a matter of interest (Belov et al. 2001; Okike & Collier 2011; Okike 2020a; Alhassan et al. 2022a). Events with magnitudes $\leq 3\%$ are referred to as weak or small-amplitude FDs (Cane et al. 1993; Pudovkin & Veretenenko 1995; Oh et al. 2008; Okike 2021b), while those with magnitudes $\geq 3\%$ are known as strong or large-amplitude FDs (e.g., Cane et al. 1993; Van Allen 1993; Belov 2008; Oh et al. 2008; Harrison & Ambaum 2010; Laken et al. 2012). Belov et al. (2001) and Oh et al. (2008) suggest that the former is a result of lower solar wind speed (SWS) and weaker IMF intensity while the latter is due to the higher SWS and IMF strength respectively. Badruddin et al. (1991) who first investigated CR intensity depression at the Calgary NM station found that large-amplitude FDs are a result of shocks connected to helium (He) enhancement, while those that are not connected with the He shocks show relatively small depression in CR intensity of about CR (%). Fortunately, Kristjansson et al. (2008), Oh et al. (2008), Belov et al. (2001, 2014) and Okike (2021a) investigated CR intensity depressions and reported different results, ranging from GCR (%) -3 to -5 . They attributed these to the thresholds of the NM stations and suggested that the strength of FDs is related to the condition of the solar wind plasma that originates them. Jamsen et al. (2007) and Lagoida et al. (2023) independently used catalogs of FDs in their research works and opined that the energy or rigidity of NMs plays a big role in the recovery time of FD events. Furthermore, Okike & Nwuzo (2020) argued that other factors might have contributed to the modulation of GCR intensity at a significant station, using statistical methods of analysis.

CR intensity modulation can be well comprehended through correlation analysis between FDs and solar-geomagnetic characteristics. Recent works from literature have shown good examples of this analysis (see Kilpua et al. 2011; Mavromichalaki & Paouris 2012; Blanco et al. 2013; Mustajab & Badruddin 2013; Okike & Nwuzo 2020; Alhassan et al. 2021, 2022b; Menteso et al. 2023; Ugwu et al. 2024). In the work of Mavromichalaki & Paouris (2012), they investigated the GCR flux modulation and its effects on solar activity indices and heliospheric characteristics during the 23 and 24 yr solar cycles using the CME-index. Kilpua et al. (2011) compared the properties of ICMEs during a minimum 22 yr solar cycle and a minimum 23 yr solar cycle and suggested that

the maximum magnetic fields of the ICMEs at a 23 yr solar cycle were about 30% lower with radial widths of about 15% lower. Moreover, Blanco et al. (2013) studied the effects of 59 shock-driving ICMEs on FDs discovered by the Oulu NM and reported only 25% of them were related to the FDs $> 3\%$. Nevertheless, despite the potential benefits, it was shown through searching the literature that little work has yet been done in comprehending the statistical relationship between FDs and solar-geomagnetic characteristics due to insufficient FDs. Previously, FDs were detected by manual (Moraal et al. 2000a, 2000b; Shea & Smart 2000; Kristjansson et al. 2008; Oh et al. 2008; Lee et al. 2015) methods which are grueling and substandard in research work of handling data. Moreover, Belov (2008), Ramirez et al. (2013), Belov et al. (2018a), Abunina et al. (2020) and Light et al. (2020) improved the method by employing semi-automated FD detections, but yet the paucity of FDs is still on the high side. This can be a result of the noise signal in the CR data like diurnal CR anisotropies (Okike 2020b), periodicities and cycles, including the short-term random modulations in the amplitude and timing of FDs first suggested by Cane et al. (1996) and Oh et al. (2008) and recently confirmed by Richardson & Cane (2011).

Recently, some researchers (e.g., Ramirez et al. 2013; Okike 2019a, 2019b, 2020a, 2020b; Okike & Umahi 2019a; Light et al. 2020; Alhassan et al. 2022b) and the Pushkov Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation, Russian Academy of Sciences (IZMIRAN) group have used automated methods in investigation of FDs. The IZMIRAN group developed catalogs of FDs, both the large and the very small ones, using the global survey method (GSM). This technique aids in acquiring CR data detected by all NMs installed all over the globe. Currently, Alhassan et al. (2022b) developed a comprehensive list of FDs using the automated method of investigation. This large volume of FD data (see Tables 2 and 3) from Alhassan et al. (2022b) obtained through the same automated method of approach helps us to carry out a critical statistical analysis study.

In this work, we statistically investigated the effects of these FDs on solar-geomagnetic variables using data from Inuvik (INVK) and Magadan (MGDN) NM stations. Section 1 is the introductory part of this work, while the data source is in subsection one. Section 2 discusses the methodology applied in this work, while analysis, results obtained and discussion of these results are in Section 3. Result validation is shown in Section 4, while Section 5 summarizes and concludes the work.

1.1. Data Source

The daily averaged CR data were obtained from the IZMIRAN common website:⁵ between 1998 and 2002 (solar cycle 23) observed from INVK and MGDN NMs stations.

⁵ <http://cr0.izmiran.ru/common>

Table 1
Characteristics of INVK and MGDN NMs

S/N	NM Name	NM Type	Longitude	Latitude	Altitude (m)	Rigidity (GV)
1	INVK	18NM64	−133.72N	63.35E	21	0.17
2	MGDN	18NM64	151.02N	66.12E	220	1.99

Their characteristics are presented in Table 1. The full solar cycle 23 (1998–2002) daily averaged pressure corrected data for the two stations have been downloaded from the IZMIRAN common website and employed in the current study. Daily solar-geophysical parameters, namely: IMF, SWS, and geomagnetic storm indices (kp, SSN, Dst and SI) data, are downloaded from the OMNI database.⁶

2. Methodology

Alhassan et al. (2022b) are the architects of the R-based FD location code employed in the present work. According to the authors, the R-code was created by Robert Gentleman and Ross Ihaka from the Department of Statistics, University of Auckland (R Foundation for Statistical Computing platform). They investigated FDs from three NM stations, including the two NMs of the current work. The parameters of these stations are displayed in Table 1. The two NM stations with different locations and rigidities, (see Table 1) are expected to behave differently with respect to the values of FD magnitude, number and timing, due to the great impact of CR diurnal anisotropy (Ugwu et al. 2024).

Alhassan et al. (2022b) employed a computer software algorithm in selecting the FDs which is adapted here in the current work without much variation. This current work accepts raw CR data as an input signal, thereby giving the opportunity to develop a large volume of CR data so easily. The depressions exhibited in the time series CR data are the indications of FDs. For the past eight decades, researchers have been employing the manual method of FD selection. This involves visual identification of the point of the maximum depression in the plotted graph, indicating the onset phase, and end time and finally calculating the amplitude of each FD (Alhassan et al. 2022b and references therein). Dumbovic et al. (2011) and Okike (2020c) suggested that this method is not only tedious but is also full of flaws in the results.

Moreover, although the semi-automated technique employed by Ramirez et al. (2013), Light et al. (2020) and the IZMIRAN team (see Belov et al. 2018a, 2018b; Abunina et al. 2020) produced more improvement when compared to the usual manual one, there are still several potential pitfalls that are yet to be addressed. This method lacks a sophisticated statistical approach and also adopts the manual ways of FD event single

analysis at a time. All these techniques mentioned above could hardly detect the small-amplitude FDs, thereby making it difficult for researchers to work with a large volume of FD catalogs.

The current work utilizes an automated method that overcomes the challenges imposed by the manual technique due to its sensitivity, and hence can detect all sorts of FD events with both large and small amplitude. The very large volume of the FD catalog presented in Tables 2 and 3 gave us ample opportunity to study, for the first time, the statistical significance of FD events and solar-geomagnetic characteristics. Besides the capability of the algorithm to detect the accurate FDs of magnitude $<0.01\%$, the code measurements of the event magnitude and timing are very apt and correct. It is also pleasing to note that this computer software algorithm takes care of the bias that may arise from the problematic CR diurnal anisotropy.

3. Analysis, Result and Discussion

This investigation was based on two separate FD catalogs. The FDs were distinctly selected from INVK and MGDN NM stations. The strength of the FDs are 224 and 229 respectively for INVK and MGDN (see Tables 2 and 3). A critical look at the tables shows that the data have both small and large FD events with amplitude FD range of -0.03% to -15.77% . It is interesting to note that the very highest FD event was detected by MGDN NM station on 2000 July 16th while the smallest one was detected by INVK station on 1999 August 25th. The corresponding solar-geomagnetic parameters attached to the highest FD amplitude are IMF = 21.8, SWS = 816, Kp = 43, SSN = 283, Dst = −172 and SI = 226.1, while those for the smallest FD amplitude are: IMF = 7.7, SWS = 538, Kp = 20, SSN = 196, Dst = −15 and SI = 212.9. Hence, the order of the columns in Tables 2 and 3 is interpreted as follows: S/N represents the serial number, and Date is the FD date of occurrence. Other columns represent the solar-geomagnetic parameters in the order of IMF, SWS, Kp, SSN, Dst and SI. Finally, the last column represents the FD magnitude.

Okike (2019a, 2019b, 2020a, 2020c), Okike & Umahi (2019a, 2019b), Menteso et al. (2023), Alhassan et al. (2022b) and Ugwu et al. (2024) show that the statistical arrangement of these data can be possible with the aid of an R-algorithm using the FD dates as the input signals. Furthermore, the simultaneous FDs at the two stations were selected using the

⁶ <https://omniweb.gsfc.nasa.gov/>

Table 2
INVK FDs and the Corresponding Solar-geomagnetic Characteristics

<i>S/N</i>	Date	IMF	SWS	kp	SSN	Dst	SI	FD _{INVK} (%)
1	1998-08-27	14.1	630	70	131	-129	137.8	-1.63
2	1998-09-25	18.0	713	60	149	-118	139.2	-0.57
3	1999-01-24	7.6	517	30	94	-38	156.8	-1.07
4	1999-02-18	17.1	599	60	155	-84	164.2	-2.95
5	1999-08-22	6.0	428	20	103	-27	176.7	-1.07
6	1999-08-25	7.7	538	20	196	-15	212.9	-0.03
7	1999-10-17	5.2	520	33	181	-33	176.8	-0.82
8	1999-10-22	14.2	608	57	124	-134	158.8	-0.95
9	1999-10-25	4.5	566	30	174	-45	177.2	-1.04
10	1999-11-14	5.9	440	27	206	-62	214.2	-0.56
11	1999-11-17	10.6	447	27	235	-30	216.3	-0.96
12	1999-11-20	8.1	443	20	215	-16	199.5	-1.60
13	1999-12-03	12.7	425	30	97	-7	147.5	-0.51
14	1999-12-13	11.4	489	33	141	-46	161.0	-4.85
15	1999-12-22	3.9	302	0	130	9	195.1	-0.87
16	1999-12-27	7.9	410	17	95	2	156.4	-2.25
17	2000-01-01	6.5	721	40	71	-30	125.6	-0.26
18	2000-01-04	5.8	577	27	95	-15	130.3	-0.39
19	2000-01-07	4.5	522	23	126	-21	144.8	-0.37
20	2000-01-20	9.3	376	23	140	-1	165.3	-0.23
21	2000-01-24	10.1	366	27	118	-40	136.3	-1.74
22	2000-01-28	8.0	718	43	89	-28	122.2	-0.37
23	2000-01-30	5.6	646	30	75	-18	128.7	-0.33
24	2000-02-07	5.4	629	43	191	-35	177.0	-0.22
25	2000-02-09	5.6	459	23	160	-18	170.8	-0.05
26	2000-02-13	6.2	558	30	158	-49	155.9	-3.90
27	2000-02-21	14.3	423	33	135	-1	148.7	-2.72
28	2000-03-01	7.6	480	33	217	-22	228.7	-3.61
29	2000-03-09	6.5	391	10	229	-14	203.0	-1.62
30	2000-03-13	3.5	366	10	190	-13	186.0	-2.49
31	2000-03-16	4.1	278	3	157	12	182.5	-2.33
32	2000-03-20	7.3	348	13	236	7	208.7	-1.90
33	2000-03-24	6.6	649	23	295	-3	217.7	-3.86
34	2000-03-28	7.6	358	10	266	1	200.3	-3.16
35	2000-03-30	5.2	446	27	233	-2	205.1	-3.48
36	2000-04-02	7.0	450	30	294	-40	219.3	-2.42
37	2000-04-04	9.2	384	33	250	-38	206.9	-2.63
38	2000-04-07	9.9	573	50	143	-162	175.4	-4.38
39	2000-04-14	6.6	318	3	174	-2	166.3	-1.31
40	2000-04-17	6.2	457	23	168	-23	159.2	-1.87
41	2000-04-20	5.9	503	27	185	-13	182.4	-2.56
42	2000-04-24	9.4	485	33	244	-25	208.1	-2.58
43	2000-04-29	6.4	403	27	153	-10	177.5	-1.65
44	2000-05-03	6.2	520	30	104	-12	139.6	-3.96
45	2000-05-08	9.8	360	10	87	19	139.6	-4.98
46	2000-05-15	9.1	414	27	280	7	249.9	-4.03
47	2000-05-24	13.7	636	60	183	-90	194.3	-8.22
48	2000-05-30	6.2	617	37	127	-29	150.5	-4.09
49	2000-06-02	3.4	424	17	119	-4	192.7	-3.87
50	2000-06-09	10.2	609	13	184	-34	174.1	-10.29
51	2000-06-20	6.2	379	17	239	5	189.7	-6.37
52	2000-06-24	9.0	551	27	179	-20	173.9	-6.05
53	2000-07-02	5.5	378	10	202	11	167.9	-3.90
54	2000-07-06	5.9	427	13	221	5	180.1	-3.90
55	2000-07-11	13.7	458	43	290	13	249.7	-5.81
56	2000-07-13	11.1	573	37	279	-4	239.6	-8.49
57	2000-07-16	21.8	816	43	283	-172	226.1	-15.27
58	2000-07-20	8.1	533	43	346	-67	261.1	-11.07

Table 2
(Continued)

S/N	Date	IMF	SWS	kp	SSN	Dst	SI	FD _{INVK} (%)
59	2000-07-29	8.8	460	37	162	-38	157.9	-8.66
60	2000-08-06	6.0	515	30	198	-32	170.8	-8.19
61	2000-08-12	25.0	599	67	235	-128	194.3	-9.83
62	2000-08-25	7.5	395	7	112	-2	136.0	-4.21
63	2000-08-29	6.8	596	43	191	-33	166.5	-4.32
64	2000-09-02	8.4	470	37	168	-32	156.7	-5.46
65	2000-09-08	7.4	448	33	121	-27	165.7	-6.72
66	2000-09-12	8.2	374	33	50	-30	134.2	-6.28
67	2000-09-20	5.4	508	23	176	-38	213.1	-7.67
68	2000-09-25	7.1	509	33	218	-32	226.8	-4.66
69	2000-09-29	5.5	378	17	169	-19	192.6	-4.49
70	2000-10-01	4.3	418	27	164	-37	201.9	-4.66
71	2000-10-04	14.0	402	50	214	-77	184.1	-5.01
72	2000-10-08	3.1	343	7	103	-20	148.6	-4.74
73	2000-10-14	12.0	411	47	148	-80	162.3	-4.90
74	2000-10-20	4.9	433	7	134	-2	159.3	-2.89
75	2000-10-29	13.7	381	40	161	-89	184.5	-7.90
76	2000-11-01	6.3	425	17	207	-16	201.2	-6.28
77	2000-11-03	4.4	342	7	209	2	195.5	-5.77
78	2000-11-07	20.2	512	43	181	-89	176.6	-9.00
79	2000-11-11	7.2	804	30	133	-35	146.6	-7.39
80	2000-11-14	4.3	500	13	124	-7	145.4	-6.84
81	2000-11-23	4.7	326	17	135	-10	200.1	-6.02
82	2000-11-29	9.2	512	47	182	-81	183.2	-11.30
83	2000-12-14	4.5	376	7	185	8	176.5	-4.31
84	2000-12-19	4.8	356	13	162	-7	192.2	-4.99
85	2000-12-23	9.2	306	33	140	-38	184.7	-5.53
86	2000-12-27	7.7	390	20	162	-1	181.4	-5.83
87	2000-12-30	6.9	350	7	152	-1	176.1	-4.52
88	2001-01-03	6.8	351	20	131	-8	164.2	-4.48
89	2001-01-05	6.0	403	10	164	-7	170.5	-4.14
90	2001-01-09	4.0	403	13	172	-13	160.8	-4.94
91	2001-01-18	5.8	354	10	90	5	146.6	-5.11
92	2001-01-24	5.3	434	33	176	-35	167.2	-5.92
93	2001-01-29	9.2	409	27	134	-16	160.5	-4.94
94	2001-01-31	7.6	409	30	128	-22	148.8	-4.94
95	2001-02-06	11.0	415	27	166	-1	165.3	-2.25
96	2001-02-11	5.3	398	17	151	0	147.4	-2.25
97	2001-02-14	5.8	513	33	103	-34	134.6	-2.77
98	2001-02-20	6.9	315	17	115	5	142.3	-1.63
99	2001-02-27	7.2	370	23	75	-15	128.1	-0.75
100	2001-03-04	6.9	448	33	134	-17	138.7	-1.34
101	2001-03-20	18.0	401	57	117	-117	152.1	-0.78
102	2001-04-01	7.5	746	43	279	-137	257.2	-6.19
103	2001-04-05	7.5	617	33	200	-31	207.8	-6.98
104	2001-04-08	10.8	612	47	173	-33	169.7	-8.13
105	2001-04-12	15.1	659	40	155	-131	149.8	-13.93
106	2001-04-16	4.0	453	20	87	-24	124.3	-6.02
107	2001-04-19	7.9	436	17	93	-41	145.8	-4.73
108	2001-04-22	11.8	360	43	164	-55	194.6	-3.42
109	2001-04-26	6.8	438	17	179	-6	198.7	-2.24
110	2001-04-30	4.9	458	3	168	-13	190.7	-6.95
111	2001-05-04	7.7	377	17	194	4	178.6	-3.70
112	2001-05-08	9.2	410	27	81	-20	131.1	-2.18
113	2001-05-14	6.8	543	20	150	-25	141.2	-2.28
114	2001-05-25	6.6	557	17	165	5	166.1	-3.68
115	2001-05-28	9.1	505	33	151	-8	146.9	-4.80
116	2001-06-03	5.3	508	17	150	-7	149.5	-2.81

Table 2
(Continued)

S/N	Date	IMF	SWS	kp	SSN	Dst	SI	FD _{INVK} (%)
117	2001-06-10	4.9	592	30	241	-20	168.0	-2.63
118	2001-06-12	5.2	433	10	259	-2	171.6	-2.46
119	2001-06-18	10.6	353	43	232	-34	228.5	-2.42
120	2001-06-20	5.9	700	23	206	-20	205.0	-2.92
121	2001-06-26	6.2	464	27	173	-2	173.5	-2.22
122	2001-06-30	5.7	371	17	98	4	141.2	-1.73
123	2001-07-04	6.9	381	17	107	8	131.3	-2.81
124	2001-07-08	6.2	440	27	81	13	130.5	-2.44
125	2001-07-17	8.9	592	30	185	-13	150.4	-0.95
126	2001-07-20	4.9	479	10	177	1	147.2	-1.27
127	2001-07-23	6.3	371	23	152	-1	147.8	-2.07
128	2001-07-25	7.4	545	33	119	-12	137.5	-2.27
129	2001-07-30	6.8	312	17	86	10	118.0	-2.02
130	2001-08-03	7.2	405	27	141	0	135.5	-3.00
131	2001-08-07	5.1	426	17	179	-8	171.0	-2.58
132	2001-08-13	11.9	403	33	138	-7	155.5	-2.35
133	2001-08-18	11.8	518	27	161	-43	159.9	-4.03
134	2001-08-23	4.5	491	17	181	-14	173.4	-3.42
135	2001-08-28	7.5	520	23	184	-11	203.1	-7.25
136	2001-09-07	6.1	369	7	262	6	229.5	-2.98
137	2001-09-14	10.1	414	20	234	1	239.3	-1.54
138	2001-09-19	6.5	422	20	226	-5	200.6	-1.24
139	2001-09-26	10.7	549	33	277	-72	284.0	-7.37
140	2001-09-30	11.8	520	37	261	-44	236.3	-7.71
141	2001-10-09	8.3	445	30	122	-37	175.9	-4.31
142	2001-10-12	11.4	501	40	196	-51	178.5	-7.09
143	2001-10-22	15.1	578	60	209	-150	230.4	-6.19
144	2001-10-28	11.2	450	47	215	-99	224.2	-5.04
145	2001-11-06	27.8	599	67	232	-202	233.2	-6.28
146	2001-11-14	3.2	319	7	196	-8	212.6	-2.02
147	2001-11-22	7.5	418	23	144	-17	185.3	-2.83
148	2001-11-25	11.5	650	20	121	-106	165.6	-7.14
149	2001-12-01	8.0	348	17	215	0	215.1	-0.89
150	2001-12-06	6.4	432	27	229	-20	239.5	-3.22
151	2001-12-17	8.8	471	30	192	-30	199.0	-2.72
152	2001-12-21	8.4	386	27	194	-29	226.7	-1.51
153	2001-12-29	15.4	397	27	221	34	255.7	-2.30
154	2002-01-03	5.9	342	7	220	-16	213.0	-7.26
155	2002-01-12	6.1	563	30	209	-31	225.7	-6.47
156	2002-01-19	8.8	372	27	160	4	206.9	-3.23
157	2002-01-21	7.9	452	27	191	-10	217.5	-3.39
158	2002-01-30	5.9	338	7	193	-1	248.8	-5.41
159	2002-02-01	11.2	347	27	179	-17	238.5	-5.32
160	2002-02-12	6.4	515	20	174	-18	203.1	-1.23
161	2002-02-14	5.7	419	7	146	-11	191.3	-1.18
162	2002-02-18	8.1	372	23	127	-8	188.4	-1.32
163	2002-02-23	6.4	362	10	149	-6	184.2	-2.35
164	2002-02-26	6.7	333	20	195	-15	203.5	-2.02
165	2002-02-28	9.5	372	37	154	-11	200.4	-1.96
166	2002-03-02	9.9	386	13	117	-14	187.6	-1.83
167	2002-03-06	5.8	641	33	167	-20	175.0	-1.35
168	2002-03-12	7.9	453	27	135	-3	176.2	-1.68
169	2002-03-16	6.3	310	7	141	13	182.7	-1.54
170	2002-03-25	15.4	433	17	163	-33	169.1	-6.39
171	2002-03-30	11.6	521	33	166	-5	188.2	-4.15
172	2002-04-06	6.8	358	10	211	4	206.7	-1.90
173	2002-04-12	8.7	432	30	251	-1	213.0	-2.16
174	2002-04-15	8.8	357	13	214	-8	204.7	-2.11

Table 2
(Continued)

<i>S/N</i>	Date	IMF	SWS	kp	SSN	Dst	SI	FD _{INVK} (%)
175	2002-04-18	12.8	485	53	164	-104	189.8	-5.52
176	2002-04-20	10.1	563	53	158	-106	179.0	-4.98
177	2002-04-24	7.1	488	17	232	-30	178.9	-4.90
178	2002-05-08	8.5	366	20	220	-19	190.2	-1.12
179	2002-05-13	6.0	457	17	161	-21	175.6	-2.33
180	2002-05-16	6.2	371	17	130	-27	162.0	-2.81
181	2002-05-20	9.0	453	23	166	-12	175.4	-4.31
182	2002-05-23	17.0	606	47	211	-38	184.8	-6.16
183	2002-05-27	9.6	593	33	191	-39	191.6	-4.24
184	2002-06-03	7.9	437	23	194	-21	175.4	-2.95
185	2002-06-11	7.7	386	20	99	-19	152.4	-3.14
186	2002-06-19	10.6	468	27	115	-2	150.5	-2.92
187	2002-06-24	7.1	474	13	108	-3	155.3	-1.87
188	2002-06-29	5.1	344	13	96	6	147.5	-0.89
189	2002-07-03	3.8	361	10	129	1	152.4	-1.69
190	2002-07-09	7.4	440	27	103	-8	140.9	-3.05
191	2002-07-11	5.1	386	13	99	5	141.0	-2.77
192	2002-07-18	5.7	441	13	149	-8	186.6	-4.32
193	2002-07-20	7.4	789	30	124	-20	190.7	-6.16
194	2002-07-25	8.0	461	27	215	-2	224.5	-5.32
195	2002-07-30	7.5	422	17	281	5	234.1	-8.12
196	2002-08-02	12.1	489	43	199	-59	185.7	-9.05
197	2002-08-20	7.2	479	33	211	-48	232.8	-7.03
198	2002-08-23	8.8	402	17	186	-18	229.5	-6.67
199	2002-08-29	6.6	464	20	124	-16	172.6	-7.40
200	2002-09-04	12.6	422	47	247	-72	174.2	-5.78
201	2002-09-08	11.7	479	33	213	-101	194.4	-6.16
202	2002-09-10	8.6	417	37	202	-65	223.5	-5.32
203	2002-09-19	6.6	613	27	192	-24	166.7	-4.09
204	2002-09-24	9.3	376	7	177	-8	158.9	-5.01
205	2002-09-28	10.7	307	13	137	3	149.1	-4.59
206	2002-10-01	19.5	388	50	90	-100	140.1	-4.24
207	2002-10-03	11.5	464	47	104	-78	146.1	-4.37
208	2002-10-13	6.5	301	13	185	-30	178.3	-1.77
209	2002-10-21	5.8	571	20	144	-18	180.8	-6.30
210	2002-10-25	6.8	689	43	119	-68	170.9	-5.11
211	2002-10-27	7.6	582	37	130	-51	155.2	-5.02
212	2002-10-30	8.9	478	30	186	-34	165.3	-3.82
213	2002-11-03	9.7	478	43	190	-65	166.5	-4.54
214	2002-11-05	8.4	545	37	188	-46	180.0	-5.44
215	2002-11-12	12.4	569	30	154	-15	174.6	-6.28
216	2002-11-18	9.3	378	23	128	-37	174.8	-7.87
217	2002-11-27	9.8	538	33	105	-50	138.8	-4.82
218	2002-12-01	6.4	506	33	121	-32	145.5	-3.54
219	2002-12-08	7.1	599	27	164	-28	149.8	-4.68
220	2002-12-15	8.9	502	20	199	-28	196.6	-5.16
221	2002-12-18	12.5	376	7	224	15	190.6	-5.24
222	2002-12-20	6.1	528	33	208	-47	190.3	-5.41
223	2002-12-23	10.1	517	37	126	-42	153.7	-6.64
224	2002-12-25	7.2	491	27	59	-32	127.6	-6.22

coincident algorithm. A simultaneous FD refers to an FD event that is observed at the same time by two or more NM stations. In the current work, the timing is with reference to the FD minimum point. We note that analysis of FDs with reference to

the event's time of minimum reduction (see also Okike & Nwuzo 2020) is more precise than the traditional event timing based on onset point or main phase (see Lockwood 1990; Tinsley & Deen 1991; Belov 2008; Oh et al. 2008, 2009;

Table 3
MGDN FDs and the Corresponding Solar-geomagnetic Characteristics

<i>S/N</i>	Date	IMF	SWS	kp	SSN	Dst	SI	FD _{MGDN} (%)
1	1998-08-27	14.1	630	70	131	-129	137.8	-1.53
2	1998-09-25	18.0	713	60	149	-118	139.2	-0.16
3	1999-02-18	17.1	599	60	155	-84	164.2	-0.29
4	1999-08-23	10.3	417	40	115	-53	191.7	-0.11
5	1999-10-12	7.3	578	50	210	-48	182.9	-0.31
6	1999-10-16	5.3	622	40	176	-33	187.8	-1.43
7	1999-10-22	14.2	608	57	124	-134	158.8	-1.82
8	1999-10-25	4.5	566	30	174	-45	177.2	-1.36
9	1999-10-28	8.0	395	33	195	-45	181.5	-0.41
10	1999-10-31	9.2	400	23	187	-9	158.1	-0.71
11	1999-11-13	8.7	445	47	232	-67	219.1	-0.93
12	1999-11-18	6.0	541	33	225	-31	212.9	-0.99
13	1999-11-23	8.6	444	33	155	-24	180.9	-1.82
14	1999-12-01	9.5	340	13	142	5	160.4	-1.27
15	1999-12-03	12.7	425	30	97	-7	147.5	-1.21
16	1999-12-13	11.4	489	33	141	-46	161.0	-4.89
17	1999-12-21	3.5	349	7	128	8	210.1	-0.40
18	1999-12-27	7.9	410	17	95	2	156.4	-2.23
19	2000-01-02	5.1	679	30	75	-19	128.5	-0.31
20	2000-01-05	6.0	521	33	108	-25	132.0	-0.34
21	2000-01-07	4.5	522	23	126	-21	144.8	-0.64
22	2000-01-13	5.1	537	23	226	-23	195.4	-0.27
23	2000-01-24	10.1	366	27	118	-40	136.3	-0.64
24	2000-02-01	4.6	530	20	104	-6	134.1	-0.27
25	2000-02-08	4.4	570	30	188	-24	169.0	-0.64
26	2000-02-12	14.7	553	50	166	-76	159.1	-4.00
27	2000-02-22	11.2	367	17	147	2	168.6	-2.21
28	2000-03-01	7.6	480	33	217	-22	228.7	-2.94
29	2000-03-13	3.5	366	10	190	-13	186.0	-2.78
30	2000-03-20	7.3	348	13	236	7	208.7	-1.99
31	2000-03-25	4.8	613	20	291	-9	204.1	-4.03
32	2000-03-28	7.6	358	10	266	1	200.3	-3.43
33	2000-03-30	5.2	446	27	233	-2	205.1	-3.70
34	2000-04-01	8.6	380	27	285	-18	222.7	-2.95
35	2000-04-04	9.2	384	33	250	-38	206.9	-3.34
36	2000-04-07	9.9	573	50	143	-162	175.4	-5.19
37	2000-04-17	6.2	457	23	168	-23	159.2	-2.30
38	2000-04-20	5.9	503	27	185	-13	182.4	-2.81
39	2000-04-24	9.4	485	33	244	-25	208.1	-3.37
40	2000-05-03	6.2	520	30	104	-12	139.6	-4.47
41	2000-05-09	5.9	343	20	135	0	152.5	-5.42
42	2000-05-12	8.7	315	27	181	-15	194.4	-3.28
43	2000-05-15	9.1	414	27	280	7	249.9	-4.77
44	2000-05-17	8.9	509	33	232	-51	268.1	-4.22
45	2000-05-24	13.7	636	60	183	-90	194.3	-8.77
46	2000-05-30	6.2	617	37	127	-29	150.5	-4.58
47	2000-06-09	10.2	609	13	184	-34	174.1	-10.35
48	2000-06-20	6.2	379	17	239	5	189.7	-6.56
49	2000-06-24	9.0	551	27	179	-20	173.9	-6.45
50	2000-06-26	11.5	512	43	194	-36	183.4	-6.14
51	2000-07-04	8.1	401	20	164	13	163.7	-4.12
52	2000-07-06	5.9	427	13	221	5	180.1	-4.08
53	2000-07-11	13.7	458	43	290	13	249.7	-6.45
54	2000-07-16	21.8	816	43	283	-172	226.1	-15.77
55	2000-07-20	8.1	533	43	346	-67	261.1	-11.15
56	2000-07-29	8.8	460	37	162	-38	157.9	-8.74
57	2000-08-06	6.0	515	30	198	-32	170.8	-8.30
58	2000-08-12	25.0	599	67	235	-128	194.3	-9.89

Table 3
(Continued)

S/N	Date	IMF	SWS	kp	SSN	Dst	SI	FD _{MGDN} (%)
59	2000-08-15	5.5	503	20	253	-20	198.9	-8.28
60	2000-08-25	7.5	395	7	112	-2	136.0	-4.68
61	2000-08-29	6.8	596	43	191	-33	166.5	-4.89
62	2000-09-03	6.8	413	17	182	-14	156.7	-4.39
63	2000-09-07	9.3	443	30	156	-21	175.8	-5.08
64	2000-09-12	8.2	374	33	50	-30	134.2	-5.38
65	2000-09-15	6.7	363	20	109	4	161.1	-5.88
66	2000-09-18	19.2	744	53	159	-103	205.7	-9.72
67	2000-09-26	5.9	566	37	229	-41	224.7	-3.97
68	2000-09-29	5.5	378	17	169	-19	192.6	-3.97
69	2000-10-01	4.3	418	27	164	-37	201.9	-4.06
70	2000-10-05	13.4	486	67	183	-138	173.7	-4.61
71	2000-10-08	3.1	343	7	103	-20	148.6	-4.27
72	2000-10-13	13.9	441	37	173	-34	167.2	-3.20
73	2000-10-18	5.9	459	23	135	-11	149.9	-2.57
74	2000-10-20	4.9	433	7	134	-2	159.3	-2.43
75	2000-10-26	4.9	373	20	104	-21	168.9	-1.78
76	2000-10-29	13.7	381	40	161	-89	184.5	-6.78
77	2000-11-01	6.3	425	17	207	-16	201.2	-5.51
78	2000-11-04	12.0	436	40	192	-22	191.4	-5.12
79	2000-11-07	20.2	512	43	181	-89	176.6	-8.07
80	2000-11-11	7.2	804	30	133	-35	146.6	-6.43
81	2000-11-14	4.3	500	13	124	-7	145.4	-5.32
82	2000-11-29	9.2	512	47	182	-81	183.2	-10.72
83	2000-12-03	10.0	430	23	162	-9	158.9	-6.78
84	2000-12-23	9.2	306	33	140	-38	184.7	-4.23
85	2000-12-26	6.8	418	13	166	-1	182.6	-4.55
86	2000-12-30	6.9	350	7	152	-1	176.1	-3.13
87	2001-01-02	5.8	286	7	140	12	170.2	-3.15
88	2001-01-05	6.0	403	10	164	-7	170.5	-2.91
89	2001-01-09	4.0	403	13	172	-13	160.8	-3.09
90	2001-01-15	4.8	352	17	137	-12	163.8	-2.81
91	2001-01-18	5.8	354	10	90	5	146.6	-3.32
92	2001-01-25	3.5	387	13	158	-27	163.4	-4.20
93	2001-02-01	5.2	410	20	118	-25	156.2	-3.10
94	2001-02-10	5.1	410	13	158	2	156.5	-1.31
95	2001-02-14	5.8	513	33	103	-34	134.6	-1.59
96	2001-02-20	6.9	315	17	115	5	142.3	-1.05
97	2001-03-05	10.7	488	30	152	-34	153.4	-0.10
98	2001-03-20	18.0	401	57	117	-117	152.1	-0.23
99	2001-03-28	8.9	608	43	343	-53	272.6	-2.81
100	2001-04-01	7.5	746	43	279	-137	257.2	-3.69
101	2001-04-05	7.5	617	33	200	-31	207.8	-4.80
102	2001-04-09	8.6	622	33	165	-53	165.4	-6.49
103	2001-04-12	15.1	659	40	155	-131	149.8	-12.63
104	2001-04-16	4.0	453	20	87	-24	124.3	-5.87
105	2001-04-19	7.9	436	17	93	-41	145.8	-4.76
106	2001-04-22	11.8	360	43	164	-55	194.6	-3.26
107	2001-04-25	8.6	429	17	179	-6	196.3	-1.63
108	2001-04-29	7.6	596	23	170	-18	194.5	-6.30
109	2001-05-04	7.7	377	17	194	4	178.6	-3.76
110	2001-05-08	9.2	410	27	81	-20	131.1	-2.44
111	2001-05-15	6.0	462	23	141	-19	145.2	-2.62
112	2001-05-20	5.4	384	13	121	0	144.9	-1.78
113	2001-05-25	6.6	557	17	165	5	166.1	-3.66
114	2001-05-28	9.1	505	33	151	-8	146.9	-5.24
115	2001-06-02	11.4	499	33	150	-14	137.8	-2.84
116	2001-06-05	3.6	405	13	161	1	158.0	-1.87

Table 3
(Continued)

S/N	Date	IMF	SWS	kp	SSN	Dst	SI	FD _{MGDN} (%)
117	2001-06-07	8.1	393	20	195	0	169.8	-2.09
118	2001-06-10	4.9	592	30	241	-20	168.0	-2.40
119	2001-06-12	5.2	433	10	259	-2	171.6	-2.41
120	2001-06-18	10.6	353	43	232	-34	228.5	-1.91
121	2001-06-20	5.9	700	23	206	-20	205.0	-2.36
122	2001-06-26	6.2	464	27	173	-2	173.5	-2.06
123	2001-06-30	5.7	371	17	98	4	141.2	-1.67
124	2001-07-05	7.0	423	27	93	5	123.6	-2.63
125	2001-07-08	6.2	440	27	81	13	130.5	-1.95
126	2001-07-11	7.8	344	17	104	-17	136.3	-1.50
127	2001-07-16	11.1	435	27	170	-1	154.7	-0.34
128	2001-07-20	4.9	479	10	177	1	147.2	-1.30
129	2001-07-24	7.7	420	27	135	8	136.7	-2.01
130	2001-07-27	3.7	469	17	90	-4	125.1	-2.07
131	2001-07-30	6.8	312	17	86	10	118.0	-1.64
132	2001-08-02	5.6	414	13	123	8	124.3	-2.64
133	2001-08-06	7.0	440	30	182	-18	168.3	-2.51
134	2001-08-09	5.4	367	17	158	4	167.8	-1.88
135	2001-08-13	11.9	403	33	138	-7	155.5	-2.27
136	2001-08-18	11.8	518	27	161	-43	159.9	-4.69
137	2001-08-23	4.5	491	17	181	-14	173.4	-3.62
138	2001-08-29	4.2	459	13	146	-7	200.9	-7.49
139	2001-09-07	6.1	369	7	262	6	229.5	-2.99
140	2001-09-14	10.1	414	20	234	1	239.3	-1.85
141	2001-09-16	4.4	508	20	191	-11	209.3	-1.75
142	2001-09-19	6.5	422	20	226	-5	200.6	-1.38
143	2001-09-21	5.0	334	10	273	10	240.5	-1.47
144	2001-09-26	10.7	549	33	277	-72	284.0	-7.08
145	2001-09-30	11.8	520	37	261	-44	236.3	-7.55
146	2001-10-02	7.5	497	50	223	-87	201.1	-8.61
147	2001-10-09	8.3	445	30	122	-37	175.9	-4.82
148	2001-10-12	11.4	501	40	196	-51	178.5	-6.49
149	2001-10-22	15.1	578	60	209	-150	230.4	-5.12
150	2001-10-28	11.2	450	47	215	-99	224.2	-4.79
151	2001-11-03	4.9	326	3	166	-18	212.5	-0.79
152	2001-11-07	6.5	635	30	204	-110	263.9	-6.09
153	2001-11-14	3.2	319	7	196	-8	212.6	-1.73
154	2001-11-22	7.5	418	23	144	-17	185.3	-2.95
155	2001-11-25	11.5	650	20	121	-106	165.6	-8.72
156	2001-12-06	6.4	432	27	229	-20	239.5	-3.53
157	2001-12-17	8.8	471	30	192	-30	199.0	-3.00
158	2001-12-22	7.7	379	20	218	-40	234.9	-0.99
159	2001-12-25	7.1	450	20	231	-24	250.3	-0.39
160	2002-01-01	7.4	439	20	220	-33	224.5	-6.55
161	2002-01-03	5.9	342	7	220	-16	213.0	-6.67
162	2002-01-12	6.1	563	30	209	-31	225.7	-6.06
163	2002-01-21	7.9	452	27	191	-10	217.5	-3.41
164	2002-01-23	7.0	379	20	227	-10	219.4	-3.34
165	2002-01-29	6.7	367	10	188	-8	253.2	-4.71
166	2002-02-01	11.2	347	27	179	-17	238.5	-4.98
167	2002-02-12	6.4	515	20	174	-18	203.1	-0.73
168	2002-02-19	7.7	401	13	124	-17	185.1	-0.84
169	2002-02-23	6.4	362	10	149	-6	184.2	-1.91
170	2002-02-25	6.6	329	17	192	-3	206.4	-1.78
171	2002-02-28	9.5	372	37	154	-11	200.4	-1.85
172	2002-03-02	9.9	386	13	117	-14	187.6	-1.35
173	2002-03-05	9.5	646	33	158	-22	169.4	-0.64
174	2002-03-07	4.4	575	20	139	-11	177.0	-0.21

Table 3
(Continued)

S/N	Date	IMF	SWS	kp	SSN	Dst	SI	FD _{MGDN} (%)
175	2002-03-12	7.9	453	27	135	-3	176.2	-1.63
176	2002-03-16	6.3	310	7	141	13	182.7	-1.45
177	2002-03-23	7.6	432	23	158	-8	169.4	-5.40
178	2002-03-25	15.4	433	17	163	-33	169.1	-5.42
179	2002-03-30	11.6	521	33	166	-5	188.2	-3.86
180	2002-04-12	8.7	432	30	251	-1	213.0	-2.90
181	2002-04-15	8.8	357	13	214	-8	204.7	-2.30
182	2002-04-18	12.8	485	53	164	-104	189.8	-5.39
183	2002-04-20	10.1	563	53	158	-106	179.0	-5.74
184	2002-04-22	5.6	425	23	144	-40	171.7	-4.98
185	2002-04-24	7.1	488	17	232	-30	178.9	-6.54
186	2002-04-30	6.9	486	17	132	-3	155.6	-2.69
187	2002-05-03	5.5	428	13	231	2	182.0	-1.22
188	2002-05-12	5.3	488	27	202	-59	187.1	-3.46
189	2002-05-15	6.3	411	27	115	-43	162.7	-3.74
190	2002-05-21	5.8	401	20	188	-16	190.4	-5.12
191	2002-05-23	17.0	606	47	211	-38	184.8	-6.70
192	2002-05-27	9.6	593	33	191	-39	191.6	-4.43
193	2002-06-03	7.9	437	23	194	-21	175.4	-2.64
194	2002-06-07	5.0	308	13	197	-3	163.1	-2.42
195	2002-06-11	7.7	386	20	99	-19	152.4	-3.57
196	2002-06-19	10.6	468	27	115	-2	150.5	-2.73
197	2002-06-24	7.1	474	13	108	-3	155.3	-1.67
198	2002-06-28	4.7	339	3	88	13	141.9	-0.93
199	2002-07-03	3.8	361	10	129	1	152.4	-1.52
200	2002-07-09	7.4	440	27	103	-8	140.9	-2.97
201	2002-07-11	5.1	386	13	99	5	141.0	-3.06
202	2002-07-18	5.7	441	13	149	-8	186.6	-3.91
203	2002-07-20	7.4	789	30	124	-20	190.7	-5.61
204	2002-07-23	4.8	472	30	196	-12	204.6	-4.87
205	2002-07-30	7.5	422	17	281	5	234.1	-8.19
206	2002-08-02	12.1	489	43	199	-59	185.7	-8.63
207	2002-08-20	7.2	479	33	211	-48	232.8	-6.91
208	2002-08-23	8.8	402	17	186	-18	229.5	-6.06
209	2002-08-29	6.6	464	20	124	-16	172.6	-7.17
210	2002-09-02	7.1	350	17	233	-13	176.9	-4.91
211	2002-09-08	11.7	479	33	213	-101	194.4	-5.69
212	2002-09-11	9.6	458	37	187	-61	219.0	-4.81
213	2002-09-23	8.3	404	3	192	-12	154.8	-4.63
214	2002-09-28	10.7	307	13	137	3	149.1	-3.76
215	2002-10-01	19.5	388	50	90	-100	140.1	-3.46
216	2002-10-03	11.5	464	47	104	-78	146.1	-4.06
217	2002-10-08	7.4	473	40	157	-79	165.1	-1.41
218	2002-10-13	6.5	301	13	185	-30	178.3	-1.40
219	2002-10-21	5.8	571	20	144	-18	180.8	-5.29
220	2002-11-03	9.7	478	43	190	-65	166.5	-5.03
221	2002-11-05	8.4	545	37	188	-46	180.0	-5.81
222	2002-11-12	12.4	569	30	154	-15	174.6	-7.15
223	2002-11-18	9.3	378	23	128	-37	174.8	-8.08
224	2002-11-25	7.0	460	30	86	-46	133.2	-3.70
225	2002-11-28	6.9	497	27	108	-34	136.0	-4.44
226	2002-12-08	7.1	599	27	164	-28	149.8	-4.40
227	2002-12-15	8.9	502	20	199	-28	196.6	-4.53
228	2002-12-20	6.1	528	33	208	-47	190.3	-5.44
229	2002-12-23	10.1	517	37	126	-42	153.7	-6.40

Table 4
Simultaneous FDs in INVK and MGDN and the Corresponding Solar-geomagnetic Characteristics

S/N	Date	FD _{INVK} (%)	FD _{MGDN} (%)	IMF	SWS	Kp	SSN	Dst	SI
1	1998-08-27	-1.63	-1.53	14.1	630	70	131	-129	137.8
2	1998-09-25	-0.57	-0.16	18.0	713	60	149	-118	139.2
3	1999-02-18	-2.95	-0.29	17.1	599	60	155	-84	164.2
4	1999-10-22	-0.95	-1.82	14.2	608	57	124	-134	158.8
5	1999-10-25	-1.04	-1.36	4.5	566	30	174	-45	177.2
6	1999-12-03	-0.51	-1.21	12.7	425	30	97	-7	147.5
7	1999-12-13	-4.85	-4.89	11.4	489	33	141	-46	161.0
8	1999-12-27	-2.25	-2.23	7.9	410	17	95	2	156.4
9	2000-01-07	-0.37	-0.64	4.5	522	23	126	-21	144.8
10	2000-01-24	-1.74	-0.64	10.1	366	27	118	-40	136.3
11	2000-03-01	-3.61	-2.94	7.6	480	33	217	-22	228.7
12	2000-03-13	-2.49	-2.78	3.5	366	10	190	-13	186.0
13	2000-03-20	-1.90	-1.99	7.3	348	13	236	7	208.7
14	2000-03-28	-3.16	-3.43	7.6	358	10	266	1	200.3
15	2000-03-30	-3.48	-3.70	5.2	446	27	233	-2	205.1
16	2000-04-04	-2.63	-3.34	9.2	384	33	250	-38	206.9
17	2000-04-07	-4.38	-5.19	9.9	573	50	143	-162	175.4
18	2000-04-17	-1.87	-2.30	6.2	457	23	168	-23	159.2
19	2000-04-20	-2.56	-2.81	5.9	503	27	185	-13	182.4
20	2000-04-24	-2.58	-3.37	9.4	485	33	244	-25	208.1
21	2000-05-03	-3.96	-4.47	6.2	520	30	104	-12	139.6
22	2000-05-15	-4.03	-4.77	9.1	414	27	280	7	249.9
23	2000-05-24	-8.22	-8.77	13.7	636	60	183	-90	194.3
24	2000-05-30	-4.09	-4.58	6.2	617	37	127	-29	150.5
25	2000-06-09	-10.29	-10.35	10.2	609	13	184	-34	174.1
26	2000-06-20	-6.37	-6.56	6.2	379	17	239	5	189.7
27	2000-06-24	-6.05	-6.45	9.0	551	27	179	-20	173.9
28	2000-07-06	-3.90	-4.08	5.9	427	13	221	5	180.1
29	2000-07-11	-5.81	-6.45	13.7	458	43	290	13	249.7
30	2000-07-16	-15.27	-15.77	21.8	816	43	283	-172	226.1
31	2000-07-20	-11.07	-11.15	8.1	533	43	346	-67	261.1
32	2000-07-29	-8.66	-8.74	8.8	460	37	162	-38	157.9
33	2000-08-06	-8.19	-8.30	6.0	515	30	198	-32	170.8
34	2000-08-12	-9.83	-9.89	25.0	599	67	235	-128	194.3
35	2000-08-25	-4.21	-4.68	7.5	395	7	112	-2	136.0
36	2000-08-29	-4.32	-4.89	6.8	596	43	191	-33	166.5
37	2000-09-12	-6.28	-5.38	8.2	374	33	50	-30	134.2
38	2000-09-29	-4.49	-3.97	5.5	378	17	169	-19	192.6
39	2000-10-01	-4.66	-4.06	4.3	418	27	164	-37	201.9
40	2000-10-08	-4.74	-4.27	3.1	343	7	103	-20	148.6
41	2000-10-20	-2.89	-2.43	4.9	433	7	134	-2	159.3
42	2000-10-29	-7.90	-6.78	13.7	381	40	161	-89	184.5
43	2000-11-01	-6.28	-5.51	6.3	425	17	207	-16	201.2
44	2000-11-07	-9.00	-8.07	20.2	512	43	181	-89	176.6
45	2000-11-11	-7.39	-6.43	7.2	804	30	133	-35	146.6
46	2000-11-14	-6.84	-5.32	4.3	500	13	124	-7	145.4
47	2000-11-29	-11.30	-10.72	9.2	512	47	182	-81	183.2
48	2000-12-23	-5.53	-4.23	9.2	306	33	140	-38	184.7
49	2000-12-30	-4.52	-3.13	6.9	350	7	152	-1	176.1
50	2001-01-05	-4.14	-2.91	6.0	403	10	164	-7	170.5
51	2001-01-09	-4.94	-3.09	4.0	403	13	172	-13	160.8
52	2001-01-18	-5.11	-3.32	5.8	354	10	90	5	146.6
53	2001-02-14	-2.77	-1.59	5.8	513	33	103	-34	134.6
54	2001-02-20	-1.63	-1.05	6.9	315	17	115	5	142.3
55	2001-03-20	-0.78	-0.23	18.0	401	57	117	-117	152.1
56	2001-04-01	-6.19	-3.69	7.5	746	43	279	-137	257.2
57	2001-04-05	-6.98	-4.80	7.5	617	33	200	-31	207.8
58	2001-04-12	-13.93	-12.63	15.1	659	40	155	-131	149.8

Table 4
(Continued)

S/N	Date	FD _{INVK} (%)	FD _{MGDN} (%)	IMF	SWS	Kp	SSN	Dst	SI
59	2001-04-16	-6.02	-5.87	4.0	453	20	87	-24	124.3
60	2001-04-19	-4.73	-4.76	7.9	436	17	93	-41	145.8
61	2001-04-22	-3.42	-3.26	11.8	360	43	164	-55	194.6
62	2001-05-04	-3.70	-3.76	7.7	377	17	194	4	178.6
63	2001-05-08	-2.18	-2.44	9.2	410	27	81	-20	131.1
64	2001-05-25	-3.68	-3.66	6.6	557	17	165	5	166.1
65	2001-05-28	-4.80	-5.24	9.1	505	33	151	-8	146.9
66	2001-06-10	-2.63	-2.40	4.9	592	30	241	-20	168.0
67	2001-06-12	-2.46	-2.41	5.2	433	10	259	-2	171.6
68	2001-06-18	-2.42	-1.91	10.6	353	43	232	-34	228.5
69	2001-06-20	-2.92	-2.36	5.9	700	23	206	-20	205.0
70	2001-06-26	-2.22	-2.06	6.2	464	27	173	-2	173.5
71	2001-06-30	-1.73	-1.67	5.7	371	17	98	4	141.2
72	2001-07-08	-2.44	-1.95	6.2	440	27	81	13	130.5
73	2001-07-20	-1.27	-1.30	4.9	479	10	177	1	147.2
74	2001-07-30	-2.02	-1.64	6.8	312	17	86	10	118.0
75	2001-08-13	-2.35	-2.27	11.9	403	33	138	-7	155.5
76	2001-08-18	-4.03	-4.69	11.8	518	27	161	-43	159.9
77	2001-08-23	-3.42	-3.62	4.5	491	17	181	-14	173.4
78	2001-09-07	-2.98	-2.99	6.1	369	7	262	6	229.5
79	2001-09-14	-1.54	-1.85	10.1	414	20	234	1	239.3
80	2001-09-19	-1.24	-1.38	6.5	422	20	226	-5	200.6
81	2001-09-26	-7.37	-7.08	10.7	549	33	277	-72	284.0
82	2001-09-30	-7.71	-7.55	11.8	520	37	261	-44	236.3
83	2001-10-09	-4.31	-4.82	8.3	445	30	122	-37	175.9
84	2001-10-12	-7.09	-6.49	11.4	501	40	196	-51	178.5
85	2001-10-22	-6.19	-5.12	15.1	578	60	209	-150	230.4
86	2001-10-28	-5.04	-4.79	11.2	450	47	215	-99	224.2
87	2001-11-14	-2.02	-1.73	3.2	319	7	196	-8	212.6
88	2001-11-22	-2.83	-2.95	7.5	418	23	144	-17	185.3
89	2001-11-25	-7.14	-8.72	11.5	650	20	121	-106	165.6
90	2001-12-06	-3.22	-3.53	6.4	432	27	229	-20	239.5
91	2001-12-17	-2.72	-3.00	8.8	471	30	192	-30	199.0
92	2002-01-03	-7.26	-6.67	5.9	342	7	220	-16	213.0
93	2002-01-12	-6.47	-6.06	6.1	563	30	209	-31	225.7
94	2002-01-21	-3.39	-3.41	7.9	452	27	191	-10	217.5
95	2002-02-01	-5.32	-4.98	11.2	347	27	179	-17	238.5
96	2002-02-12	-1.23	-0.73	6.4	515	20	174	-18	203.1
97	2002-02-23	-2.35	-1.91	6.4	362	10	149	-6	184.2
98	2002-02-28	-1.96	-1.85	9.5	372	37	154	-11	200.4
99	2002-03-02	-1.83	-1.35	9.9	386	13	117	-14	187.6
100	2002-03-12	-1.68	-1.63	7.9	453	27	135	-3	176.2
101	2002-03-16	-1.54	-1.45	6.3	310	7	141	13	182.7
102	2002-03-25	-6.39	-5.42	15.4	433	17	163	-33	169.1
103	2002-03-30	-4.15	-3.86	11.6	521	33	166	-5	188.2
104	2002-04-12	-2.16	-2.90	8.7	432	30	251	-1	213.0
105	2002-04-15	-2.11	-2.30	8.8	357	13	214	-8	204.7
106	2002-04-18	-5.52	-5.39	12.8	485	53	164	-104	189.8
107	2002-04-20	-4.98	-5.74	10.1	563	53	158	-106	179.0
108	2002-04-24	-4.90	-6.54	7.1	488	17	232	-30	178.9
109	2002-05-23	-6.16	-6.70	17.0	606	47	211	-38	184.8
110	2002-05-27	-4.24	-4.43	9.6	593	33	191	-39	191.6
111	2002-06-03	-2.95	-2.64	7.9	437	23	194	-21	175.4
112	2002-06-11	-3.14	-3.57	7.7	386	20	99	-19	152.4
113	2002-06-19	-2.92	-2.73	10.6	468	27	115	-2	150.5
114	2002-06-24	-1.87	-1.67	7.1	474	13	108	-3	155.3
115	2002-07-03	-1.69	-1.52	3.8	361	10	129	1	152.4
116	2002-07-09	-3.05	-2.97	7.4	440	27	103	-8	140.9

Table 4
(Continued)

<i>S/N</i>	Date	FD _{INVK} (%)	FD _{MGDN} (%)	IMF	SWS	Kp	SSN	Dst	SI
117	2002-07-11	-2.77	-3.06	5.1	386	13	99	5	141.0
118	2002-07-18	-4.32	-3.91	5.7	441	13	149	-8	186.6
119	2002-07-20	-6.16	-5.61	7.4	789	30	124	-20	190.7
120	2002-07-30	-8.12	-8.19	7.5	422	17	281	5	234.1
121	2002-08-02	-9.05	-8.63	12.1	489	43	199	-59	185.7
122	2002-08-20	-7.03	-6.91	7.2	479	33	211	-48	232.8
123	2002-08-23	-6.67	-6.06	8.8	402	17	186	-18	229.5
124	2002-08-29	-7.40	-7.17	6.6	464	20	124	-16	172.6
125	2002-09-08	-6.16	-5.69	11.7	479	33	213	-101	194.4
126	2002-09-28	-4.59	-3.76	10.7	307	13	137	3	149.1
127	2002-10-01	-4.24	-3.46	19.5	388	50	90	-100	140.1
128	2002-10-03	-4.37	-4.06	11.5	464	47	104	-78	146.1
129	2002-10-13	-1.77	-1.40	6.5	301	13	185	-30	178.3
130	2002-10-21	-6.30	-5.29	5.8	571	20	144	-18	180.8
131	2002-11-03	-4.54	-5.03	9.7	478	43	190	-65	166.5
132	2002-11-05	-5.44	-5.81	8.4	545	37	188	-46	180.0
133	2002-11-12	-6.28	-7.15	12.4	569	30	154	-15	174.6
134	2002-11-18	-7.87	-8.08	9.3	378	23	128	-37	174.8
135	2002-12-08	-4.68	-4.40	7.1	599	27	164	-28	149.8
136	2002-12-15	-5.16	-4.53	8.9	502	20	199	-28	196.6
137	2002-12-20	-5.41	-5.44	6.1	528	33	208	-47	190.3
138	2002-12-23	-6.64	-6.40	10.1	517	37	126	-42	153.7

Table 5
Regression Results for FD and Related Solar-terrestrial Parameters at INVK

<i>S/N</i>	<i>Parameter</i>	R^2	r	p -value
1	FD-IMF	0.11	-0.33**	3.23×10^{-07}
2	FD-SWS	0.07	-0.27**	2.72×10^{-05}
3	FD-Kp	0.05	-0.24**	0.01
4	FD-SSN	0.06	-0.26**	0.012
5	FD-Dst	0.15	0.39**	1.80×10^{-09}
6	FD-SI	0.06	-0.23**	0.03

Note. “*S/N*” stands for serial number, “*Parameter*” represents each of the two continuous variables, R^2 indicates coefficient of determination (that proportion of the dependent variable that is predicated from the independent variable), r indicates correlation coefficient and p -value represents chance probability. Note: “**” represents statistically significant correlations at the 95% confidence level.

Kane 2010, for example). While the differences in the timing of simultaneous FDs using the onset or event main phase at different locations may be significantly different (or imprecise as they may be difficult to estimate), Okike & Nwuzo (2020) (see Figure 1 of the publication) clearly demonstrated that timing of simultaneous FDs with reference to FD minimum is comparatively more accurate. The coincident code developed by Okike (2021b), which identifies FD minimums occurring at the same hour or day across multiple CR detectors, is employed in this work. The selection accuracy of the implemented code (Okike & Menteso 2024) guarantees that there are no differences in the timing of the simultaneous FDs. The

simultaneous FD data with their associated solar-geomagnetic parameters are presented in Table 4.

The scatter plots and correlation analysis were run to ascertain the level of dependence between the FD magnitude and the solar-geomagnetic characteristics. The product-moment correlation coefficient is applied in determining the degree of statistical correlation according to Fisher (1915) via

$$r = \frac{\sum_{i=1}^n (A_i - \bar{A})(B_i - \bar{B})}{\sqrt{\sum_{i=1}^n (A_i - \bar{A})^2 \sum_{i=1}^n (B_i - \bar{B})^2}}, \quad (1)$$

where A_i and B_i represent the values of the two parameters under consideration.

Table 6
Regression Results for FD and Related Solar-terrestrial Parameters at MGDN

<i>S/N</i>	<i>Parameter</i>	R^2	r	p -value
1	FD-IMF	0.12	-0.35**	3.61×10^{-08}
2	FD-SWS	0.11	-0.33**	1.7×10^{-07}
3	FD-Kp	0.06	-0.25**	0.02
4	FD-SSN	0.06	-0.25**	0.01
5	FD-Dst	0.15	0.39**	9.53×10^{-10}
6	FD-SI	0.049	-0.22**	0.06

Note. “*S/N*” stands for serial number, “*Parameter*” represents each of the two continuous variables, R^2 indicates coefficient of determination (that proportion of the dependent variable that is predicated from the independent variable), r indicates correlation coefficient and p -value represents chance probability. Note: “**” represents statistically significant correlations at the 95% confidence level.

Table 7
Regression Results for Simultaneous FD and Related Solar-terrestrial Parameters from INVK and MGDN

<i>S/N</i>	<i>Parameter</i>	R^2	r	P -value
1	FD_INVK-IMF	0.11	-0.33**	4.924e-05
2	FD_INVK-SWS	0.15	-0.39**	2.055e-06
3	FD_INVK-kp	0.06	-0.24**	0.003255
4	FD_INVK-SSN	0.07	-0.27**	0.001325
5	FD_INVK-Dst	0.17	0.41**	3.779e-07
6	FD_INVK-SI	0.06	-0.24**	0.003575
7	FD_MGDN-IMF	0.11	-0.34**	4.486e-05
8	FD_MGDN-SWS	0.16	-0.40**	1.154e-06
9	FD_MGDN-kp	0.06	-0.25**	0.002749
10	FD_MGDN-SSN	0.09	-0.30**	0.0002273
11	FD_MGDN-Dst	0.15	0.39**	1.25e-06
12	FD_MGDN-SI	0.06	-0.25**	0.02418

Note. “**” represents statistically significant correlations at the 95% confidence level.

The FD amplitude versus solar-geomagnetic parameter scatter plots for INVK and MGDN are presented in Figures 1 and 2 respectively for INVK and MGDN stations. In Figure 3, the relationship between the simultaneous amplitude FDs and the corresponding solar-geomagnetic variables is displayed. It is obvious from Figure 1 that there is some level of dependence between FD amplitude and solar-geomagnetic parameters. Figure 1(a) shows that FD amplitude is inversely related to IMF, with a correlation coefficient $r \sim -0.33$, $R^2 \sim 0.11$ and p -value of 3.23×10^{-07} . Figure 1(b) reveals a negative relationship between FD amplitudes and SWS, with a correlation coefficient $r \sim -0.27$, $R^2 \sim 0.07$ and p -value of 2.72×10^{-05} . In Figure 1(c), regression analysis of FD amplitude versus Kp features a negative relation, with a correlation coefficient $r \sim -0.24$, $R^2 \sim 0.05$ and p -value of 0.01. Figure 1(d) indicates a negative relationship between the FD amplitude and SSN, with a correlation coefficient $r \sim -0.26$, $R^2 \sim 0.06$ and p -value of 0.012. It was noted in Figure 1(e) that FD amplitude is positively related to Dst, with a correlation coefficient $r \sim 0.39$, $R^2 \sim 0.15$ and p -value of 1.80×10^{-09} . In Figure 1(f) it was observed that FD amplitude

is inversely related to SI, with a correlation coefficient $r \sim -0.23$, $R^2 \sim 0.06$ and p -value of 0.03. The analysis results here show that the FD amplitudes and the solar-geomagnetic characteristics at INVK relations are statistically significant at a 95% confidence level. The results of the regression analysis for FD amplitudes and solar-geomagnetic variables are presented in Table 5.

The FD amplitudes versus solar-geomagnetic parameters at MGDN are displayed in the scatter plots of Figure 2. In Figure 2(a), the amplitude FD-IMF regression result shows a negative relationship, with a correlation coefficient $r \sim -0.35$, $R^2 \sim 0.12$ and p -value of 3.61×10^{-08} . The inverse relationship is also noted in the FD-IMF regression analysis at INVK station, with a little higher trend in that of MGDN when compared to INVK. Figure 2(b) also reveals a negative trend for FD amplitude against SWS, with a correlation coefficient $r \sim -0.33$, $R^2 \sim 0.11$ and p -value of 1.71×10^{-07} . Figure 2(c), the regression analysis result of FD amplitude against Kp just like that of INVK station, shows a negative trend, with a correlation coefficient $r \sim -0.25$, $R^2 \sim 0.06$ and p -value of 0.02. In Figure 2(d), we observed an inverse

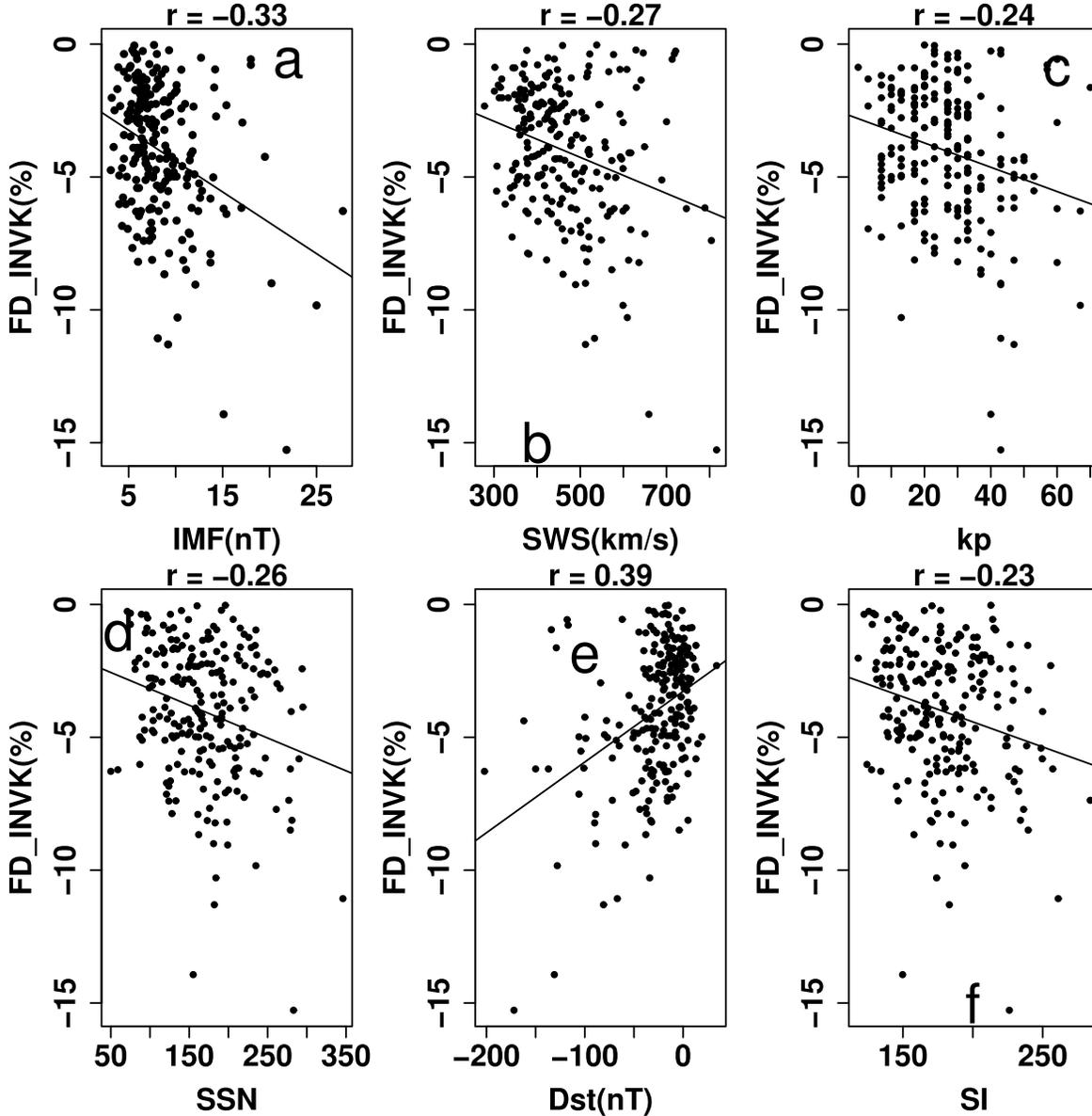


Figure 1. Scatter plots of magnitude of INVK FDs and the corresponding solar-terrestrial parameters.

relationship between FD amplitude against SSN, with a correlation coefficient, $r \sim -0.25$, $R^2 \sim 0.06$ and p -value of 0.01. Figure 2(e) shows a positive trend in the regression analysis of FD amplitude versus Dst, with a correlation coefficient $r \sim 0.39$, $R^2 \sim 0.15$ and p -value of 9.53×10^{-10} . This result is similar to what we got using data sets at the INVK NM station. The result is statistically significant at the 95% confidence level. The regression results for the FD-SI scatter plot displayed in Figure 2(f) indicate a negative trend, with a correlation coefficient $r \sim -0.22$, $R^2 \sim 0.05$ and p -value of 0.06. The regression analyses using FD amplitudes and a solar-geomagnetic variable data set at MGDN station exhibit

statistical significance at the 95% confidence level. The summary of these results is in Table 6.

We have statistically analyzed the relations between the FD amplitudes and solar-geomagnetic characteristics at two stations, INVK and MGDN, and found out that the degree of statistical significance of correlation in them cannot be over-emphasized. These statistical levels of significance of correlation indicate that the solar-geomagnetic parameters have a link in the CR intensity modulation (Belov et al. 2001; Richardson 2004; Mishra et al. 2005; Kane 2010; Dumbovic et al. 2011; Yu & Luo 2014; Okike 2020c; Alhassan et al. 2021; Fu et al. 2021a, 2021b; Mentoso et al. 2023; Melkumyan et al. 2024; Ugwu et al. 2024).

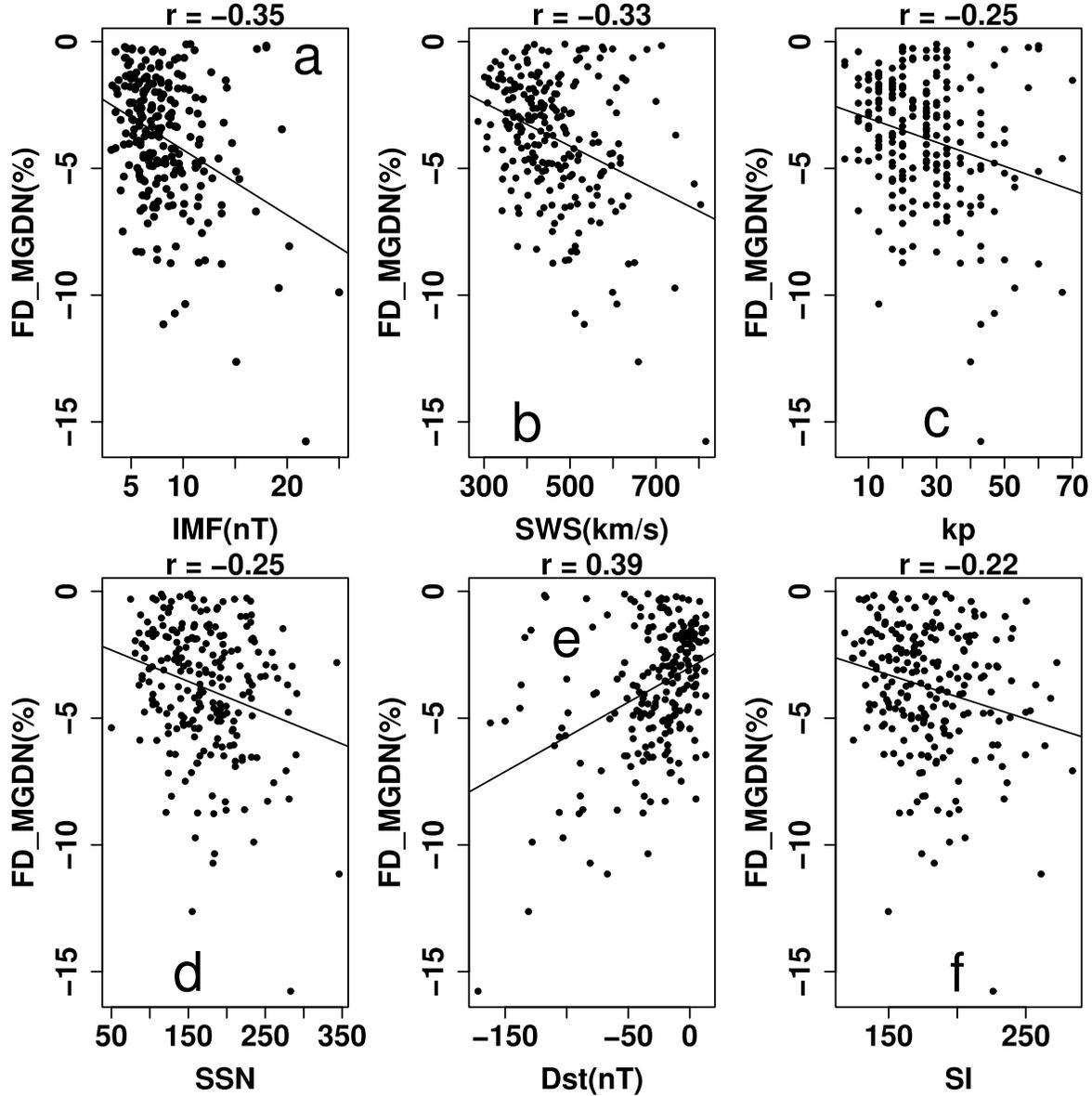


Figure 2. Scatter plots of magnitude of MGDN FDs and the corresponding solar-terrestrial parameters.

In the present work, we observed a statistically significant correlation between FD amplitudes and IMF at both INVK and MGDN stations, with $r \sim -0.33$ and -0.35 respectively at INVK and MGDN NM stations. This is good evidence that IMF has more effect on the modulation of CR intensity at MGDN when compared to that at INVK. These results are in line with the one currently reported by Ugwu et al. (2024) using FD-IMF analysis. Alhassan et al. (2021) and Dumbovic et al. (2011) revealed a stronger trend with correlation coefficient, $r \sim -0.44$ and -0.62 respectively, in FD-IMF relation when compared to the present result. The weak

correlation in the current work is expected since the FD catalogs contain the small-amplitude FDs which support the assertion that weak FDs might be a result of CME or ICME interactions with the Earth's magnetic field.

There was a stronger trend in FD-SWS relation at MGDN ($r \sim -0.33$) when compared to that at INVK ($r \sim -0.27$). These results are in line with the ones previously reported by Singh & Badruddin (2007), Bhaskar et al. (2016) and the current work of Ugwu et al. (2024), but in contrast to Menteso et al. (2023) and Alhassan et al. (2021). Menteso et al. (2023) reported lower results ($r \sim -0.1$ and -0.03) respectively for the two

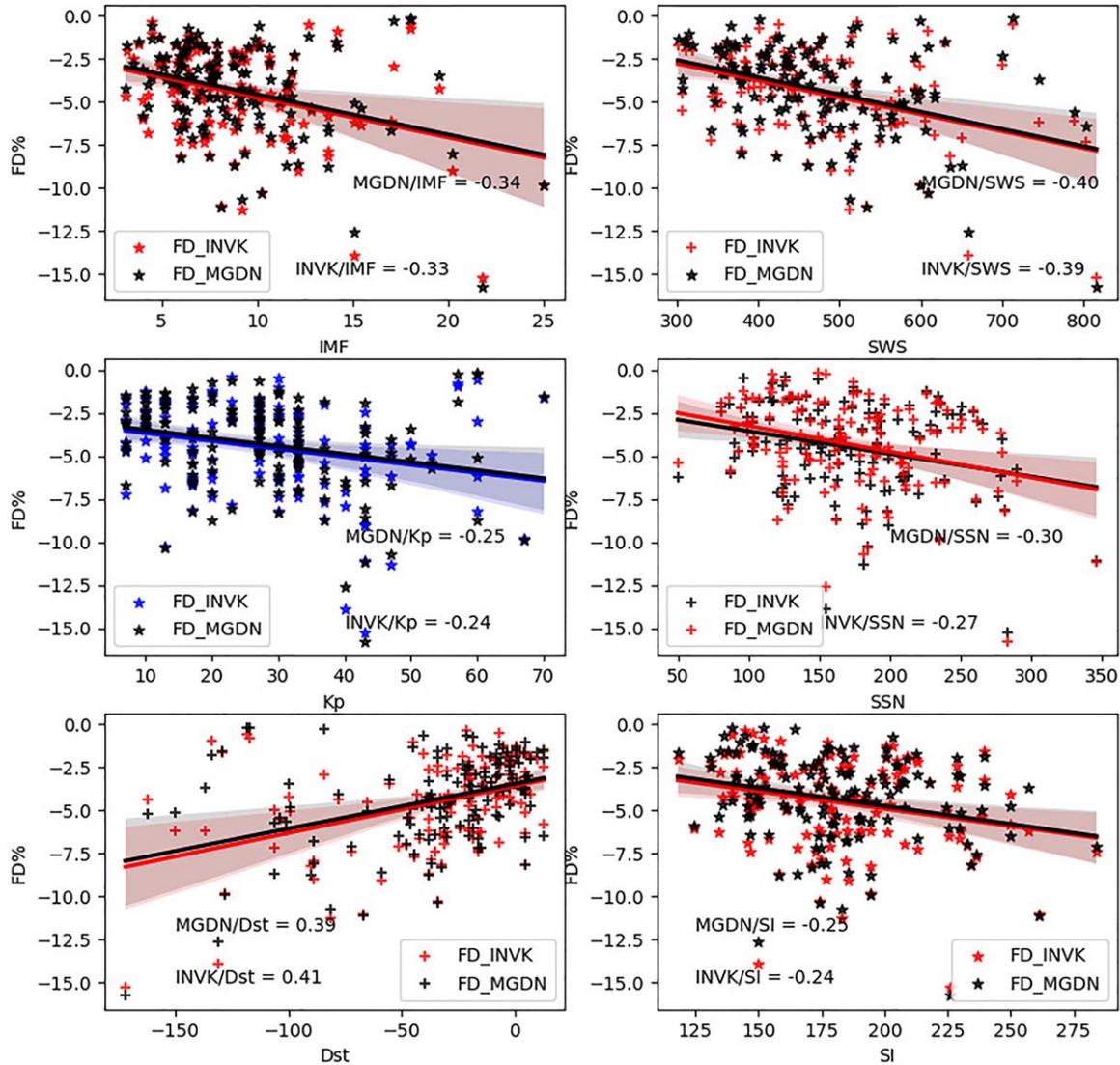


Figure 3. Scatter plots of simultaneous FDs at INVK and MGDN and the corresponding solar-terrestrial parameters.

stations they studied, while Alhassan et al. (2021) revealed higher results ($r \sim -0.44$) when compared with the results obtained here. The current results obtained here obviously support that SWS has an impact on the variation of CR intensity.

It is interesting to note that there are statistically significant correlations in FD-Kp, FD-SSN, FD-Dst and FD-SI at both INVK and MGDN stations, with inverse correlations for FD-Kp, FD-SSN and FD-SI, and a direct correlation for FD-Dst only at both stations. These trends shown in FD amplitudes and geomagnetic index relations at the stations under study emphasized the claim that all these variables might have some influence on solar activities (Richardson 2004; Mishra et al. 2005; Kane 2010; Singh & Bhargawa 2020; Fu et al.

2021a, 2021b; Kumar et al. 2023; Melkumyan et al. 2024), and the differences observed at the different NM stations (INVK and MGDN) here might be a result of differences in station characteristics such as rigidity cut-off and/or CR diurnal anisotropy of the NM stations. A large volume of data is recommended to confirm this claim. The results reported here for the relations between FD amplitude and solar-geomagnetic characteristics, with a statistical level of significance at 95%, are in agreement with other reports in the literature.

4. Result Validation

Due to the difficulties of detecting, timing as well as accurate determination of the FD events (Ramirez et al. 2013), there is a need for the validation of every new FD datum. The first step

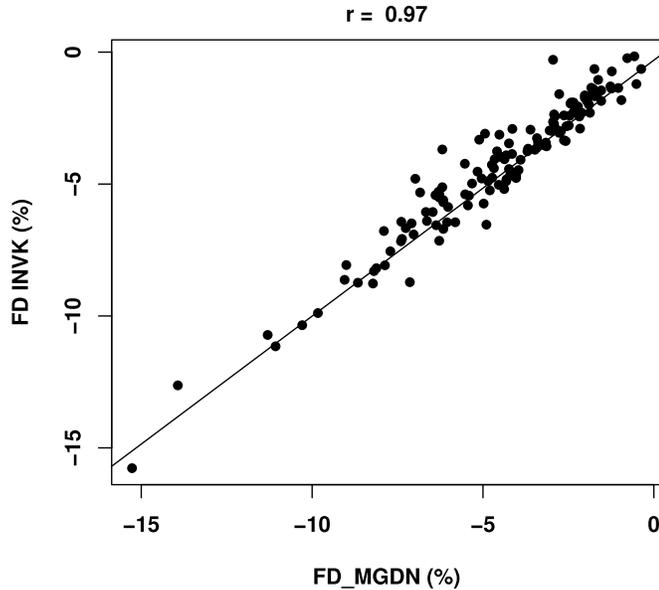


Figure 4. Scatter plots of simultaneous FDs at INVK and MGDN.

taken in this section was the correlation test discussed above. The events were also compared (not shown here) with one of the largest catalogs of FDs developed by the IZMIRAN group found at the website,⁷ within the same time lag. However, there is every indication from the literature of the difficulties of uniting two FD catalogs calculated by different methods (Abunin et al. 2013). This was obvious in Figure 9 of Menteso et al. (2023), where they implemented software measured the event's minimum reduction time while the GSM of IZMIRAN determined the onset time of the event. Furthermore, the Okike (2021a) publication has illustrated the implications of using different baselines in determining FD events, thereby stating the significant differences between IZMIRAN catalogs and those outside them.

To meet the target of a reliable validation set by Abunin et al. (2013), the two FD catalogs at INVK and MGDN selected using the same method were employed in this comparison carried out here. The total number of FDs selected from INVK and MGDN stations were 224 and 229 respectively. The simultaneous FDs at the two stations were 138 in number (see Table 4). The scatter plot of the simultaneous FDs at INVK and MGDN versus their solar parameters is presented in Figure 3, while the scatter plot of simultaneous FDs at INVK against the simultaneous FDs at MGDN is displayed in Figure 4. The simultaneous FD data show statistically significant relations with the solar variables (IMF, SWS, Kp, SSN, Dst and SI) with the correlation coefficients of $r \sim -0.33, -0.39, -0.24, -0.27, 0.41,$ and -0.24 respectively for IMF, SWS, Kp, SSN, Dst and SI at INVK station. The simultaneous FD versus the solar

variables at the MGDN station shows noticeably higher trends than those of INVK (except in Dst where there is a lower relation in MGDN when compared with that of INVK) with the correlation coefficients of $r \sim -0.34, -0.40, -0.25, -0.30, 0.39$ and -0.25 respectively for IMF, SWS, Kp, SSN, Dst and SI (see Table 7). The differences can be attributed to their (INVK and MGDN stations) different characteristics (see Table 1). There is a statistically significant relation between the simultaneous FDs at INVK and the ones in MGDN with correlation coefficient $r \sim 0.97$ and coefficient of determination $R^2 \sim 0.93$. All these results imply that 93% of the simultaneous FD variation may be attributed to the same global events according to the works of Cane (2000), Oh et al. (2009) and Lee et al. (2015). The remaining Forbush events that are non-simultaneous FDs may be a result of the different characteristics of the NM stations and the CR diurnal anisotropy that varies significantly over the Earth. Wibberenz et al. (1998), Cane & Richardson (2003), Jordan et al. (2011) and Okike & Nwuzo (2020) opined that time variation as well as the phase shifts that occurred in non-simultaneous FDs can be attributed to the location-dependent and diurnal anisotropy of the CR. Alhassan et al. (2022b) (see Figure 2 of the publication) illustrated these time variations in non-simultaneous FD events. Menteso et al. (2023) in Figure 8 of their work indicated that non-simultaneous FD events were more obvious in the high-amplitude FD events, suggesting that the solar cycle effect has contributed to the differences. All these are reflected in the current work as shown in Tables 1, 2, and 3 as well as Figures 3 and 4.

The relation between FDs with regard to timing and event magnitude has often been described using a few isolated events. For example, Figures 2 and 3 of Oh et al. (2008) and 1 and 2 of Okike & Collier (2011) graphically illustrated simultaneous and non-simultaneous FDs. These case study approaches are quite interesting. However, statistical/quantitative representations of simultaneous and non-simultaneous FDs are lacking in the literature. Table 1 of Oh et al. (2008) presents the magnitude of 49 FDs (simultaneous and non-simultaneous events) calculated at Oulu (OULU) station. Whereas the relationship among the events' main phase at the three stations is presented in the graphs, the magnitudes and timing of these events, similar to Table 1 of the article, are not presented for the remaining two stations (INVK and MGDN). Though the reader only speculates the magnitude of events at these two stations, Oh et al. (2008) concluded that high-amplitude FDs tend to be observed globally whereas small-amplitude events are non-simultaneous.

Here, we present a statistical illustration of the variation patterns for both simultaneous and non-simultaneous FDs. Figure 5 allows the reader to assess the differences and similarities between the magnitude and timing of both simultaneous (panel (a)) and non-simultaneous (panel (b)) FDs. Infinite discussions may arise from the results presented

⁷ <http://spaceweather.izmiran.ru>

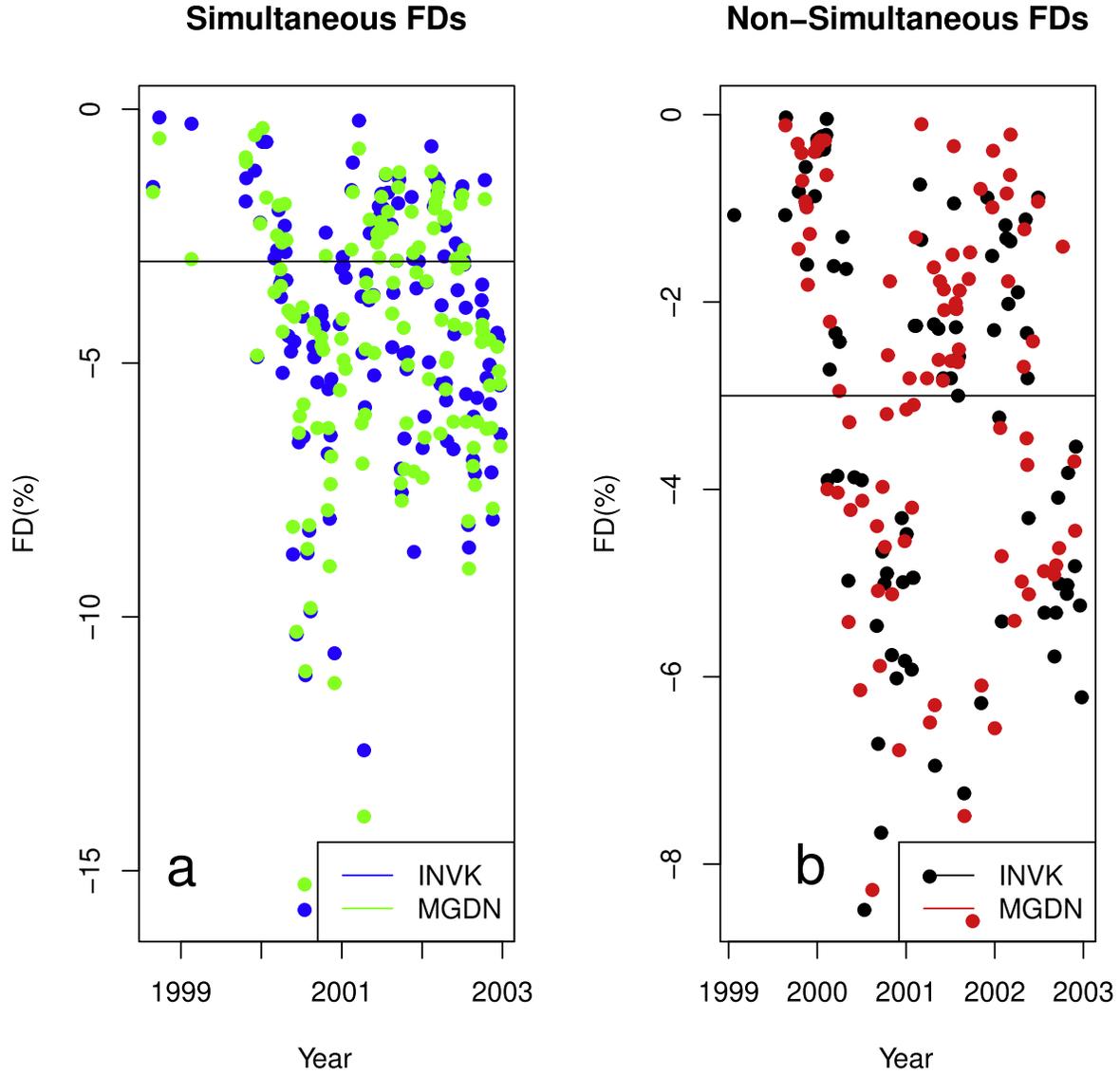


Figure 5. Scatter plots of simultaneous (panel (a)) and non-simultaneous (panel (b)) FDs at INVK and MGDN.

in Figures 4 and 5 (note that the same events are presented in both figures). While Figure 4 does not allow for comparison of event magnitudes at the two stations, panel (a) of Figure 5 shows that CR intensity variation is not only significant but also unpredictable at INVK and MGDN stations. Going upward from the bottom (or from the top, left-hand side) of the panel where there is not much event cluster, the differences in the magnitudes of some pairs of simultaneous FDs at the two stations are visually evident. For instance, the first two pairs suggest that MGDN measures larger intensity variation during the FD (event of 2000 July 16), but we have a different scenario for the next pairs of events (FD of 2001 April 12). In this case, INVK measures a much higher intensity variation. There are also cases where the differences in magnitudes at the

two stations are not significant. These uncertain patterns of CR intensity variation during the period of FDs query (see also Okike & Menteso 2024) the expectation that stations with lower rigidity ($INVK_{GV} = 0.17$ GV) should see higher intensity variation (e.g., Okike 2020c) than MGDN with higher rigidity ($INVK_{GV} = 1.99$ GV).

A comparison of panels (a) and (b) of Figure 5 is also interesting. Whereas one may point to some observable trend in panel (a), it is difficult to establish any pattern in panel (b). There are several reasons for this. Globally simultaneous FDs may easily be related to the common solar causative agents that generate them. Such association is much more difficult when dealing with non-simultaneous FDs as the forms/number/magnitude of the events may vary appreciably between

different locations. These could explain the significantly scattered data points in panel (b). While the perfect vertical alignments (reflecting unique time) for some of the events in panel (a) allow for visual matching, it is difficult to match any two events in panel (b). The non-simultaneous FDs may be the result of the complex local CR phenomena (e.g., CR anisotropy and solar cycle oscillation) at each of the stations. Further, it is easy to infer from the two figures that simultaneous FDs are, on average, larger than the non-simultaneous FDs as suggested by the horizontal line (see also Oh et al. 2008). The mean variations for simultaneous FDs at INVK and MGDN are respectively 4.5% and 4.3%. For the non-simultaneous FDs in panel (b), the mean event magnitudes at INVK and MGDN are respectively 3.3% and 3.0%. The black horizontal lines on both diagrams represent $FD_{\text{magnitude}} = -3\%$. The number of non-simultaneous FDs at INVK is 86 whereas those detected at MGDN is 91.

5. Summary and Conclusion

The proposed link between GCR flux intensity and solar emission characteristics has been investigated. The interrelationships between the two have been a big challenge in the field of astrophysics. The traditional manual selection methods of depressions in GCR count rates have thrown many researchers off balance, especially when considering FD catalogs with the small/weak FD amplitudes. This bias created by the above-mentioned FD selection technique was cleared by recent work of our group (e.g., Okike & Alhassan 2021; Okike et al. 2021; Alhassan et al. 2022b). In the present work, we employed the automated method of FD selections from two NM stations via INVK and MGDN NM stations from 1998 to 2002. The associated solar-geomagnetic parameters were also generated using this computer algorithm-software code. The data analyses revealed a negative trend in FD-IMF, FD-SWS, FD-Kp, FD-SSN, and FD-SI in both stations when considered individually and at their simultaneous level. Interestingly, we noted positive relations in FD-Dst at both INVK and MGDN stations considered individually and at their simultaneous level. The results indicate statistically significant correlations, with $r \sim -0.33, -0.27, -0.24, -0.26, 0.39$ and -0.23 respectively for FD-IMF, FD-SWS, FD-Kp, FD-SSN, FD-Dst and FD-SI at INVK, while in MGDN station, we noted statistically significant correlations, with $r \sim -0.35, -0.33, -0.25, 0.25, 0.39$ and -0.22 respectively for FD-IMF, FD-SWS, FD-Kp, FD-SSN, FD-Dst and FD-SI. We observed coherent results in FD-Dst in both stations, and the differences in the correlation results noted in other parameters with the FD amplitudes could be the influence of different characteristics of the NMs, which had less impact on FD-Dst. The inconsistency observed at the different stations strongly calls for further investigation.

A critical look at Table 4 obviously shows that all the simultaneous FDs are strong/large-amplitude FD events, while

weak/small-amplitude FDs are simultaneously incapacitated at different NM stations (see Tables 8 and 9 of Mentese et al. 2023). This indicates that the possibility of getting simultaneous weak/small-amplitude FDs at two different NM stations is minimal or even zero. There was a more obvious relationship in the FD-solar-terrestrial parameters in the simultaneous FDs when compared to the relationship of the non-simultaneous ones. This will again be a topic of interest for further investigation. The implication of all these results could be that solar emission characteristics are key drivers of the GCR flux intensity modulations. We can conclude by inferring that GCR intensity modulation could be attributed to solar-geomagnetic parameters, but before we draw our curtain on this work, we need to emphasize the importance of repeating this analysis using Fourier decomposed GCR data that will take care of CR anisotropy influence, which will be the target of our further research.

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