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EMPIRICAL EVIDENCE OF SPURIOUS CORRELATIONS AMONG SPACE WEATHER VARIABLES

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Abstract. This paper investigates the prevalence and identification of spurious correlations within space weather datasets, a critical concern given the complex interdependencies of nature of geophysical phenomena. This is carried out using daily-averaged galactic cosmic ray (GCR) datasets from MOSC and OULU neutron monitor (NM) stations analyzed separately, the large Forbush Decrease (FD) (FD >3%) and the small FD (FD $\leq 3\%$) in each stations, in other to account for the effects of 11-year solar cycle oscillations. For the first time, a statistical analytical method was employed to test the link between FD amplitudes and solar-geomagnetic variables in each datasets after the effects of 11-year solar cycle oscillations are filtered. We demonstrate that while significant correlations between various space weather indices and Forbush Decrease events are empirically observable , a meticulous analysis reveals that a subset of these relationships may not represent true physical causality but rather arise from statistical artifacts or confounding factors inherent in the data. Specifically, analyses of Forbush Decreases often reveal varying correlation coefficients with geomagnetic and solar wind parameters, which can fluctuate significantly across different time periods and cosmic ray stations . For instance, correlations between Forbush Decrease amplitudes and interplanetary magnetic field strength, solar wind speed, and geomagnetic indices like Kp and Dst have been observed to exhibit both negative and positive trends, depending on the specific dataset and analytical approach employed. The results obviously show inconsistent in the datasets for both MOSC and OULU stations for the large and small Fds respectively – specifically a strong correlations were noticed for the parameters' regression analyses after the effects of 11-year solar cycle oscillations were removed for both big and small Fds. These inconsistencies strongly suggest the infulence of 11-year solar cycle oscillations on the FDs counted on both stations, thereby affecting the relationships between the Fds and the geomagnetic tested variables, echoing concerns about "spurious regression" in the stationary time series. Most of the results are statistically significant at a 95% confidence level. The results obtained here imply that 11-year solar cycle oscillations has impacts on the GCR flux intensity.

Keywords. Galactic cosmic rays; neutron monitor; Forbush decrease; solar cycle; algorithm; method; statistical – correlation analyses; terrestrial relations.

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1 Introduction

The inherent complexity of space weather phenomena, characterized by non-linear interactions and diverse temporal scales, frequently leads to the emergence of statistically significant but physically meaningless correlations, often termed spurious correlations (Okike *et al.*, 2025). This issue is particularly pronounced in studies involving extensive datasets of space weather indices, where the sheer volume of data can inflate the likelihood of detecting coincidental relationships. Chakraborty *et al.* (2023) opined that such spurious correlations can arise from common underlying drivers, autocorrelation within time series, or improper detrending techniques, leading to misinterpretations of physical connections. Consequently, distinguishing between genuine causal links and these statistical artifacts is paramount for developing accurate predictive models and fostering a robust understanding of solar-terrestrial interactions. This challenge requires the application of an advanced statistical methodologies to rigorously ascertain the true dependencies among variables like cosmic ray variations and geomagnetic parameters (Chakraborty *et al.*, 2023). This paper aims to systematically identify and characterize such spurious correlations, offering a methodological framework to mitigate the impact of 11-year solar cycle oscillations on space weather research by leveraging techniques such as mutual information and conditional mutual information analyses (Hoilijoki *et al.*, 2022; Inceoglu *et al.*, 2022; Chakraborty *et al.*, 2023; Okike *et al.*, 2025). Our methodology specifically addresses the challenge of distinguishing genuine causality from spurious connections attributable to a hidden common cause by employing advanced techniques that outperform state-of-the-art methods, particularly in large sample sizes. According to Okike *et al.* (2025), the use of multiple geomagnetic and solar wind plasma indices, as demonstrated in analyses of cosmic ray responses to coronal mass ejections, further underscores the complexity and potential for spurious correlations when assessing such phenomena. Galactic cosmic rays (GCRs), comprising primarily protons, alpha particles, and heavier nuclei with energies often reaching GeV/nucleon (Papailiou et al., 2024; Onah et al., 2025), exhibit intensity variations influenced by turbulent solar wind and embedded heliospheric magnetic fields (Usoskin *et al.*, 2004; Papailiou *et al.*, 2024; Menteso *et al.*, 2023; Ugwu *et al.*, 2024; Onah *et al.*, 2025). These variations, specifically Forbush Decreases (FDs), are transient depressions in cosmic rays (CRs) intensity as a result of solar flares and coronal mass ejections. Discovered by S. Forbush in 1937 (Forbush, 1937), FDs manifest as sudden, short-term drops in CR flux, followed by recovery over about a week. They feature four distinct phases: onset, main phase, minimum, and recovery. FDs have been extensively observed and analyzed in prior studies, with a substantial body of literature documenting their characteristics (see, for example, Lockwood, 1971; Belov *et al.*, 1979; Van Allen, 1993; Belov *et al.*, 2001; Belov, 2008; Harrison and Ambaum, 2010; Okike and Collier, 2011a, b; Okike, 2020a; Okike *et al.*, 2021a; Lagoida *et al.*, 2023; Menteso *et al.*, 2023; Ugwu *et al.*, 2024; Onah *et al.*, 2025). The study of Forbush Decreases is crucial for understanding the impact of Earth-directed solar ejections and associated geomagnetic disturbances, with traditional case event correlation and superposed epoch analysis methods facing limitations in handling the "Big Data" characteristics of modern neutron monitor measurements (see, for example, Belov *et al.*, 2001; Bhaskar *et al.*, 2016; Okike, 2020a, b, c; Okike and Nwuzor, 2020; Okike *et al.*, 2020, 2021a; Alhassan *et al.*, 2021a, b, c; Lagoida *et al.*, 2023; Okike *et al.*, 2025). Hoilijoki *et al.* (2022) and Chakraborty *et al.* (2023), formation theory metrics, suggested that mutual information has proven effective in quantifying both linear and non-linear correlations between space weather variables, providing a more comprehensive assessment than traditional linear methods. Conditional mutual information, for instance, allows for the isolation of direct influences between variables by "conditioning out" the effects of other potential drivers, thereby refining causal inference in complex systems (Chakraborty *et al.*, 2023). Specifically, Inceoglu *et al.* (2022) utilized artificial intelligence methods, such as Light Gradient Boosting Machines, to successfully applied in investigating the non-linear interplay among modulation processes affecting galactic cosmic rays, providing insights beyond traditional drift-dominated or diffusion-dominated scenarios. This approach has revealed a dynamic behavior of GCR modulation that varies across time and timescales, rather than adhering to simplified models. Such advanced automated analytical capabilities are essential for accurately interpreting the complex relationships observed in cosmic ray time-intensity variations, which are critical for understanding space weather phenomena. However, the complex and varied nature of cosmic ray data, particularly the superposition of multiple signals during short-term intensity variations like Forbush decreases and ground-level enhancements, has yet to receive adequate attention in analyses (Okike and Menteso, 2024). This oversight is critical, as manually separating these superimposed signals is both slow and ineffective, highlighting the necessity of automated, data-driven analytical strategies for more precise interpretation of neutron monitor measurements (Okike *et al.*, 2025). The application of sophisticated computational approaches is crucial for discerning nuanced, non-linear interactions within cosmic ray data, thereby enabling a more accurate attribution of physical mechanisms responsible for observed intensity variations (Inceoglu *et al.*, 2022; Okike *et al.*, 2025). In our recent work (see, for example, Onah *et al.*, 2025), it was noted that the consideration of varying geomagnetic cutoff rigidities, which influence the penetration of cosmic ray particles into the terrestrial magnetic field, further complicates the analysis of ground-based neutron monitor data. This necessitates sophisticated analytical methods capable of accounting for spatial and temporal variations in geomagnetic shielding when interpreting cosmic ray flux measurements. These advanced methods, especially those leveraging machine learning/automated computational methods are critical for accurately modeling the global heliospheric transport of galactic cosmic rays, thereby enhancing predictions of space radiation environments for deep-space missions. This integrative approach combines the strengths of data-driven insights with theoretical frameworks, crucial for accurately modeling complex space weather phenomena. Such advancements are particularly vital for mitigating uncertainties in dose rates near the open/-closed geomagnetic field boundary, which affects transcontinental flights (Bain *et al.*, 2023). Henceforth, the development of automated algorithms for real-time analysis of such data streams are paramount for operational space weather forecasting, especially given the historical challenges of processing hourly data over many decades (Okike and Umahi, 2019a).

This work will delineate the current state of research concerning spurious correlations within space weather data, possibly due to the superposing of 11-year solar cycle oscillations in the galactic cosmic rays, emphasizing advancements in statistical and analytical techniques and the evolution of observational datasets. It will highlight the challenges posed by large, diverse datasets and the methodologies developed to distinguish physically meaningful relationships from statistically coincidental ones. Furthermore, it will explore how emerging automated computational paradigms and data-driven modeling are transforming space weather prediction by extracting predictive patterns from complex data, even when underlying physical mechanisms are not fully theorized (Mannucci *et al.*, 2023). These developments are critical for addressing the limitations of traditional analytical approaches, which often struggle to identify subtle, non-linear interactions within the vast and heterogeneous datasets characteristic of space weather research. For instance, in the work of Okike and Menteso (2024), the precise identification of

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Forbush Decreases from neutron monitor data, despite their variability and unpredictable forms, has significantly advanced due to sophisticated authomated computational methods that overcome the challenges of manual event selection and inconsistent catalogues. This progress, facilitated by big data analyses, has allowed for more robust comparisons of long-term cosmic ray variability with geomagnetic indices, moving beyond single case studies (Coughlan *et al.*, 2023; Okike *et al.*, 2025). These approaches are particularly valuable for identifying subtle correlations and causal relationships that might be obscured in traditional statistical analyses, especially when examining multi-decadal cosmic ray data influenced by solar cycles (see, for example, Okike, 2021; McGranaghan *et al.*, 2022; Sitnov *et al.*, 2023; Poduval *et al.*, 2023; Argall *et al.*, 2023). The ability of these automated methods to analyze large datasets quickly and efficiently, as demonstrated by the Fully Automated Method in identifying Forbush Decreases, provide a distinct advantage over manual, time-consuming techniques (Okike and Menteso, 2024; Okike *et al.*, 2025). This capacity for rapid and comprehensive analysis is paramount in distinguishing genuine physical associations from spurious correlations, a prevalent issue in the interpretation of extensive space weather datasets. This necessitates a robust framework for validating the statistical significance of observed relationships, particularly in distinguishing between true causal links and coincidental patterns arising from the inherent complexity and multivariate nature of space weather phenomena. Consequently, rigorous statistical validation, incorporating methods like cross-validation and permutation testing, is essential to confirm the robustness of identified correlations and mitigate the risk of misinterpreting stochastic associations as physical linkages (Inceoglu *et al.*, 2022; Verniero *et al.*, 2023; Argall *et al.*, 2023). This comprehensive strategy supports not only the advancement of heliophysics modeling but also the validation of these models in operationally relevant environments, crucial for demonstrating forecasting accuracy (Whitman *et al.*, 2023; Argall *et al.*, 2023; Verbois *et al.*, 2023; Verniero *et al.*, 2023).

2 Data

This study utilizes daily averaged, pressure-corrected cosmic ray (CR) data from the Moscow (MOSC) and Oulu (OULU) neutron monitor (NM) stations, sourced from [1]. Building on Paper I (Okike and Menteso, 2024), which applied automatic filtration to CR data from these stations over Solar Cycle 23 (1996–2008) to examine 11-year solar cycle effects on large- and small-amplitude Forbush Decreases (FDs) and CR anisotropy influences, this work provides a deeper analysis of solar cycle contributions to FDs. Analysis focuses on spurious correlations among space weather variables using MOSC and OULU data across Cycle 23. Daily solar-geophysical parameters—including interplanetary magnetic field (IMF), solar wind speed (SWS), and geomagnetic indices (Kp, SSN, Dst, SI)—were obtained from the OMNI database [2]. This paper intensifies scrutiny of solar cycle impacts on FDs, addressing preliminary findings from Paper I through rigorous correlation testing.

[1] http://cr0.izmiran.rssi.ru/common/links.htm
[2] http://omniweb.gsfc.nasa.gov/ow.html

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Table 1. Characteristics of MOSC and OULU NMs

S/N	NM name	Longitude	Latitude	Altitude (m)	Rigidity (GV)
1	MOSC	37.30°N	55.50°E	200	0.77
2	OULU	-75.70°N	45.40°E	0	0.77

3 Method

This section outlines the analytical techniques used to rigorously assess the statistical significance of observed correlations within various space weather parameters, thereby distinguishing genuine physical relationships from mere statistical artifacts (Okike *et al.*, 2025). We developed a computer function (in an R program) to compute rolling means of the raw CR data. R is a statistical software package, generally referred to as "The R Foundation for Statistical Computing," and is freely available online. The statistics analyses were carried out using four groups of daily-averaged galactic (GCR) datasets from MOSC and OULU neutron monitor (NM) stations, analysed separately as the large FDs (FDs >3%) and the small FDs (FDs $\leq 3\%$) for before and after the effects of 11-year solar cycle oscillations are filtered out in each station, in other to account for the effects of the 11-year solar cycle oscillations. The regression analyses of the FDs versus the geomagnetic characteristics from the four groups of the dataset were carried out separately for each station, and the correlation coefficients, r, were recorded. This allows for a quantitative assessment of the relative importance of joint causal influences, which can significantly impact forecasting capabilities and the design of future data experiments (Chakraborty *et al.*, 2023). For instance, the application of correlation and regression analyses, alongside superposed epoch analysis, has been widely utilized in examining the relationships between cosmic ray fluxes and other solar-terrestrial variables, although potential biases stemming from data superposition tendencies warrant careful consideration (Okike *et al.*, 2025). Such analyses often incorporate extensive time series data, such as neutron monitor measurements, IMF, SWS, SSN, Dst index, and SI, to identify long-term periodic variability and specific event correlations (Okike *et al.*, 2025). The robust identification of these relationships is particularly crucial for events like Forbush Decreases, where distinguishing genuine cosmic ray anisotropies from other modulations is key to understanding their underlying physics (Okike *et al.*, 2021a; Okike, 2021b). Therefore, incorporating advanced statistical methods like principal component analysis or cluster analysis can further unravel intricate intercorrelations among diverse solar parameters, moving beyond simple linear and partial correlation techniques (Miteva *et al.*, 2018). Moreover, the inherent multifractality of cosmic ray and solar dynamics cross-correlations necessitates the application of sophisticated techniques to quantify signal-to-noise ratios, particularly in the analysis of small amplitude Forbush Decreases (Sierra-Porta, 2022; Okike *et al.*, 2025). This involves dissecting complex time series into their constituent frequency components to identify underlying periodicities and potential causal links, as proposed by early pioneers in geophysical signal analysis (Tanna and Pathak, 2013; Barbosa *et al.*, 2017; Wirsing and Mili, 2019; Christodoulakis *et al.*, 2019; Joshi *et al.*, 2020; Okike, 2021b; Sierra-Porta, 2022; Menteso *et al.*, 2023; Okike and Menteso, 2024; Papailiou *et al.*, 2024; Onah *et al.*, 2025; Okike *et al.*, 2025; Pelosi *et al.*, 2025a).

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To statistically identify spurious correlations between Forbush Decreases (FDs) and geomagnetic parameters, event catalogs from raw cosmic ray data were compared with those after solar cycle effect removal, for both large (FD >3%) and small (FD $\leq 3\%$) events at MOSC and OULU stations.

FD Catalog Comparisons

Four grouped lists were generated per station, highlighting discrepancies before and after solar cycle adjustment:

MOSC Station: (i) 353 large FDs in raw data absent post-adjustment (Table 2); (ii) 114 small FDs in raw data absent post-adjustment (Table 3); (iii) 52 large FDs post-adjustment absent in raw data (Table 6); (iv) 393 small FDs post-adjustment absent in raw data (Table 7).

OULU Station: (i) 334 large FDs in raw data absent post-adjustment (Table 4); (ii) 112 small FDs in raw data absent post-adjustment (Table 5); (iii) 38 large FDs post-adjustment absent in raw data (Table 8); (iv) 409 small FDs post-adjustment absent in raw data (Table 9).

Due to space constraints, only portions of these datasets appear in Tables 2–9. This approach isolates solar cycle-driven artifacts from genuine FD-geomagnetic links.

4 Analysis, Result, and Discussion

This section presents the findings from an extensive regression analysis of space weather variables, focusing on the identification and characterization of spurious correlations through multifractal detrended fluctuation analyses.These results were showcased in tables 10 to 13 for four groups of daily-averaged galactic (GCR) datasets from MOSC and OULU neutron monitor (NM) stations analysed separately for the large FDs (FDs >3%) and the small FDs (FD $\leq 3\%$) for both before and after the effects of 11-year solar cycle oscillations are filtered out in each station. Specifically, this analysis investigates the intricate relationships between cosmic ray intensity reductions, represented by Forbush Decreases, and various solar and geomagnetic parameters such as interplanetary magnetic field (IMF), solar wind speed (SWS), Sunspot number (SSN), Dst index and SI in the two stations (MOSC and OULU), considered seperately for the large and small FDs. This study aims to differentiate between intrinsic physical connections and misleading statistical associations that often emerge in complex, non-linear systems like space weather (Sierra-Porta, 2022). This involved employing rigorous statistical methods, including those capable of identifying and quantifying the presence of multifractality in time series data, to uncover the true dependencies between these variables. The interplay between galactic cosmic rays and the solar wind, particularly during periods of intense solar activity, underscores the importance of precisely quantifying these complex relationships (Onah *et al.*, 2025). Forbush Decreases (FDs), marked by an abrupt decrease in cosmic ray intensity lasting about one week, serve as key indicators of solar-terrestrial interactions, driven directly by solar flares and coronal mass ejections (Papailiou *et al.*, 2024). Samples from the four FD groups at each station appear in Tables 2–9. These reveal no consistent patterns or visual correlations among events before and after solar cycle filtering at MOSC and OULU. FD counts shift post-filtering: MOSC yields 471 (raw) vs. 531 (filtered, Fig. 1); OULU shows 454 (raw) vs. 545 (filtered, Fig. 2). These differences highlight solar cycle artifacts, with profound implications for interpreting FD-geomagnetic links. Forbush decreases, characterized by abrupt drops in cosmic ray intensity lasting approx-

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imately one week, are pivotal events for understanding these solar-terrestrial connections, directly influenced by solar flares and coronal mass ejections (Papailiou *et al.*, 2024). Solar cycle effects obscure a substantial number of FDs at both stations: 60 FDs in MOSC and 91 in OULU.

Figure 1 reveals fewer FDs at the start and end of Solar Cycle 23 (1996–2008), with a pronounced dome-shaped structure at the cycle's core, anti-correlated with sunspot numbers. Large FDs (>3%) dominate during peak activity (2000–2005), aligning with heightened CME rates noted by Riley *et al.* (2006), Gopalswamy (2016), and Lamy *et al.* (2019); notable peaks include 31/10/2003 and 19/01/2005 events from Menteso *et al.* (2023). Post-filtering (Fig. 2), a flat line emerges without the dome, confirming 360-day solar cycle subtraction.Solar cycle preferentially boosts large FDs over small ones (>3%), with location-dependent effects:

MOSC: 353 large FDs (raw) vs. 52 (filtered); 114 small FDs (raw) vs. 393 (filtered).

OULU: 334 large FDs (raw) vs. 38 (filtered); 112 small FDs (raw) vs. 409 (filtered).

These catalogs of large and small FDs enable novel FD-based studies at MOSC and OULU, extending Paper I to probe spurious FD-geomagnetic correlations driven by 11-year oscillations shown in the current work.

Statistical product-moment correlations quantify dependencies between FD magnitudes and solar-geomagnetic parameters (Fisher, 1915; Onah et al., 2025):

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

where A_i and B_i represent the values of the two parameters under consideration, FDs intensities from the two stations, and solar-geomagnetic parameters of interest, respectively. The p-value helps to understand how significant the coefficient is to the regression model. In reality, any p-value that is below 0.05 is assumed to be statistically significant.

Table 10 showcases the results from the statistical regression analyses of FDs and the interest geomagnetic parameters using the large FDs (FDs >3%) before (353 FDs, as displayed in Table 2) and after (52 FDs, found in Table 6) the effects of solar cycle are removed for the MOSC station. The goal is to determine the extent to which these parameters are genuinely coupled, or if apparent relationships arise from common underlying drivers or observational biases (Ahmed *et al.*, 2024). The raw FDs and the solar geomagnetic parameters relation have been in the literature (see, for example, Mishra and Agarwal, 2008; Richardson and Cane, 2011; Kumar and Badruddin, 2014; Melkumyan *et al.*, 2018; Menteso *et al.*, 2023; Ugwu *et al.*, 2024; Onah *et al.*, 2025), while the proposed impacts of 11-year solar oscillations on FDs have yet to be investigated. The current results show obvious changes in correlation coefficient with the FDs and the solar geomagnetic characteristics, which were enormous in solar wind speed after the effects of 11-year solar cycle oscillations are filtered for the large FDs, with anti-correlation coefficient r ~ -0.79 and -0.85, respectively, in MOSC and OULU stations at 95% significance levels. The corresponding p-values are 1.45×10^{-07} and 2.96×10^{-07}, respectively, in MOSC and OULU stations. All the results for the statistical correlation analyses of the large FDs (FDs >3%) and IMF, Kp, SSN, Dst, and SI before and after the effects of the 11-year solar cycle were filtered in the MOSC station are presented in Table 1. The correlation coefficients, r in FD-IMF, FD-SWS, FD-Kp, FD-SSN, FD-Dst, and FD-SI before the removal of the 11-year solar cycle effects are r ~ -0.41, -0.47,

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-0.38, -0.27, 0.25 and -0.28, respectively, while after the removal of the 11-year solar cycle effects, r ~ -0.50, -0.79, -0.59, -0.31, 0.61, and -0.35, respectively, for FD-IMF, FD-SWS, FD-Kp, FD-SSN, FD-Dst, and FD-SI. The correlation coefficient obtained in the large raw FD-IMF relation at MOSC station is comparable with the ones obtained in the work of Alhassan *et al.* (2021a) and the recent work of Ugwu *et al.* (2024), while Dumbović *et al.* (2011) showed a higher result (r ~ -0.62) for raw FD-IMF when compared with the one obtained here. The corresponding p-values before the removal of the 11-year solar cycle effects are respectively 4.77×10^{-10}, 3.92×10^{-14}, 3.86×10^{-08}, 1.66×10^{-03}, 1.33×10^{-11}, and 6.02×10^{-04}, while after the removal of the 11-year solar cycle effects, the P-values are 6.44×10^{-02}, 1.45×10^{-07}, 6.54×10^{-03}, 0.79, 3.20×10^{-03} and 0.54 respectively. All are at 95% statistical significants, except that of FD-SSN and FD-SI after the effects are removed. See Table 10 below.

Again, regression analyses were carried out using the small FDs (FDs $\leq 3\%$) in MOSC stations and results obtained are presented in Table 11 for before (114 FDs, dataset represented in Table 3) and after (393 FDs, see Table 7) the effects of solar cycle are removed for the MOSC station. These correlation coefficient results, as presented in Table 11 for the FD-IMF, FD-SWS, FD-Kp, FD-SSN, FD-Dst, and FD-SI before the removal of the 11-year solar cycle effects are r ~ -0.25, -0.33, -0.31, -0.10, 0.25, and -0.15, respectively, while after the removal of the 11-year solar cycle effects, r ~ -0.39, -0.31, -0.34, -0.39, 0.33, and -0.40, respectively, for FD-IMF, FD-SWS, FD-Kp, FD-SSN, FD-Dst, and FD-SSI. Paper I recorded a higher correlation coefficient, r ~ -0.30, when compared with the current result for the small FD-SSN relation with the raw analyis r ~ -0.10. Their corresponding p-values before the removal of the 11-year solar cycle effects are respectively 0.50, 9.99×10^{-02}, 0.17, 0.34, 0.47, and 0.73, while after the removal of the 11-year solar cycle effects, the P-values are 1.16×10^{-09}, 1.47×10^{-05}, 5.26×10^{-07}, 1.64×10^{-08}, 1.78×10^{-06}, and 1.31×10^{-10}, respectively. The results obtained in the current work using Big/large FDs before and after removal of the impacts of solar cycle indicate a higher correlation coefficient when compared with the small FDs counterparts. This is clear evidence that solar cycle effects are more recognized in the small FDs than the Big/large FDs (Okike *et al.*, 2025). The results did not show 95% statistical significance before the removal of the 11-year solar cycle effects, except that of FD-SWS, while the correlations are all in 95% statistical significance after the removal of the 11-year solar cycle effects. See Table 11.

Table 12 presents all the statistical regression analyses results using large FDs (FDs >3%) (334 FDs, as displayed in table 4) in OULU stations. There are obvious changes in the correlation coefficients results, indicating anti-correlation with FDs and the geomagnetic characteristics, except that of Dst for both before and after the removal of the 11-year solar cycle effects. There was a noticableaby stronger trend in FD-SWS after the removal of the 11-year solar cycle effects. The correlation coefficient,r, for the FD-IMF, FD-SWS, FD-Kp, FD-SSN, FD-Dst, and FD-SI before the removal of the 11-year solar cycle effects are r ~ -0.44, -0.42, -0.39, -0.22, 0.47 and -0.26, respectively, while after the removal of the 11-year solar cycle effects, r ~ -0.48, -0.85, -0.60, -0.34, 0.57, and -0.35, respectively for FD-IMF, FD-SWS, FD-Kp, FD-SSN, FD-Dst, and FD-SI. Their corresponding p-values before the removal of the 11-year solar cycle effects are respectively 9.85×10^{-11}, 5.95×10^{-10}, 3.72×10^{-08}, 3.20×10^{-02}, 6.75×10^{-13}, and 4.79×10^{-03}, while after the removal of the 11-year solar cycle effects, the P-values are 0.25, 2.96×10^{-07}, 2.99×10^{-02}, 0.88, 6.73×10^{-02} and 0.85 respectively. All the results show 95% statistical significance, except those of FD-IMF, FD-SSN and FD-SI after the effects are removed. See Table 12.

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Furthermore, still in OULU station, regression analyses were carried out using the small FDs (FDs $\leq 3\%$)before (112 FDs,ref. Table 5) and after (409 FDs, see 9) the removal of the 11-year solar cycle effects and the results obtained were presented in Table 13. There are also notable changes in the correlation coefficients for the FD-IMF, FD-SWS, FD-Kp, FD-SSN, FD-Dst, and FD-SI before and after the removal of the 11-year solar cycle effects though the trend are not stronger when compared with those obtained using the large FDs in the same station. The correlation coefficients for the FD-IMF, FD-SWS, FD-Kp, FD-SSN, FD-Dst, and FD-SI before the removal of the 11-year solar cycle effects are r ~ -0.38, -0.40, -0.52, -0.31, 0.41, and -0.35, respectively, while after the removal of the 11-year solar cycle effects, r ~ -0.40, -0.25, -0.30, -0.35, 0.34, and -0.37, respectively, for FD-IMF, FD-SWS, FD-Kp, FD-SSN, FD-Dst, and FD-SI. Their corresponding p-values before the removal of the 11-year solar cycle effects are respectively 2.37×10^{-02}, 1.51×10^{-02}, 6.51×10^{-05}, 0.16, 1.17×10^{-02}, and 6.05×10^{-02}, while after the removal of the 11-year solar cycle effects, the P-values are 1.25×10^{-10}, 1.66×10^{-03}, 1.39×10^{-05}, 8.50×10^{-08}, 4.42×10^{-07}, and 5.92×10^{-09}, respectively. The results show 95% statistical significance before and after the removal of the 11-year solar cycle effects, except only in that of FD-SSN. See Table 13.

We have statistically analyzed the relations between the FD amplitudes (large FDs and small FDs) and solar-geomagnetic characteristics at two stations, MOSC and OULU, and found out that the degree of statistical significance of correlation in them, after the removal of the influence of the solar cycle oscillations, cannot be over-emphasized. These statistical significance correlation levels imply that the 11-year solar cycle oscillations have a link in the GCR intensity variations and their relations with the solar-geomagnetic parameters (Belov *et al.*, 2001; Richardson, 2004; Dumbović *et al.*, 2011; Okike, 2020c; Alhassan *et al.*, 2021a, b; Menteso *et al.*, 2023; Ugwu *et al.*, 2024; Onah *et al.*, 2025; Okike *et al.*, 2025). In the current work, we observed obvious trends in correlations between large FD amplitudes and SWS at both MOSC and OULU stations after the removal of the influence of the solar cycle oscillations, with r ~ -0.79 and –0.85, respectively, at MOSC and OULU NM stations, while before the removal of the effects of the 11-year solar cycle on the Galactic Cosmic Rays (GCR) intensity, r ~ -0.47 and –0.42, respectively, at MOSC and OULU NM stations . This suggests that the 11-year solar cycle oscillation plays a significant role in the space weather variables, with greater impact on GCR intensity at OULU compared to that at MOSC.

5 Summary and conclusion

A rigorous analysis involving the application of automated computational technique has been used in filtration of the impacts of 11-year solar cycle oscillations on large- and small-amplitude Forbush events of CR data from two NM (MOSC and OULU) stations for a full solar cycle 23 (from 1996 to 2008). After filtration of the impacts of this short-term periodic oscillation, a larger volume of small FD datasets was obtained at MOSC and OULU stations during the solar 23 than previously recorded using the same NM stations within the same time range. For validity purposes, a group of all FDs (big/large and small) were separated from the two stations. A statistical analytical/calculation method was employed, for the first time, to test the link between FD amplitudes and solar-geomagnetic variables in each dataset from the two stations before and after the effects of 11-year solar cycle oscillations were filtered. The results obviously show inconsistency in the datasets for both MOSC and

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OULU stations for the large and small FDs, respectively – specifically, strong correlations were obtained for the parameters' regression analyses after the effects of 11-year solar cycle oscillations were removed for both big and small FDs. These inconsistencies strongly suggest the influence of solar cycle oscillation variables, echoing concerns about "spurious regression" in the stationary time series. The two-dimensional statistical regression analyses between the FDs of the catalogues and space weather characteristics imply that CR flux intensity changes are not attributed to being driven by space weather phenomenon at the time of small FD events, but could be as a result of solar wind disturbance parameters when taking them (big/large and small FDs) together. The large volume of the small FDs suggests that they are triggered by the co-rotating interaction regions (CIRs), (see for example Belov *et al.*, 2001; Dumbović *et al.*, 2011, 2012; Bhaskar *et al.*, 2016; Okike and Menteso, 2024), might have diluted the correlation between the small FDs and their corresponding space geomagnetic characteristics. Moreover, since the two stations are of the same rigidity (see table 1), the lack or weak correlation between the large / small Fds and solar wind disturbance indices could be as results of complex interactions between FDs, and multiple solar wind disturbance variable (Dumbović *et al.*, 2012, see), which was more obvious before the removal of the impact of solar cycle oscillation when compared to the one after the removal. CR modulation is influenced by a complex interconnection between solar activity, interplanetary magnetic field and geomagnetic activity. The combination of these modulation effects of these factors on CR flux intensity speaks louder on the weak or absence of correlation between FDs (large and small) and the individual geomagnetic parameters before the filtration of solar cycle effects than after the removal of the influence of the solar cycle, which is high in small FD events, hence the term "spurious correlations". Most of the results obtained here are statistically significant at 95% confidence level. The results suggest that 11-year solar cycle oscillations have an impact on the GCR flux intensity.

We cannot conclude this work without recommending, in further work, the importance of disentangling the superimposed effects of CR diurnal anisotropies on FDs through the Fast Fourier Transformation technique developed by Okike and Umahi (2019a) as used in many works (see, for example, Okike, 2020b, 2021; Okike and Menteso, 2024; Okike *et al.*, 2025).

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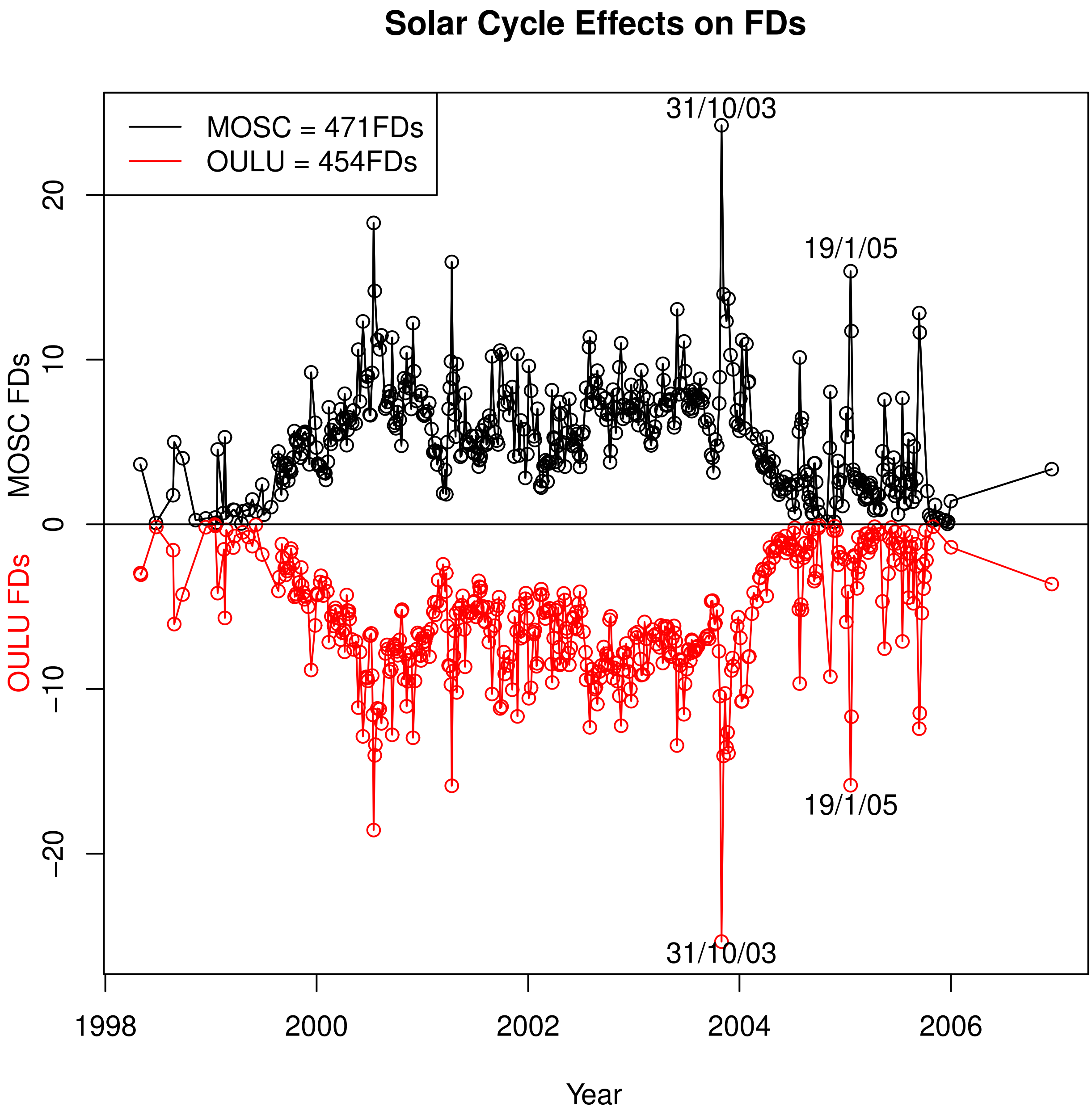

Figure 1. Solar cycle effects on FDs Before the removal of the effect of the solar cycle oscillation in MOSC (black) and OULU (red) stations.

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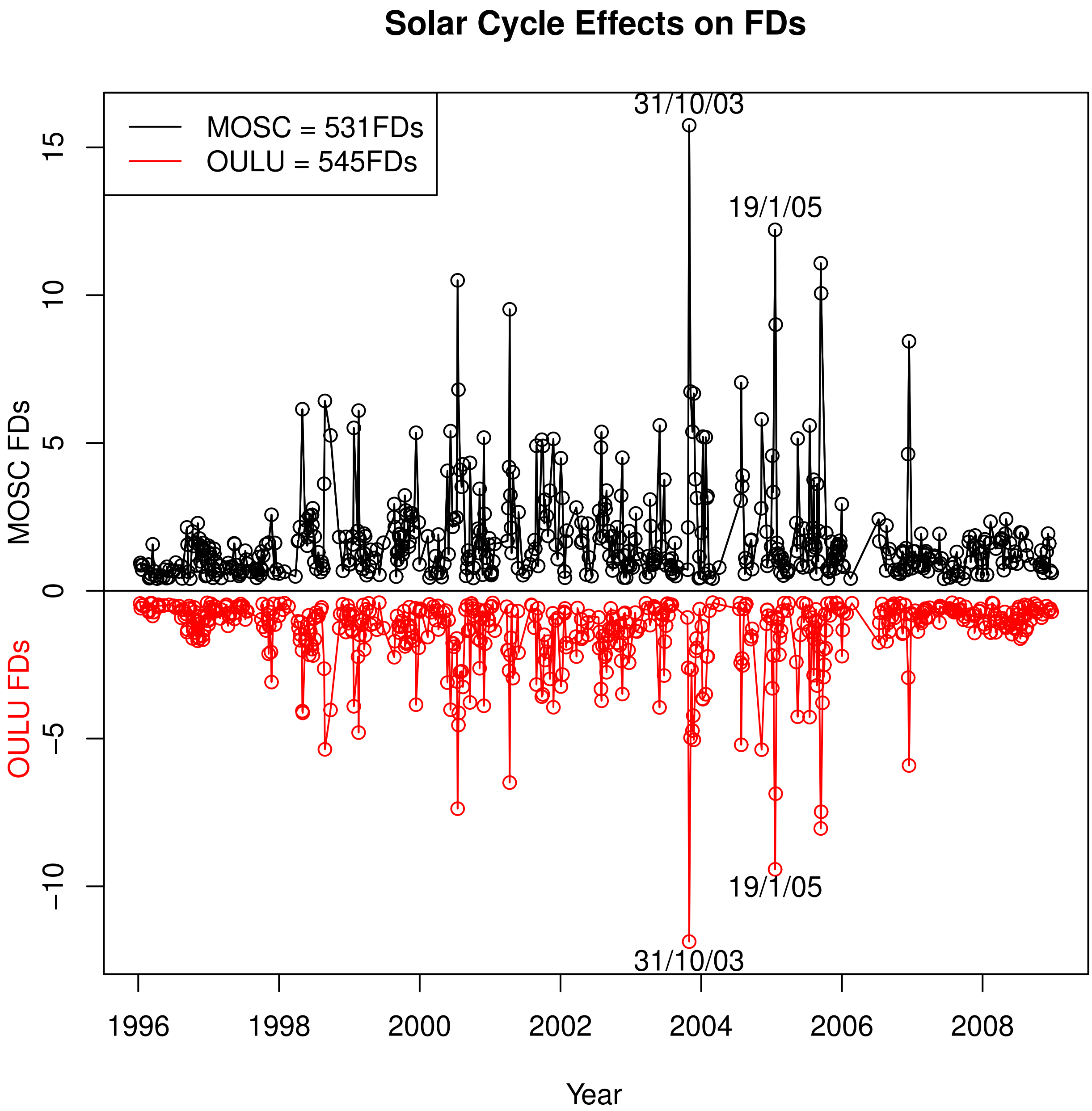

Figure 2. Solar cycle effects on FDs after the removal of the effect of the solar cycle oscillation in MOSC (black) and OULU (red) stations.

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Data Availability. The data used in the current work are available at http://cr0.izmiran.rssi.ru/common/links.htm and http://omniweb.gsfc.nasa.gov/ow.html

Author contributions. All the authors listed above worked together from Conceptualization, Data collection, Methodology, Analysis and the overall activity performed in the current manuscript.

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Table 2. MOSC FDs large/Big (FDs >3%) before the removal of solar cycle effects and the corresponding solar-geomagnetic characteristics.

S/N	Date	$FD_{MOSCBb}(\%)$	IMF	SWS	Kp	SSN	Dst	SI
1	1998-05-02	-3.64	14.5	601	53	96	-36	118.8
2	1998-08-27	-4.99	14.1	630	70	131	-129	137.8
3	1998-09-25	-4.01	18	713	60	149	-118	139.2
4	1999-01-24	-4.54	7.6	517	30	94	-38	156.8
5	1999-02-18	-5.29	17.1	599	60	155	-84	164.2
6	1999-08-20	-3.90	5.8	616	43	73	-37	155.2
7	1999-08-22	-4.42	6	428	20	103	-27	176.7
8	1999-08-25	-3.58	7.7	538	20	196	-15	212.9
9	1999-09-16	-3.63	6.2	572	40	165	-46	159.9
10	1999-09-18	-3.55	5.6	492	23	147	-23	153
11	1999-09-21	-3.72	7.2	379	23	65	-7	147.9
12	1999-09-29	-3.40	6.8	539	37	77	-30	125.3
13	1999-10-03	-3.32	7.9	400	20	98	-14	134.7
14	1999-10-05	-3.20	9.1	497	33	179	-12	146.2
15	1999-10-12	-4.06	7.3	578	50	210	-48	182.9
16	1999-10-16	-5.66	5.3	622	40	176	-33	187.8
17	1999-10-21	-5.15	18.4	441	30	140	9	157
18	1999-10-23	-5.03	7.3	620	43	114	-65	162.8
19	1999-10-25	-5.06	4.5	566	30	174	-45	177.2
20	1999-11-01	-4.77	7.2	440	23	163	-15	148.4
21	1999-11-06	-4.05	5.8	352	23	146	-1	147.4
22	1999-11-09	-4.28	6.3	615	40	239	-46	225.5
23	1999-11-14	-5.48	5.9	440	27	206	-62	214.2
24	1999-11-18	-5.55	6	541	33	225	-31	212.9
25	1999-11-20	-5.46	8.1	443	20	215	-16	199.5
26	1999-11-22	-5.62	9.8	453	23	194	-12	187.2
27	1999-12-02	-5.13	10	344	13	137	13	160.9
28	1999-12-07	-3.64	4.9	596	30	81	-14	148.8
29	1999-12-13	-9.23	11.4	489	33	141	-46	161
30	1999-12-27	-6.17	7.9	410	17	95	2	156.4
31	1999-12-31	-4.66	10.8	653	43	79	-18	125.8
32	2000-01-05	-3.69	6	521	33	108	-25	132
33	2000-01-07	-3.59	4.5	522	23	126	-21	144.8
34	2000-01-09	-3.54	3.6	357	7	112	-4	155.3
35	2000-01-13	-3.55	5.1	537	23	226	-23	195.4
36	2000-01-24	-3.15	10.1	366	27	118	-40	136.3
37	2000-01-29	-3.15	5.6	722	43	90	-26	123.9

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38	2000-01-31	-3.10	4.9	585	23	86	-12	134.5
39	2000-02-09	-3.80	5.6	459	23	160	-18	170.8
40	2000-02-12	-7.10	14.7	553	50	166	-76	159.1
41	2000-02-17	-5.12	6.3	394	13	160	-22	164.4
42	2000-02-19	-4.88	7.9	354	7	131	-5	141.5
43	2000-02-21	-5.73	14.3	423	33	135	-1	148.7
44	2000-03-01	-6.01	7.6	480	33	217	-22	228.7
45	2000-03-09	-5.45	6.5	391	10	229	-14	203
46	2000-03-15	-5.48	2.4	299	3	162	-6	175.9
47	2000-03-20	-5.48	7.3	348	13	236	7	208.7
48	2000-03-24	-6.98	6.6	649	23	295	-3	217.7
49	2000-03-30	-6.38	5.2	446	27	233	-2	205.
50	2000-04-04	-6.46	9.2	384	33	250	-38	206.9

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Table 3. MOSC small FDs (FDs $\leq 3\%$) before the removal of solar cycle effects and the corresponding solar-geomagnetic characteristics.

S/N	Date	$FD_{MOSCSb}(\%)$	IMF	SWS	Kp	SSN	Dst	SI
1	1998-06-25	-0.08	13.7	447	23	96	7	109.7
2	1998-08-23	-1.77	7.2	493	33	110	-23	129.3
3	1998-11-09	-0.25	15.8	455	57	93	-103	159.3
4	1998-12-14	-0.36	8	404	13	121	6	139.9
5	1999-01-16	-0.41	5	498	20	115	-27	153.4
6	1999-01-19	-0.10	5.4	371	10	168	-19	170.3
7	1999-01-21	-0.10	8.8	471	13	158	-18	169.7
8	1999-02-13	-0.68	5.8	483	20	198	-12	193.4
9	1999-02-23	-0.40	6.3	396	20	62	-21	124.3
10	1999-03-19	-0.89	5.4	377	17	152	-7	138.1
11	1999-03-24	-0.86	5.5	411	7	62	2	107.6
12	1999-04-16	-0.05	7.8	424	30	98	12	123.8
13	1999-04-22	-0.80	8	451	10	59	-6	101.4
14	1999-05-10	-0.89	5.2	419	10	191	5	172.8
15	1999-05-24	-1.51	7	435	23	120	21	140.4
16	1999-06-06	-0.77	4.6	387	7	220	15	172.9
17	1999-06-27	-2.41	10.8	507	37	259	2	214.3
18	1999-07-03	-0.58	5.3	544	20	217	-18	203.5
19	1999-07-28	-1.04	5.7	395	20	220	-7	203.9
20	1999-09-01	-1.79	6.1	531	33	140	-40	165.8
21	1999-09-05	-2.77	5.9	408	13	106	-9	123.8
22	1999-09-07	-2.52	9.4	433	30	103	-7	114.1
23	1999-09-09	-2.83	7.4	407	20	109	5	108
24	1999-09-25	-2.66	5.6	409	7	43	-16	126.1
25	2000-02-02	-2.70	4.6	457	20	94	-7	140.2
26	2001-03-13	-1.89	7.7	390	23	108	-14	145.6
27	2001-03-24	-1.82	5.5	423	23	218	-27	217.5
28	2001-12-22	-2.82	7.7	379	20	218	-40	234.9
29	2002-02-11	-2.33	8.1	491	27	173	-17	196.6
30	2002-02-15	-2.23	6.3	371	7	163	-3	190.3
31	2002-02-19	-2.62	7.7	401	13	124	-17	185.1
32	2002-03-09	-2.59	5.5	413	13	111	-5	204.8
33	2004-04-15	-2.80	6	382	17	51	1	97.4
34	2004-05-09	-2.49	3.8	447	13	42	1	95
35	2004-05-12	-2.69	5.7	422	23	70	-7	100.9
36	2004-05-16	-1.80	5	329	10	128	-3	121

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37	2004-05-19	-2.12	8.8	329	20	102	12	111.4
38	2004-05-25	-2.00	4.6	470	13	97	-1	105.1
39	2004-05-30	-2.58	8.5	436	23	61	2	102.4
40	2004-06-07	-2.14	5.3	450	17	57	-1	91.2
41	2004-06-10	-2.88	6.4	477	20	48	2	85
42	2004-06-21	-2.41	3.9	384	10	134	14	119.6
43	2004-06-26	-2.40	7.2	343	17	52	14	102.2
44	2004-06-30	-1.92	5	551	20	34	3	84.5
45	2004-07-03	-1.18	4.2	443	17	33	2	82.2
46	2004-07-10	-0.66	7.4	309	17	62	18	96.4
47	2004-07-17	-2.65	7.1	505	27	130	-39	154.1
48	2004-07-20	-2.42	6	527	20	149	-4	180.8
49	2004-08-15	-2.61	5.1	367	10	104	-7	142.4
50	2004-08-27	-1.64	7.1	399	13	36	-6	92.3

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Table 4. OULU large/Big FDs (FDs >3%) before the removal of solar cycle effects and the corresponding solar-geomagnetic characteristics.

S/N	Date	$FD_{OULUBb}(\%)$	IMF	SWS	Kp	SSN	Dst	SI
1	1998-05-04	-3.06	17.4	670	53	96	-118	123.2
2	1998-08-27	-6.06	14.1	630	70	131	-129	137.8
3	1998-09-25	-4.26	18	713	60	149	-118	139.2
4	1999-01-24	-4.18	7.6	517	30	94	-38	156.8
5	1999-02-18	-5.69	17.1	599	60	155	-84	164.2
6	1999-08-22	-4.05	6	428	20	103	-27	176.7
7	1999-08-25	-3.21	7.7	538	20	196	-15	212.9
8	1999-09-16	-3.08	6.2	572	40	165	-46	159.9
9	1999-10-17	-4.41	5.2	520	33	181	-33	176.8
10	1999-10-22	-4.23	14.2	608	57	124	-134	158.8
11	1999-10-24	-4.36	5.8	571	40	130	-58	157.1
12	1999-11-01	-3.53	7.2	440	23	163	-15	148.4
13	1999-11-12	-3.71	4.9	554	23	266	-34	227.1
14	1999-11-17	-4.15	10.6	447	27	235	-30	216.3
15	1999-11-20	-4.55	8.1	443	20	215	-16	199.5
16	1999-11-22	-4.37	9.8	453	23	194	-12	187.2
17	1999-12-03	-5.01	12.7	425	30	97	-7	147.5
18	1999-12-13	-8.84	11.4	489	33	141	-46	161
19	1999-12-27	-6.14	7.9	410	17	95	2	156.4
20	1999-12-31	-4.26	10.8	653	43	79	-18	125.8
21	2000-01-02	-4.21	5.1	679	30	75	-19	128.5
22	2000-01-04	-4.29	5.8	577	27	95	-15	130.3
23	2000-01-06	-4.26	6.9	533	33	126	-22	140
24	2000-01-13	-3.50	5.1	537	23	226	-23	195.4
25	2000-01-16	-3.13	5	389	17	241	-10	201
26	2000-01-24	-4.32	10.1	366	27	118	-40	136.3
27	2000-01-29	-3.58	5.6	722	43	90	-26	123.9
28	2000-02-07	-4.07	5.4	629	43	191	-35	177
29	2000-02-12	-7.16	14.7	553	50	166	-76	159.1
30	2000-02-21	-5.59	14.3	423	33	135	-1	148.7
31	2000-03-01	-6.17	7.6	480	33	217	-22	228.7
32	2000-03-06	-5.07	8.9	411	27	203	-8	219.1
33	2000-03-09	-5.28	6.5	391	10	229	-14	203
34	2000-03-13	-6.06	3.5	366	10	190	-13	186
35	2000-03-19	-5.71	8.3	366	20	198	2	206.5
36	2000-03-24	-6.10	6.6	649	23	295	-3	217.7

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37	2000-03-30	-6.58	5.2	446	27	233	-2	205.1
38	2000-04-05	-6.41	7.3	387	20	197	-34	194.7
39	2000-04-07	-7.74	9.9	573	50	143	-162	175.4
40	2000-04-14	-4.29	6.6	318	3	174	-2	166.3
41	2000-04-17	-5.23	6.2	457	23	168	-23	159.2
42	2000-04-19	-5.44	10.1	461	23	157	-7	169.2
43	2000-04-22	-5.26	5.5	449	13	221	1	204.1
44	2000-04-24	-5.75	9.4	485	33	244	-25	208.1
45	2000-05-03	-6.10	6.2	520	30	104	-12	139.6
46	2000-05-08	-7.60	9.8	360	10	87	19	139.6
47	2000-05-16	-7.11	8.4	444	30 258	-8	264.5	
48	2000-05-24	-11.13	13.7	636	60	183	-90	194.3
49	2000-05-30	-7.76	6.2	617	37	127	-29	150.5
50	2000-06-09	-12.88	10.2	609	13	184	-34	174.1

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Table 5. OULU small FDs (FDs $\leq 3\%$) before the removal of solar cycle effects and the corresponding solar-geomagnetic characteristics.

S/N	Date	$FD_{OULUSb}(\%)$	IMF	SWS	Kp	SSN	Dst	SI
1	1998-05-02	-2.96	14.5	601	53	96	-36	118.8
2	1998-06-26	-0.16	10.6	469	43	106	-43	112.8
3	1998-08-23	-1.57	7.2	493	33	110	-23	129.3
4	1998-12-14	-0.18	8	404	13	121	6	139.9
5	1999-01-14	-0.02	12.2	461	40	90	-67	132.4
6	1999-01-16	-0.10	5	498	20	115	-27	153.4
7	1999-02-15	-1.52	7.5	576	30	213	-9	185.5
8	1999-02-23	-0.34	6.3	396	20	62	-21	124.3
9	1999-03-19	-1.41	5.4	377	17	152	-7	138.1
10	1999-03-24	-0.71	5.5	411	7	62	2	107.6
11	1999-04-21	-0.49	7.1	537	23	62	-16	104.4
12	1999-05-10	-0.78	5.2	419	10	191	5	172.8
13	1999-05-24	-1.33	7	435	23	120	21	140.4
14	1999-06-05	-0.03	4.8	424	10	217	12	168.8
15	1999-06-27	-1.83	10.8	507	37	259	2	214.3
16	1999-09-03	-1.20	7.1	456	27	115	-20	141.7
17	1999-09-05	-1.99	5.9	408	13	106	-9	123.8
18	1999-09-13	-2.66	7.9	578	47	152	-60	156.5
19	1999-09-21	-2.83	7.2	379	23	65	-7	147.9
20	1999-09-29	-2.66	6.8	539	37	77	-30	125.3
21	1999-10-03	-1.68	7.9	400	20	98	-14	134.7
22	1999-10-05	-1.47	9.1	497	33	179	-12	146.2
23	1999-10-12	-2.40	7.3	578	50	210	-48	182.9
24	1999-11-09	-2.62	6.3	615	40	239	-46	225.5
25	2001-03-13	-2.43	7.7	390	23	108	-14	145.6
26	2001-03-24	-2.96	5.5	423	23	218	-27	217.5
27	2004-03-20	-2.77	6.2	403	23	76	-7	112.7
28	2004-03-22	-2.70	5.3	424	27	87	-9	115.6
29	2004-03-29	-2.85	5	612	23	101	-11	128.3
30	2004-04-11	-2.66	5	432	23	20	-14	90
31	2004-04-13	-2.35	3.5	468	17	53	-10	93.6
32	2004-04-15	-1.41	6	382	17	51	1	97.4
33	2004-04-24	-1.65	7.3	445	23	57	-4	112.9
34	2004-04-28	-2.02	7.7	481	20	35	6	90.7
35	2004-05-02	-1.64	7.9	390	17	49	1	99.1
36	2004-05-06	-1.41	7	540	20	35	-1	88

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37	2004-05-08	-1.42	4.6	481	23	30	-4	88.9
38	2004-05-14	-0.89	6.3	382	13	95	1	112.1
39	2004-05-22	-0.99	6.2	489	17	83	4	105
40	2004-05-24	-1.00	5.6	484	23	109	-3	107.9
41	2004-05-26	-1.17	4.4	427	7	76	9	106.1
42	2004-06-07	-0.71	5.3	450	17	57	-1	91.2
43	2004-06-10	-1.73	6.4	477	20	48	2	85
44	2004-06-13	-1.46	7.2	340	10	43	24	98.2
45	2004-06-21	-1.52	3.9	384	10	134	14	119.6
46	2004-06-26	-1.15	7.2	343	17	52	14	102.2
47	2004-06-30	-1.34	5	551	20	34	3	84.5
48	2004-07-06	-0.52	5.2	398	13	28	6	81.6
49	2004-07-10	-0.21	7.4	309	17	62	18	96.4
50	2004-07-13	-1.55	5.8	530	27	144	-3	131.6

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Table 6. MOSC FDs large/Big (FDs >3%) after the removal of solar cycle effects and the corresponding solar-geomagnetic characteristics.

S/N	Date	$FD_{MOSC_Ab}(\%)$	IMF	SWS	Kp	SSN	Dst	SI
1	1998-05-02	-5.74	14.5	601	53	96	-36	118.8
2	1998-08-23	-3.22	7.2	493	33	110	-23	129.3
3	1998-08-27	-6.02	14.1	630	70	131	-129	137.8
4	1998-09-25	-4.86	18	713	60	149	-118	139.2
5	1999-01-24	-5.11	7.6	517	30	94	-38	156.8
6	1999-02-18	-5.70	17.1	599	60	155	-84	164.2
7	1999-12-13	-4.95	11.4	489	33	141	-46	161
8	2000-05-24	-3.66	13.7	636	60	183	-90	194.3
9	2000-06-09	-5.00	10.2	609	13	184	-34	174.1
10	2000-07-16	-10.10	21.8	816	43	283	-172	226.1
11	2000-07-20	-6.40	8.1	533	43	346	-67	261.1
12	2000-07-29	-3.69	8.8	460	37	162	-38	157.9
13	2000-08-06	-3.12	6	515	30	198	-32	170.8
14	2000-08-12	-3.88	25	599	67	235	-128	194.3
15	2000-09-18	-3.93	19.2	744	53	159	-103	205.7
16	2000-11-07	-3.05	20.2	512	43	181	-89	176.6
17	2000-11-29	-4.78	9.2	512	47	182	-81	183.2
18	2001-04-09	-3.79	8.6	622	33	165	-53	165.4
19	2001-04-12	-9.12	15.1	659	40	155	-131	149.8
20	2001-04-29	-3.61	7.6	596	23	170	-18	194.5
21	2001-08-29	-4.51	4.2	459	13	146	-7	200.9
22	2001-09-26	-4.71	10.7	549	33	277	-72	284
23	2001-10-02	-4.50	7.5	497	50	223	-87	201.1
24	2001-11-25	-4.74	11.5	650	20	121	-106	165.6
25	2002-01-03	-4.08	5.9	342	7	220	-16	213
26	2002-07-30	-4.45	7.5	422	17	281	5	234.1
27	2002-08-02	-4.97	12.1	489	43	199	-59	185.7
28	2002-11-18	-4.10	9.3	378	23	128	-37	174.8
29	2003-05-31	-5.20	6.3	703	27	67	-43	116.3
30	2003-06-24	-3.35	8.5	541	37	104	-38	118.3
31	2003-10-31	-15.35	15.8	1003	63	239	-117	245.2
32	2003-11-07	-6.34	5.8	509	20	15	-9	89.4
33	2003-11-17	-4.98	6	750	47	42	-35	118.2
34	2003-11-24	-6.27	9.1	550	27	132	-29	172.8
35	2003-12-01	-3.37	6.7	447	23	143	-18	139.3
36	2004-01-10	-4.81	11.3	551	37	58	-24	115.3

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37	2004-01-25	-4.80	9.9	472	43	26	-65	99.1
38	2004-07-27	-6.65	17.4	904	77	90	-120	121.8
39	2004-08-01	-3.13	6.5	471	17	39	-25	85.8
40	2004-08-04	-3.50	5.6	334	7	56	-10	87.9
41	2004-11-10	-5.40	18.4	691	70	52	-176	102.6
42	2005-01-04	-4.17	5.7	713	37	22	-25	85.1
43	2005-01-19	-11.81	12.6	840	50	69	-64	128.3
44	2005-01-22	-8.60	13.2	766	40	48	-72	99.1
45	2005-05-16	-4.75	10.2	638	43	62	-85	101.4
46	2005-07-17	-5.19	10	457	33	12	-9	76.5
47	2005-08-07	-3.35	5.2	657	27	65	-25	94.9
48	2005-08-25	-3.21	5.3	664	33	68	-71	94.4
49	2005-09-13	-10.68	6	722	47	85	-76	115
50	2005-09-15	-9.66	7.8	684	47	66	-49	120.6

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Table 7. MOSC small FDs (FDs ≤ 3%) after the removal of solar cycle effects and the corresponding solar-geomagnetic characteristics.

S/N	Date	$FD_{MOSC_{A}s}(\%)$	IMF	SWS	Kp	SSN	Dst	SI
1	1996-01-21	-0.313019390581721	4.8	425	20	10	-11	69.5
2	1996-01-24	-0.472770083102496	4.6	362	13	13	-3	70.7
3	1996-02-23	-0.48545706371191	6.2	414	30	14	-15	72.3
4	1996-02-27	-0.0256786703601028	5.6	528	27	12	-20	70.7
5	1996-03-16	-1.17185595567867	5.5	370	17	14	-11	70.3
6	1996-03-23	-0.261634349030464	4.2	469	17	22	-28	71.6
7	1996-05-11	-0.0750692520775556	4.8	351	13	25	1	78
8	1996-05-16	-0.312465373961222	3.6	431	20	13	-14	72.6
9	1996-06-07	-0.0495290858725821	5.2	394	10	28	-2	75.4
10	1996-06-11	-0.301163434903046	4.3	339	10	13	9	70.2
11	1996-07-03	-0.269501385041549	6	450	23	13	-7	71.3
12	1996-07-31	-0.253185595567866	7.6	497	30	30	-13	82.7
13	1996-08-11	-0.448864265927987	3.6	361	10	29	7	74.8
14	1996-08-16	-0.0163711911357314	5.9	428	23	14	-5	69.3
15	1996-11-11	-1.16138504155124	3	353	10	20	-4	70
16	1996-11-19	-0.595290858725766	5.3	437	23	14	-23	72.6
17	1996-11-28	-0.418975069252083	4.5	454	17	47	-16	95.4
18	1996-11-30	-1.05509695290859	6.7	328	3	35	-3	85.1
19	1996-12-10	-0.775373961218829	8.3	533	37	17	-23	70.2
20	1996-12-16	-0.0978670360110846	4.8	518	27	25	-17	83.5
21	1996-12-24	-0.119972299168967	9.7	368	10	13	1	76.4
22	1997-01-30	-0.851412742382272	4.9	549	30	14	-20	71.5
23	1997-02-02	-0.279667590027693	5.4	472	23	33	-14	76.2
24	1997-02-04	-0.154598337950138	3.9	345	10	45	-11	78.4
25	1997-02-06	-0.593185595567866	4.9	422	23	26	-12	72.2
26	1997-03-07	-0.0322991689750779	5.1	359	17	14	-19	73.1
27	1997-04-01	-0.37972299168976	8.6	403	20	25	-3	76.2
28	1997-04-12	-0.53916897506926	3.9	496	20	18	-18	76.9
29	1997-04-19	-0.399916897506919	4.7	475	27	16	-34	70.6
30	1997-04-23	-0.134515235457056	7.5	372	20	13	-17	69.7
31	1997-05-13	-1.20451523545706	2.8	287	3	17	5	75.4
32	1997-05-15	-1.18124653739613	19.9	434	47	15	-62	74.7
33	1997-05-23	-0.472437673130189	2.2	305	7	55	-1	78.1
34	1997-05-26	-0.297091412742375	7.8	321	17	48	-2	82
35	1997-05-29	-0.293711911357332	2.5	327	3	19	-11	77.6
36	1997-06-08	-0.100775623268692	6.2	374	23	31	-28	75.4

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37	1997-06-11	-0.169113573407194	3.4	342	7	13	-7	73
38	1997-06-14	-0.238393351800551	2.6	301	3	31	1	72.9
39	1997-06-26	-0.276731301939053	2.8	373	10	24	-2	74.2
40	1997-07-10	-0.955207756232685	4.5	424	17	16	-14	70.8
41	1997-08-11	-0.23916897506926	4.2	408	17	53	-11	81.6
42	1997-09-04	-0.310193905817177	5.6	516	27	49	-50	94.6
43	1997-09-07	-0.0365927977839419	3.3	370	7	79	-8	103.6
44	1997-09-11	-0.286842105263149	4.6	463	20	100	-25	110
45	1997-09-15	-0.205650969529088	5.2	388	23	76	-32	99.1
46	1997-09-18	-0.744903047091411	11.2	346	30	38	-40	89
47	1997-09-26	-0.138282548476454	4.9	330	10	30	-5	89.5
48	1997-09-28	-0.369916897506919	4.8	440	27	21	-28	87.5
49	1997-10-02	-0.924210526315783	9.7	446	13	30	-32	86
50	1997-10-04	-0.296260387811635	5.7	379	10	30	-18	83.4

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Table 8. OULU large/Big FDs (FDs >3%) after the removal of solar cycle effects and the corresponding solar-geomagnetic characteristics.

S/N	Date	$FD_{OULU Ab}(\%)$	IMF	SWS	Kp	SSN	Dst	SI
1	1998-05-02	-3.67268698060941	14.5	601	53	96	-36	118.8
2	1998-05-04	-3.73047091412743	17.4	670	53	96	-118	123.2
3	1998-08-27	-4.96628808864266	14.1	630	70	131	-129	137.8
4	1998-09-25	-3.63232686980609	18	713	60	149	-118	139.2
5	1999-01-24	-3.50952908587257	7.6	517	30	94	-38	156.8
6	1999-02-18	-4.3983379501385	17.1	599	60	155	-84	164.2
7	1999-12-13	-3.45551246537396	11.4	489	33	141	-46	161
8	2000-06-09	-3.62565096952909	10.2	609	13	184	-34	174.1
9	2000-07-16	-6.97180055401662	21.8	816	43	283	-172	226.1
10	2000-07-20	-4.14288088642659	8.1	533	43	346	-67	261.1
11	2000-07-22	-3.73432132963989	5.7	425	27	310	-40	259
12	2000-09-18	-3.37836565096953	19.2	744	53	159	-103	205.7
13	2000-11-29	-3.49174515235457	9.2	512	47	182	-81	183.2
14	2001-04-12	-6.08980609418282	15.1	659	40	155	-131	149.8
15	2001-09-26	-3.18257617728532	10.7	549	33	277	-72	284
16	2001-10-01	-3.10545706371191	11.1	498	47	260	-99	216.9
17	2001-11-25	-3.541108033241	11.5	650	20	121	-106	165.6
18	2002-08-02	-3.32293628808864	12.1	489	43	199	-59	185.7
19	2002-11-18	-3.09426592797784	9.3	378	23	128	-37	174.8
20	2003-05-30	-3.54706371191136	16.7	669	50	70	-74	120.4
21	2003-10-31	-11.4693074792244	15.8	1003	63	239	-117	245.2
22	2003-11-07	-4.56839335180055	5.8	509	20	15	-9	89.4
23	2003-11-17	-4.32883656509695	6	750	47	42	-35	118.2
24	2003-11-21	-3.82698060941828	9.6	513	40	119	-140	172.8
25	2003-11-24	-4.64265927977839	9.1	550	27	132	-29	172.8
26	2004-01-08	-3.2494459833795	5.8	563	17	86	-16	116.1
27	2004-01-10	-3.26817174515236	11.3	551	37	58	-24	115.3
28	2004-01-25	-3.10016620498615	9.9	472	43	26	-65	99.1
29	2004-07-27	-4.81121883656509	17.4	904	77	90	-120	121.8
30	2004-11-10	-4.97612188365651	18.4	691	70	52	-176	102.6
31	2005-01-19	-9.02429362880886	12.6	840	50	69	-64	128.3
32	2005-01-22	-6.46462603878116	13.2	766	40	48	-72	99.1
33	2005-05-16	-3.86315789473684	10.2	638	43	62	-85	101.4
34	2005-07-17	-3.87495844875346	10	457	33	12	-9	76.5
35	2005-09-13	-7.6418836565097	6	722	47	85	-76	115
36	2005-09-15	-7.07662049861496	7.8	684	47	66	-49	120.6
37	2005-09-22	-3.38897506925207	5.4	345	17	24	-20	84.3
38	2006-12-15	-5.5108864265928	9.4	698	57	21	-116	84.4

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Table 9. OULU small FDs (FDs $\leq 3\%$) after the removal of solar cycle effects and the corresponding solar-geomagnetic characteristics.

S/N	Date	$FD_{OULUSa}(\%)$	IMF	SWS	Kp	SSN	Dst	SI
1	1996-01-21	-0.100997229916893	4.8	425	20	10	-11	69.5
2	1996-01-25	-0.0875069252077537	5.4	386	13	10	-4	71.7
3	1996-02-23	-0.272548476454294	6.2	414	30	14	-15	72.3
4	1996-02-25	-0.316121883656506	5.5	482	33	23	-32	71.8
5	1996-03-13	-0.0317451523545697	5.4	554	33	22	-28	70.5
6	1996-03-16	-0.45468144044321	5.5	370	17	14	-11	70.3
7	1996-03-19	-0.323157894736842	5.3	413	30	11	-20	69.4
8	1996-03-22	-0.324155124653744	3.9	602	30	22	-33	73.4
9	1996-04-13	-0.1486703601108	4.8	437	20	11	-18	69.3
10	1996-04-19	-0.110664819944595	5.1	685	40	16	-26	71.2
11	1996-05-12	-0.0976731301939071	5.3	342	10	22	5	75.1
12	1996-06-09	-0.0777839335180033	4.7	362	10	35	3	72
13	1996-07-03	-0.108282548476454	6	450	23	13	-7	71.3
14	1996-07-31	-0.120886426592797	7.6	497	30	30	-13	82.7
15	1996-08-11	-0.514072022160663	3.6	361	10	29	7	74.8
16	1996-08-17	-0.236759002770086	6.4	520	23	15	-10	69.5
17	1996-08-29	-0.465955678670362	7.2	568	43	15	-34	75
18	1996-11-09	-0.6386703601108	5.7	372	23	11	-12	68.9
19	1996-11-19	-0.454958448753459	5.3	437	23	14	-23	72.6
20	1996-11-30	-1.12357340720222	6.7	328	3	35	-3	85.1
21	1996-12-02	-1.25470914127423	8.6	303	20	13	3	75.7
22	1996-12-08	-0.942188365650973	3.5	370	7	14	-5	66.6
23	1996-12-12	-0.514487534626041	3.8	577	20	30	-17	78.6
24	1996-12-24	-0.00883656509695356	9.7	368	10	13	1	76.4
25	1997-01-06	-0.177396121883658	5.4	349	7	16	8	70.6
26	1997-01-27	-0.307229916897504	4.9	510	30	12	-22	71.3
27	1997-01-30	-0.23678670360111	4.9	549	30	14	-20	71.5
28	1997-02-02	-0.130027700831024	5.4	472	23	33	-14	76.2
29	1997-02-04	-0.140221606648201	3.9	345	10	45	-11	78.4
30	1997-02-06	-0.233268698060938	4.9	422	23	26	-12	72.2
31	1997-03-07	-0.239806094182823	5.1	359	17	14	-19	73.1
32	1997-03-30	-0.140332409972298	5	471	23	28	-31	73.8
33	1997-04-02	-0.080969529085869	4.7	461	20	46	-16	80.4
34	1997-04-04	-0.0737119113573408	5	420	27	40	-16	78.6
35	1997-04-11	-0.787368421052633	13.8	467	40	34	-39	77.4
36	1997-04-17	-0.484099722991687	6.3	517	37	19	-44	72.3

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37	1997-04-19	-0.461024930747926	4.7	475	27	16	-34	70.6
38	1997-05-12	-0.365540166204983	3.9	301	3	14	1	73.7
39	1997-05-15	-0.555069252077565	19.9	434	47	15	-62	74.7
40	1997-05-26	-0.133905817174518	7.8	321	17	48	-2	82
41	1997-06-08	-0.118393351800551	6.2	374	23	31	-28	75.4
42	1997-06-12	-0.152271468144045	4.4	339	13	26	-4	71.8
43	1997-06-14	-0.119445983379501	2.6	301	3	31	1	72.9
44	1997-06-16	-0.0492520775623234	5.7	391	13	33	-1	74.4
45	1997-06-24	-0.141274238227143	5	386	10	15	-4	72.2
46	1997-06-29	-0.120443213296403	5.3	407	17	13	-23	72.6
47	1997-07-10	-0.573130193905818	4.5	424	17	16	-14	70.8
48	1997-07-20	-0.297340720221609	5.8	472	13	14	-12	73.5
49	1997-10-01	-0.568642659279776	9.2	466	43	36	-48	87.3
50	1997-10-08	-0.0472853185595523	6.6	391	27	23	-24	82.7

Table 10. Regression results for FD and related solar-terrestrial parameters at MOSC station before and after the effects of the 11-year solar cycle are removed for large (Big) FD (FD >3%). "S/N" stands for serial number, "Parameter" represents each of the two continuous variables, (FD-BB represents FD values of large/big FD before the effects of solar cycle are removed; FD-BA represents the FD values of large/big FD after the effects of solar cycle are removed), "r" indicates correlation coefficient and "p-value" represents chance probability. Note: "" represents statistically significant correlations at the 95% confidence level; while "*" represents not statistically significant correlations at the 95% confidence level.**

S/N	$parameter$	r	$p-values$
1	FD-BB-IMF	-0.41**	4.77×10^{-10}
2	FD-BB-SWS	-0.47**	3.92×10^{-14}
3	FD-BB-Kp	-0.38**	3.86×10^{-08}
4	FD-BB-SSN	-0.27**	1.66×10^{-03}
5	FD-BB-Dst	0.25**	1.33×10^{-11}
6	FD-BB-SI	-0.28**	6.02×10^{-04}
7	FD-BA-IMF	-0.50**	6.44×10^{-02}
8	FD-BA-SWS	-0.79**	1.45×10^{-07}
9	FD-BA-Kp	-0.59**	6.54×10^{-03}
10	FD-BA-SSN	-0.31*	0.79
11	FD-BA-Dst	0.61**	3.20×10^{-03}
12	FD-BA-SI	-0.35*	0.54

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Table 11. Regression Results for Fd and corresponding solar-parameters at MOSC station before and after the effects of the 11-year solar cycle are removed for Small FDs (FD $\leq 3\%$). "S/N" stands for serial number, "Parameter" represents each of the two continuous variables, (FD-SB represents FD values of small FDs before the effects of solar cycle are removed; FD-SA represents the FD values of small FDs after the effects of solar cycle are removed), "r" indicates correlation coefficient and "p-value "represents chance probability. Note: "" represents statistically significant correlations at the 95% confidence level; while "*" represents not statistically significant correlations at the 95% confidence level..**

S/N	$parameter$	r	$p-values$
1	FD-SB-IMF	-0.25*	0.50
2	FD-SB-SWS	-0.33**	9.99×10^{-02}
3	FD-SB-Kp	-0.31*	0.17
4	FD-SB-SSN	-0.10*	0.34
5	FD-SB-Dst	0.25*	0.47
6	FD-SB-SI	-0.15*	0.73
7	FD-SA-IMF	-0.39**	1.16×10^{-09}
8	FD-SA-SWS	-0.31**	1.47×10^{-05}
9	FD-SA-Kp	-0.34**	5.26×10^{-07}
10	FD-SA-SSN	-0.39**	1.64×10^{-08}
11	FD-SA-Dst	0.33**	1.78×10^{-06}
12	FD-SA-SI	-0.40**	1.31×10^{-10}

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Table 12. Regression results for FD and related solar-terrestrial parameters at OULU station before and after the effects of the 11-year solar cycle are removed for large (Big) FD (FD >3%). "S/N" stands for serial number, "Parameter" represents each of the two continuous variables, (FD-BB represents FD values of large/big FD before the effects of solar cycle are removed; FD-BA represents the FD values of large/big FD after the effects of solar cycle are removed), "r" indicates correlation coefficient and "p-value" represents chance probability. Note: "" represents statistically significant correlations at the 95% confidence level; while "*" represents not statistically significant correlations at the 95% confidence level.**

S/N	$parameter$	r	$p-values$
1	FD-BB-IMF	-0.44**	9.85×10^{-11}
2	FD-BB-SWS	-0.42**	5.95×10^{-10}
3	FD-BB-Kp	-0.39**	3.72×10^{-08}
4	FD-BB-SSN	-0.22**	3.20×10^{-02}
5	FD-BB-Dst	0.47**	6.75×10^{-13}
6	FD-BB-SI	-0.26**	4.76×10^{-03}
7	FD-BA-IMF	-0.48*	0.25
8	FD-BA-SWS	-0.85**	2.96×10^{-07}
9	FD-BA-Kp	-0.60**	2.99×10^{-02}
10	FD-BA-SSN	-0.34*	0.88
11	FD-BA-Dst	0.57**	6.73×10^{-02}
12	FD-BA-SI	-0.35*	0.85

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Table 13. Regression Results for Fd and corresponding solar-parameters at OULU station before and after the effects of the 11-year solar cycle are removed for Small FDs (FD $\leq 3\%$). "S/N" stands for serial number, "Parameter" represents each of the two continuous variables, (FD-SB represents FD values of small FDs before the effects of solar cycle are removed; FD-SA represents the FD values of small FDs after the effects of solar cycle are removed), "r" indicates correlation coefficient and "p-value "represents chance probability. Note: "" represents statistically significant correlations at the 95% confidence level; while "*" represents not statistically significant correlations at the 95% confidence level..**

S/N	$parameter$	r	$p-values$
1	FD-SB-IMF	-0.38**	2.37×10^{-02}
2	FD-SB-SWS	-0.40**	1.51×10^{-02}
3	FD-SB-Kp	-0.52**	6.51×10^{-05}
4	FD-SB-SSN	-0.31*	0.16
5	FD-SB-Dst	0.41**	1.17×10^{-02}
6	FD-SB-SI	-0.35**	6.05×10^{-02}
7	FD-SA-IMF	-0.40**	1.25×10^{-10}
8	FD-SA-SWS	-0.25**	1.66×10^{-03}
9	FD-SA-Kp	-0.30**	1.39×10^{-05}
10	FD-SA-SSN	-0.35**	8.50×10^{-08}
11	FD-SA-Dst	0.34**	4.42×10^{-07}
12	FD-SA-SI	-0.37**	5.92×10^{-09}