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The Dependence between Solar Flare Emergence and the Average Background Solar X-Ray Flux Emission

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Abstract

Solar flares, sudden bursts of intense electromagnetic radiation from the Sun, can significantly disrupt technological infrastructure, including communication and navigation satellites. To mitigate these risks, accurate forecasting of solar activity is crucial. This study investigates the potential of the Sun's background X-ray flux as a tool for predicting solar flares. We analyzed data collected by solar telescopes and satellites between the years 2013 and 2023, focusing on the duration, frequency, and intensity of solar flares. We compared these characteristics with the background X-ray flux at the time of each flare event. Our analysis employed statistical methods to identify potential correlations between these solar phenomena. The key finding of this study reveals a significant positive correlation between solar flare activity and the Sun's background X-ray flux. This suggests that these phenomena are interconnected within the framework of overall solar activity. We observed a clear trend: periods with increased occurrences of solar flares coincided with elevated background flux levels. This finding has the potential to improve solar activity forecasting. By monitoring background flux variations, we may be able to develop a more effective early warning system for potentially disruptive solar flares. This research contributes to a deeper understanding of the complex relationship between solar flares and the Sun's overall radiative output. These findings indicate that lower-resolution X-ray sensors can be a valuable tool for identifying periods of increased solar activity by allowing us to monitor background flux variations. A more affordable approach to solar activity monitoring is advised.

Keywords

Space Weather, Solar Flare, Solar Activity, Sunspots, Solar Cycle

1. Introduction

Solar flares, intense bursts of energy, and radiation originating from the Sun's surface are closely associated with temporary phenomena known as sunspots—darker spots on the Sun's photosphere. The solar activity cycle, also termed the solar or sunspot cycle, typically spans around 11 years, with variations in individual cycle durations. This cycle consists of a period of increasing solar activity, termed solar maximum, followed by a period of decreasing activity known as solar minimum.

During solar maximum, the Sun becomes more active, with an elevated probability of solar flares occurring [1]. These flares release substantial energy across the electromagnetic spectrum, including X-rays and other forms of radiation. Sun activity occurs due to the thermo-nuclear process with very high temperatures in the Sun [2]. Such solar flares can impact space weather, influencing Earth's ionosphere and communication systems [3].

Understanding solar activity cycles is crucial for comprehending the Sun's behavior and its impact on space weather. Researchers utilize various instruments, such as solar telescopes and satellites, to monitor solar activity and predict the timing and intensity of solar cycles. This knowledge is particularly vital for space agencies, satellite operators, and other organizations reliant on accurate space weather forecasts to safeguard equipment and human activities in space.

The Geostationary Operational Environmental Satellites (GOES) play a pivotal role in observing and measuring solar phenomena, including solar flares. Positioned in geostationary orbits, GOES satellites continuously monitor specific Earth regions [4], offering real-time data on various space weather aspects, including X-ray flux from the Sun. Solar flare sizes are categorized as A, B, C, M, and X, measured in X-ray flux units of 10^{-7} to 10^{-4} $W \cdot m^{-2}$. Information gathered by these satellites is crucial for predicting space weather events that can impact communication systems, navigation, and other Earth technologies.

Within the solar activity cycle, a higher probability of solar flares occurs during the more active phase [1], characterized by increased solar flares and stronger solar flares, as well as more active areas and sunspots. The correlation between the Sun's activity, active areas (such as sunspots), background flux, and the intensity of solar flares is a complex and dynamic relationship. Researchers use correlations and data from these satellites to develop models for predicting solar activity, enhancing our ability to forecast space weather events. Understanding this correlation helps scientists and researchers predict solar activity during different phases of the solar cycle. The correlation between the size of active zones, background flux, and the intensity of solar flares aligns with the general understanding that increased solar activity, marked by the presence of sunspots and higher background flux, is associated with a higher likelihood of solar flares occurring, and those flares can be more intense [5].

A significant research study focused on tracking the progression of the solar cycle by analyzing the solar X-ray background. The study demonstrated that the variance in this X-ray background follows a cyclical pattern from solar minimum to maximum. Consequently, the X-ray background could serve as an important tool in forecasting X-ray flares [6].

McIntosh performed a correlation study with solar flares, predicting X-ray solar flares' appearance based on sunspot activity [7]. They found a correlation between sunspots, background flux, and solar flare activity. It was also discovered that a higher number of sunspots correlates with an increased occurrence of Solar Flares with higher intensity, especially in the peak active years of the solar cycle [8].

Previous studies on solar cycles 22, 23, and 24 utilized machine learning and prediction techniques based on the ratio of peak X-ray flare flux to background X-ray flux. This approach successfully classified solar flares according to their intensity, highlighting a strong link between flares and background flux. The studies achieved high prediction rates based on peak flare energy: 100% for X-class flares, 76% for M-class, 80% for C-class, and 81% for B-class flares, specifically for solar cycle 24 [9].

Utilizing machine learning models has shown promise in predicting strong solar flares and background X-ray fluxes based on the number of solar flares and their duration [10]. Moreover, there are studies [11] [12] that utilized artificial intelligence algorithms to predict solar flare occurrence by integrating data on sunspots, solar magnetic fields, and historical solar flare events. Integrating multiple parameters through machine learning models enhances the predictive accuracy of solar activity, offering valuable insights for space weather forecasting.

The Sun, often perceived as a constant source of energy, displays a surprising degree of variability. This variation manifests primarily through solar flares, sudden bursts of intense radiation erupting from the Sun's surface. These flares are intricately linked to the Sun's magnetic field, which undergoes an approximate 11-year cycle. Conversely, solar minimums bring a decline in flare activity, resulting in a calmer Sun. This cyclical fluctuation in solar flare occurrence classifies the Sun as a variable star, albeit a subtle one compared to the dramatic variations observed in other stellar types.

2. Data

Solar flare activity is monitored by the GOES-15 satellite by an onboard XRS instrument that measures 1 to 8 Ångströms X-rays near Earth at 2-second intervals. The system aims to measure disk-integrated solar X-ray and EUV fluxes (https://space.oscar.wmo.int/satellites/view/goes_15). Solar flares were traced daily from the SpaceWeatherLive website
(https://www.spaceweatherlive.com/en/solar-activity/solar-flares), which reports flare details as well as presents their plots sorted by flare appearance. We have collected and analyzed data on solar flares from 2013 to 2023, focusing only on flares of class C, M, and X having units ranging from 10^{-6} to 10^{-4} W·m^{-2}. In particular, the year 2014 from solar cycle 24 showed a very active year. As of 2020,

we are currently experiencing the lowest phase of solar activity in solar cycle 25. Although solar flare appearances cannot be predicted with complete accuracy, we estimate that maximal solar activity should occur during the years 2024-2025 in the current solar cycle 25. As part of this research, we have also gathered data on the disk-integrated solar X-ray daily background.

The solar flares are also characterized by their duration and rise time distribution. A solar flare can last from seconds to several hours.

In this study, we aimed to investigate the correlation between high-magnitude solar flares and background flux. After collecting and analyzing data, we searched for evidence to support this relationship.

3. Results and Discussion

In January 2014, one of the longest flares that lasted for more than 19 hours was observed. Another flare that lasted for over 10 hours was observed in August 2014. The sun was quite active in the year 2014, which was the peak year of the previous 24th solar cycle. The time distribution of solar flares is an essential component in studying their activity and analyzing data diversity. For this research, we collected data on solar flares and background flux from 2013 to 2023 to analyze their relationship and understand the variations in background flux behavior along with strong solar flares rise.

Table 1. A sample list of solar flare and background flux data that were collected between the years 2013 and 2023.

Year	Date	SF Class and Size	Start	Maximum	End	Duration	Background Flux W/m^2	M and X SF number on the day	Total number of SF on That Day	Total number of SF on the day Before
2014	27/01/2014	M4.9	22:05	22:10	22:15	0:10	C1.2	3	10	3
2014	28/01/2014	M4.9	19:00	19:40	19:46	0:46	C1.4	7	13	10
2014	30/01/2014	M6.6	15:48	16:11	16:28	0:40	C1.2	3	9	11
2014	01/02/2014	M3.0	7:14	7:23	7:36	0:22	C1.4	2	9	6
2014	02/02/2014	M3.1	18:05	18:11	18:18	0:13	C1.8	4	17	9
2014	28/09/2014	M5.1	2:39	2:58	3:19	0:40	C1.3	2	6	5
2014	06/11/2014	M5.4	3:32	3:46	4:02	0:30	B9.9	3	7	6
2014	16/11/2014	M5.7	17:35	17:48	17:57	0:22	B9.5	1	8	4
2015	28/09/2015	M7.6	14:53	14:58	15:03	0:10	C1.0	4	17	16
2017	03/04/2017	M5.8	14:19	14:29	14:34	0:15	C1.2	2	16	10
2022	26/08/2022	M7.2	12:08	12:14	12:21	0:13	C1.64	3	16	27
2023	15/01/2023	M6.03	3:08	3:42	4:08	1:00	C3.32	2	5	10
2023	20/05/2023	M8.96	12:25	12:35	12:40	0:15	C2.3	8	27	21
2023	26/07/2023	M4.63	10:17	10:37	10:48	0:31	C1.96	3	14	10

We have been examining the solar flare (SF) activity on a daily basis from 2013 to 2023. Our team has created a comprehensive database that includes the year, date, strong SF intensity, start time, maximum time, end time, and total duration. We have also kept a record of the total number of SFs, the number of class M or class X SFs on a particular day, and the number of SFs on the previous day. Additionally, we have included the background flux for each day. An example is listed in **Table 1**.

3.1. Background Flux Subtraction of the Current Day Minus the Day Before

A subtraction was performed on the current day's background flux size and the previous day's to recognize the change in background flux. We specifically examined days with a positive delta of at least 150 W/m^2. A total of 2233 class C, M, and X SF events were collected between 2013 and 2023. Out of all the events, 983 SF events (44%) showed a positive delta above 1 W/m^2. There were 316 events (14%) that had a delta of 0, and 299 events (approximately 13%) showed a difference of over 150 $W \cdot m^{-2}$ in the subtraction.

For the group of events that showed a background difference of over 150 $W \cdot m^{-2}$ we found that out of the total 299 events observed, 210 events (70%) had a high number of daily SFs, with over 7 SFs occurring per day. Additionally, 111 events (37%) had a long-duration SF, with the highest SF on that day lasting for more than 30 minutes. Furthermore, 54 events (18%) had both a high number of daily SFs and long-duration SFs. From the collected data analysis, it was shown that there is a strong correspondence between numeroussolar flares and long-duration solar flares to changes in background flux.

The Pearson Coefficient correlation is widely used for performing linear statistical correlation analysis between two sets of data. The correlation sign, denoted by "r", ranges between −1 to 1. When "r" equals 0, it indicates no correlation between the two sets of data. This correlation method helps to determine the strength and direction of the relationship between the two sets of parameters. In other words, if one parameter changes direction, the second parameter is also expected to change direction.

We conducted various correlation tests to examine the entire database of solar flares and background flux variations over the years. Test 1 involved analyzing events with a background deviation of above 200 $W \cdot m^{-2}$ only, in comparison to long-duration solar flares. The Pearson correlation coefficient for Test 1 was 0.527, indicating a strong positive correlation. This means that when a solar flare lasts over 30 minutes, there will be a significant increase above 200 $W \cdot m^{-2}$ in the background flux. In Test 2, we examined events that had a background deviation of more than 200 $W \cdot m^{-2}$. We compared these events to high daily amounts of solar flares with a long duration. The Pearson correlation coefficient for Test 2 was 0.431, which indicates a moderate positive correlation between the two. Our findings suggest that when there is a solar flare with a long duration of over 30 minutes and a high amount of solar flares above 7, we can expect a significant jump above 200 W·m^{-2} in the background flux. Test 3 is similar to Test 1, but includes events with a background deviation above 150 W·m^{-2} compared to long-duration solar flares. The Pearson correlation coefficient for Test 3 was 0.527, which remained unchanged compared to Test 1. Test 4 is similar to Test 1, but it includes events with a background deviation above 400 W·m^{-2} in comparison to long-duration solar flares. The Pearson correlation coefficient for Test 4 was 0.506, which indicates a strong positive correlation, although it is lower than the coefficient of Test 1. For Test 5, we analyzed events that had a background deviation of more than 400 W·m^{-2}. We compared these events to days with high amounts of solar flares that lasted for a long time. The Pearson correlation coefficient for Test 5 was 0.448, which is slightly higher than the correlation coefficient of Test 2.

The data in **Figure 1** shows a high frequency of daily solar flares and a correlation between changes in background flux and long durations. During the years 2013-2023, there is a correlation between the background increase above 150 W·m^{-2} and the occurrence of two solar flare properties: SF long duration and high daily flare count.

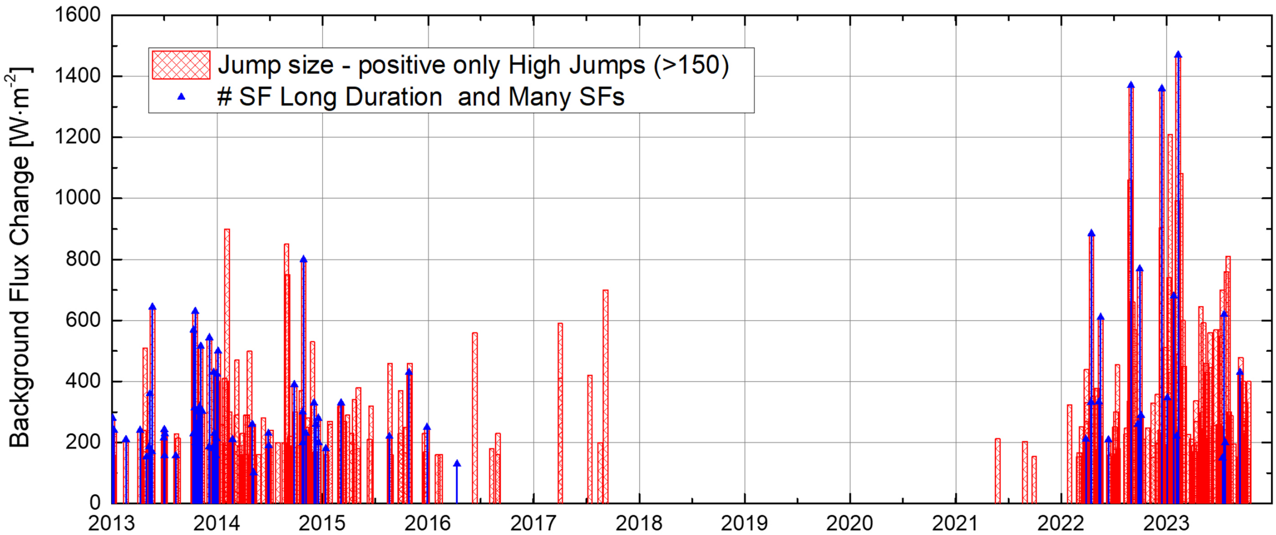


Figure 1. Correlation between background rise above 150 W·m^{-2} and solar flare properties during 2013-2023.

Our analysis reveals a clear relationship between the duration of solar flares and subsequent increases in background flux. This trend strengthens when we consider not only duration but also the total number of flares occurring on a given day. In this case, a moderate to strong association emerges between the combined influence of flare duration and frequency on the magnitude of background flux increase.

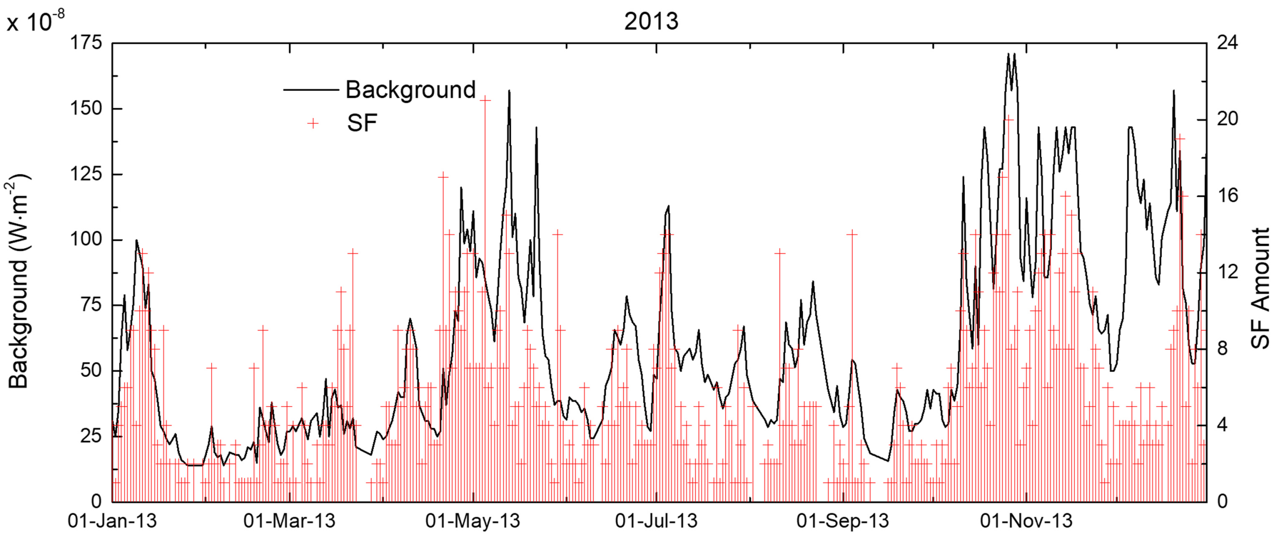
3.2. Solar Flare Amount against Background Flux

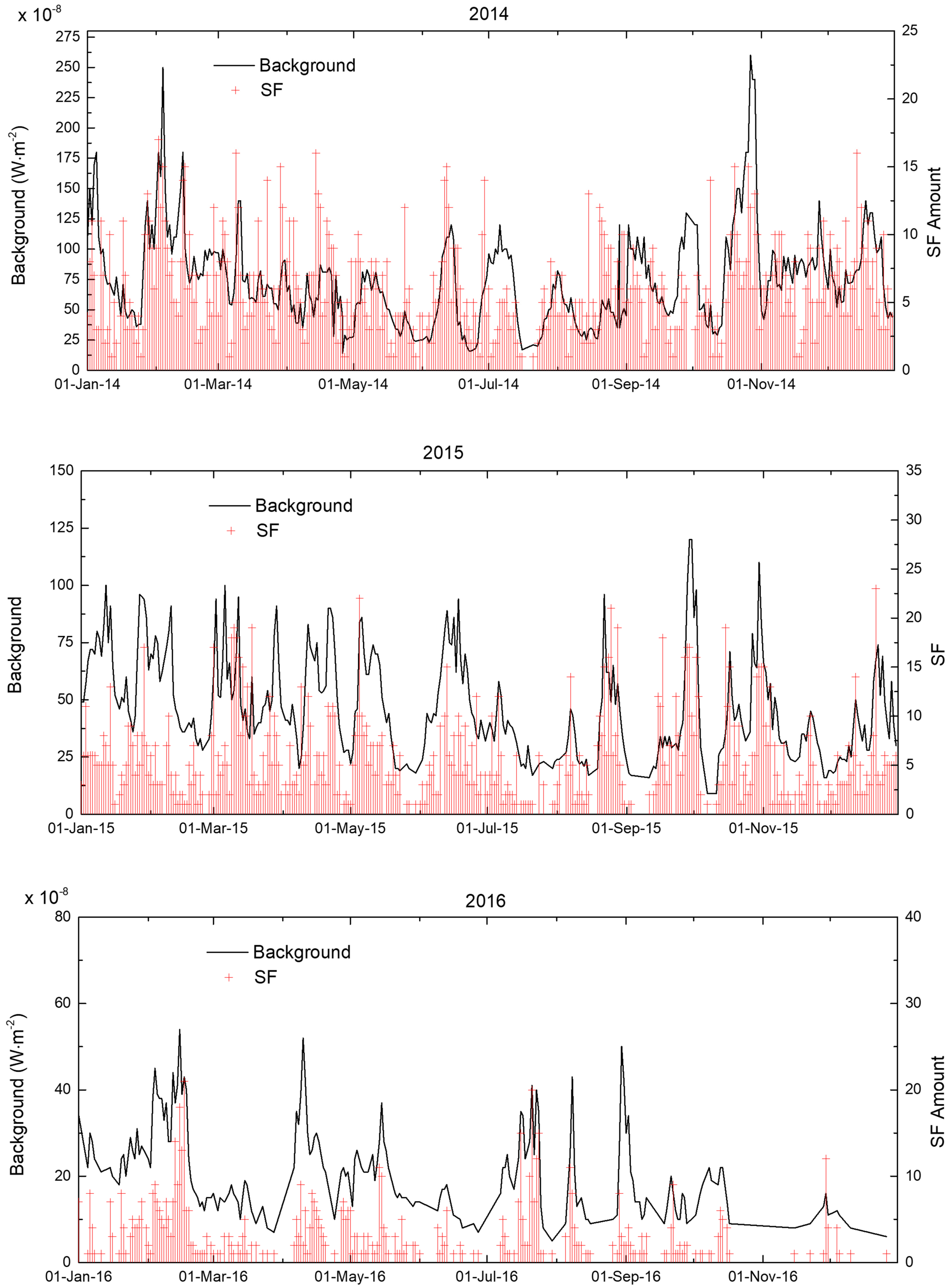
We examined our database to find a relationship between daily solar flarenumbers and background flux intensities each year. We considered the 11-year solar activity cycle, which affects the occurrence of solar flares from year to year. Table 2 lists the Pearson correlation coefficients between daily solar flare amount and background flux. Figure 2 depicts the solar flares' daily amount and the background flux in each year from 2013 to 2023.

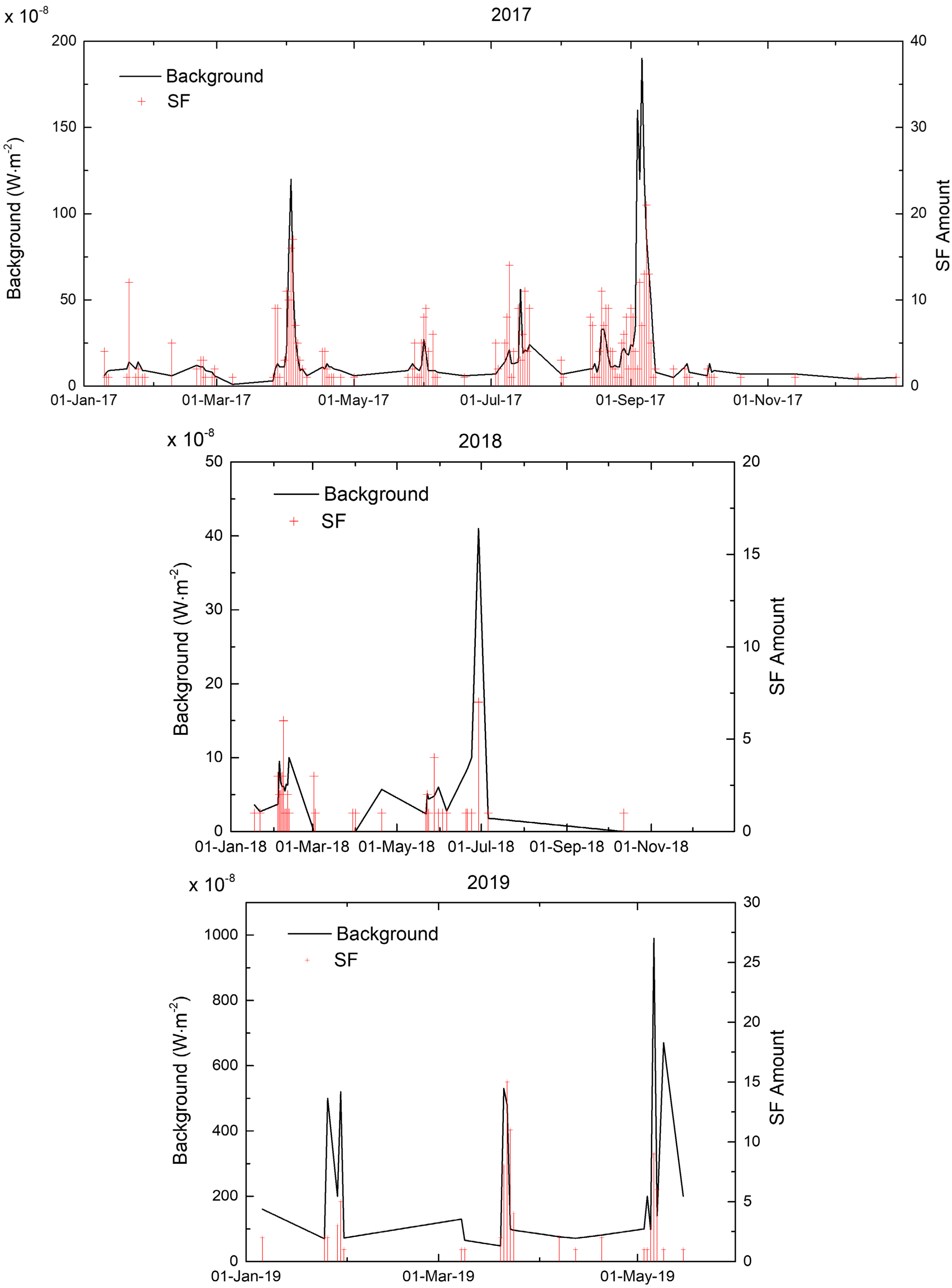
Table 2. Pearson correlation coefficient (PCC r) values between total solar flare amount and background flux for each year from 2013 to 2023.

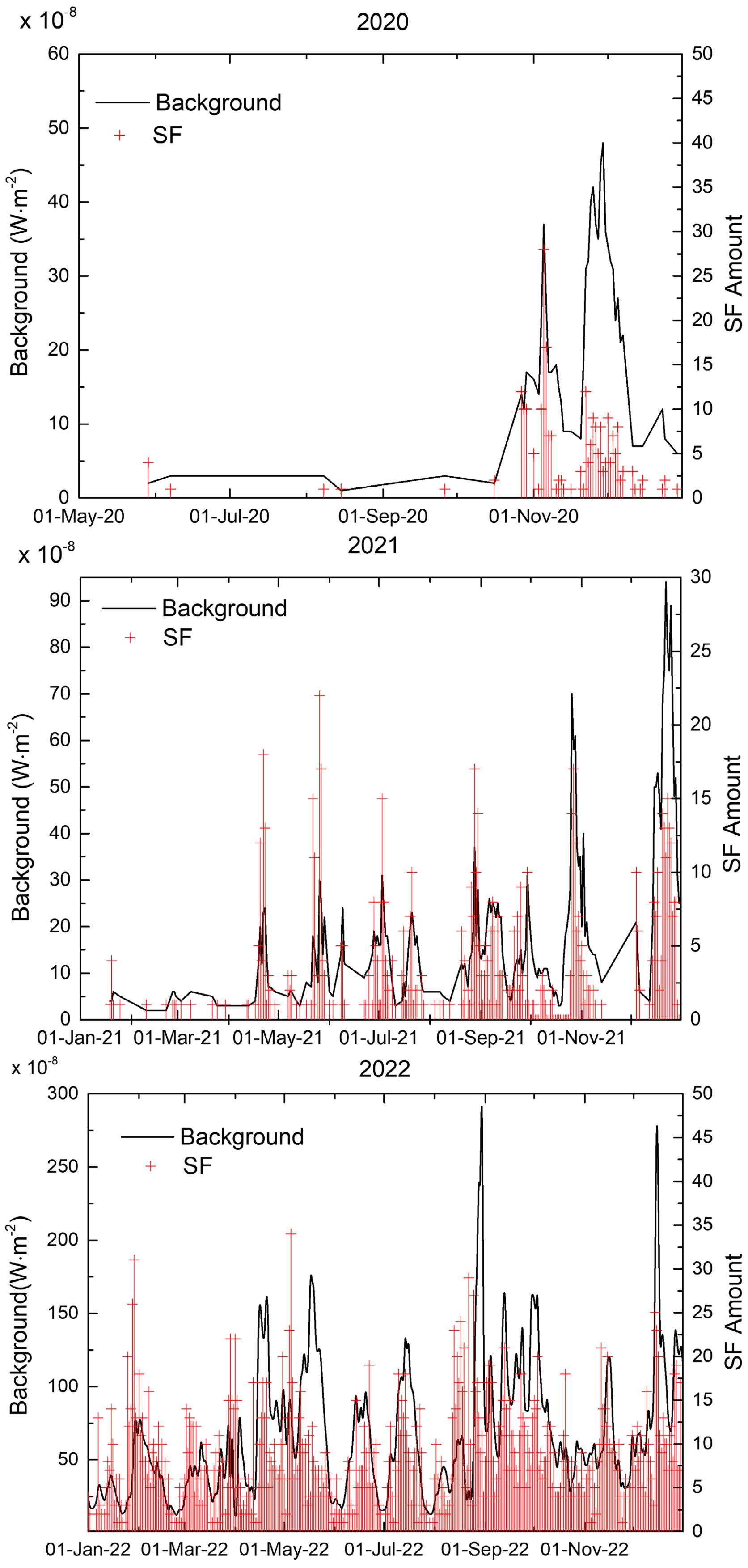
Year	Total Solar Flares	PCC r
2013	1908	0.59162
2014	2175	0.42129
2015	1875	0.51585
2016	715	0.65397
2017	484	0.49819
2018	53	0.6162
2019	84	0.4432
2020	236	0.49692
2021	719	0.64575
2022	3113	0.39752
2023	3385	0.40529

While the PCC r values in Table 2 range from 0.3975 to 0.654, indicating some variation, the yearly total number of solar flares does not appear to significantly influence these values.




2014
x 10^-8
Background (W·m^-2)
SF Amount
Background
SF
01-Jan-14
01-Mar-14
01-May-14
01-Jul-14
01-Sep-14
01-Nov-14
2015
Background
SF
01-Jan-15
01-Mar-15
01-May-15
01-Jul-15
01-Sep-15
01-Nov-15
2016
x 10^-8
Background (W·m^-2)
SF Amount
Background
SF
01-Jan-16
01-Mar-16
01-May-16
01-Jul-16
01-Sep-16
01-Nov-16


2017
x 10^-8
Background (W·m^-2)
SF Amount
Background
SF
200
150
100
50
0
40
30
20
10
0
01-Jan-17
01-Mar-17
01-May-17
01-Jul-17
01-Sep-17
01-Nov-17
2018
x 10^-8
Background (W·m^-2)
SF Amount
Background
SF
50
40
30
20
10
0
20
15
10
5
0
01-Jan-18
01-Mar-18
01-May-18
01-Jul-18
01-Sep-18
01-Nov-18
2019
x 10^-8
Background (W·m^-2)
SF Amount
Background
SF
1000
800
600
400
200
0
30
25
20
15
10
5
0
01-Jan-19
01-Mar-19
01-May-19


x 10^-8
2020
Background (W·m^-2)
SF Amount
Background
SF
01-May-20
01-Jul-20
01-Sep-20
01-Nov-20
x 10^-8
2021
Background (W·m^-2)
SF Amount
Background
SF
01-Jan-21
01-Mar-21
01-May-21
01-Jul-21
01-Sep-21
01-Nov-21
x 10^-8
2022
Background(W·m^-2)
SF Amount
Background
SF
01-Jan-22
01-Mar-22
01-May-22
01-Jul-22
01-Sep-22
01-Nov-22

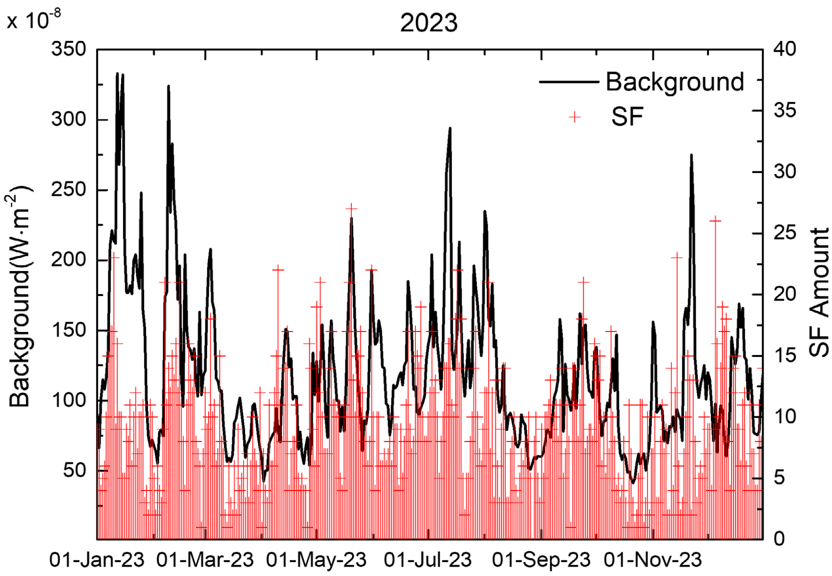


Figure 2. Solar flare daily quantities and background flux for each year from 2013 to 2023.

Figure 2 demonstrates that there is a strong positive correlation between solar flare events and background flux. Throughout the analyzed years, each graph consistently displayed a trend: an increase in solar flare events coincided with a rise in background flux.

Previous research employing machine learning models has identified a positive correlation between sunspot activity and both solar flare occurrence rate and daily flare probability. Additionally, these studies revealed that periods of peak solar activity, characterized by a higher number of sunspots, coincide with an increase in the frequency of more intense M-class and X-class flares [8].

4. Conclusions

Solar flares (SFs) and background flux changes have distinct origins and characteristics. Solar flares arise from localized, energetic events on the Sun's surface, while background flux variations reflect broader changes throughout the Sun's atmosphere.

The cyclical fluctuation in solar flare occurrence classifies the Sun as a variable star, albeit subtle compared to the dramatic variations observed in other stellar types.

This study investigated the relationship between solar flares and background flux. The key findings are:

- Large solar flares (M, X classes) are associated with significant increases in background flux. This connection is particularly strong for flares lasting over 30 minutes and days with a high number of flares.
- The combined effect of long duration and high daily flare count has a stronger influence on background flux increase compared to just duration alone.
- A positive correlation exists between daily solar flare amount and background flux intensity for each year. This trend holds even during the 11-year

solar activity cycle.

- Yearly solar flare totals do not significantly impact the strength of the correlation between daily flares and background flux.

The research suggests that monitoring for variations in the baseline X-ray solar flux with lower-resolution sensors could be a valuable tool for pinpointing periods of increased solar activity. This approach offers an advantage in terms of efficiency.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Solanki, S.K., Usoskin, I.G., Kromer, B., Schüssler, M. and Beer, J. (2004) Unusual Activity of the Sun during Recent Decades Compared to the Previous 11, 000 Years. *Nature*, **431**, 1084-1087. https://doi.org/10.1038/nature02995

[2] Zhu, C., Qiu, J. and Longcope, D.W. (2018) Two-Phase Heating in Flaring Loops. *The Astrophysical Journal*, **856**, Article 27. https://doi.org/10.3847/1538-4357/aaad10

[3] Kumar, A. and Kumar, S. (2014) Space Weather Effects on the Low Latitude D-Region Ionosphere during Solar Minimum. *Earth*, *Planets and Space*, **66**, Article No. 76. https://doi.org/10.1186/1880-5981-66-76

[4] Loto'aniu, P., Rodriguez, J., Redmon, R., Machol, J., Kress, B., Seaton, D., Darnel, J., Rowland, W., Tilton, M., Denig, W., Boudouridis, A., Codrescu, S. and Claycomb, A. (2017) Space Weather Monitoring with GOES-16: Instruments and Data Products. *Geophysical Research Abstracts*, **19**, 9663.

[5] Sammis, I., Tang, F. and Zirin, H. (2000) The Dependence of Large Flare Occurrence on the Magnetic Structure of Sunspots. *The Astrophysical Journal*, **540**, 583-587. https://doi.org/10.1086/309303

[6] Winter, L.M. and Balasubramaniam, K.S. (2014) Estimate of Solar Maximum Using the 1-8 Å *Geostationary* Operational Environmental Satellites X-Ray Measurements. *The Astrophysical Journal*, **793**, L45. https://doi.org/10.1088/2041-8205/793/2/l45

[7] McIntosh, P.S. (1990) The Classification of Sunspot Groups. *Solar Physics*, **125**, 251-267. https://doi.org/10.1007/bf00158405

[8] Lee, K., Moon, Y.J., Lee, J., Lee, K. and Na, H. (2012) Solar Flare Occurrence Rate and Probability in Terms of the Sunspot Classification Supplemented with Sunspot Area and Its Changes. *Solar Physics*, **281**, 639-650. https://doi.org/10.1007/s11207-012-0091-9

[9] Winter, L.M. and Balasubramaniam, K. (2015) Using the Maximum X-Ray Flux Ratio and X-Ray Background to Predict Solar Flare Class. *Space Weather*, **13**, 286-297. https://doi.org/10.1002/2015sw001170

[10] Tlatov, A.G., Illarionov, E.A., Berezin, I.A. and Shramko, A.D. (2020) Prediction of Solar Flares and Background Fluxes of X-Ray Radiation According to Synoptic Ground-Based Observations Using Machine-Learning Models. *Cosmic Research*, **58**, 444-449. https://doi.org/10.1134/s0010952520060106

[11] Qahwaji, R. and Colak, T. (2007) Automatic Short-Term Solar Flare Prediction Us-

ing Machine Learning and Sunspot Associations. *Solar Physics*, **241**, 195-211. https://doi.org/10.1007/s11207-006-0272-5

[12] Yi, K., Moon, Y., Shin, G. and Lim, D. (2020) Forecast of Major Solar X-Ray Flare Flux Profiles Using Novel Deep Learning Models. *The Astrophysical Journal Letters*, **890**, L5. https://doi.org/10.3847/2041-8213/ab701b