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Comparative Analysis of Solar Flare Activity in Solar Cycle 24 and 25

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Abstract

Solar cycles display roughly 11-year periodicities driven by the solar magnetic dynamo. This study presents a comparative analysis of solar flare activity, sunspot number progression, and geomagnetic responses between Solar Cycle 24 (SC24: 2008–2019) and Solar Cycle 25 (SC25: 2019–present). Solar Cycle 24 was characterized as a weak cycle, displaying a double-peaked sunspot maximum (peak smoothed sunspot number $Rz \approx 116.4$) and low overall eruptive productivity. In contrast, Solar Cycle 25 has exceeded initial prediction models, showing rapid magnetic flux emergence and high flare productivity during its maximum phase. Using solar soft X-ray (SXR) flux data from the Geostationary Operational Environmental Satellite (GOES) network and solar wind/geomagnetic indices (Dst and Kp), we evaluate flare frequency distributions and active region magnetic topologies ($\beta\gamma\delta$). While SC24 produced isolated extreme events such as the X9.3 flare of September 6, 2017, SC25 exhibits a higher occurrence rate of M- and X-class flares along with intense geo effective storms (e.g., May 2024). The space weather implications of these variations are discussed in relation to ionosphere perturbations, Total Electron Content (TEC) fluctuations, and radio communication blackouts.

1. Introduction

Solar flares are sudden explosions in the Sun's atmosphere caused by the rapid release of stored magnetic energy via magnetic reconnection. Classified by peak soft X-ray (SXR) flux in the 0.1–0.8 nm band into A, B, C, M, and X classes, each class represents a tenfold energy increase. M-class (≥ 10−5 W/m2) and X-class (≥ 10−4 W/m2) flares, alongside Coronal Mass Ejections (CMEs), drive space weather events that disturb Earth's ionosphere and magnetosphere. These events cause Sudden Ionosphere Disturbances (SIDs), radio blackouts, High Frequency (HF) communication degradation, satellite drag, and geomagnetic ally induced currents (GICs). Understanding solar flare occurrence rates across different solar cycles is essential for space climate modeling and space weather forecasting. Solar Cycle 24 (SC24), which lasted from December 2008 to December 2019, was recorded as one of the weakest cycles in the modern space age. Solar Cycle 25 (SC25) began in December 2019. Initial consensus forecasts predicted an amplitude similar to SC24, but observational evidence indicates faster growth, higher magnetic complexity, and stronger flare output. Solar flare activity correlates with ionosphere plasma variations, Total Electron Content (TEC) enhancements, and severe geomagnetic storms across low- and mid-latitude ionosphere regions (Gour et al., 2024; Meena & Gour, 2024; Vaswani et al., 2022). Comparing flare frequency and active region dynamics between SC24 and SC25 provides insight into the underlying solar magnetic dynamo and its space-weather effects (Meena, Meena, & Gour, 2022).

2. Methodology & Data Sources

Form Figure 1 to evaluate and compare solar flare activity across SC24 and SC25, multi-instrument observational datasets were acquired and processed using the following protocol:

1. Solar Flare Identification and Classification: Soft X-ray (SXR) flux measurements in the 0.1–0.8 nm band were extracted from the GOES satellite series (GOES-13, 14, 15 for SC24; GOES-16, 17, 18 for SC25) maintained by the NOAA Space Weather Prediction Center (SWPC). Solar flare events were categorized into C (10−6 to 10−5 W/m2), M (10−5 to 10−4 W/m2), and X (≥ 10−4 W/m2) classes.
2. Sunspot Progression Metrics: Daily and smoothed monthly sunspot numbers (SSN) were obtained from the Royal Observatory of Belgium's World Data Center for Sunspot Index and Long-term Solar Observations (SILSO).
3. Active Region (AR) Topology & Solar Wind Dynamics: Active region magnetic Classifications (α, β, γ, δ) were cross-examined using Solar Dynamics Observatory (SDO) Atmospheric Imaging Assembly (AIA) and Helioseismic and Magnetic Imager (HMI) magnetograms.
4. Geomagnetic Impact Metrics: Interplanetary Magnetic Field (IMF) Bz components, solar wind velocities, and geomagnetic disturbance indices (Dst and Kp) were retrieved from the NASA/GSFC OMNI Web database. CME parameters were cross-referenced with the SOHO/LASCO CME catalog.

2.1 Overview: Solar Cycle 24 vs. Solar Cycle 25

Parameter	Solar Cycle 24	Solar Cycle 25
Starts	Dec-2008	Dec-2019
Peaks	~2014	~2024-2025
Rel. strength	Weak cycle	strong cycle
Strong flare	X (9.3) Sep 17	X (8.7) May 24 so far
Frequency	Lower flare produced	Higher flare freq.
Sunspot Activity	Rel. Weak	Higher

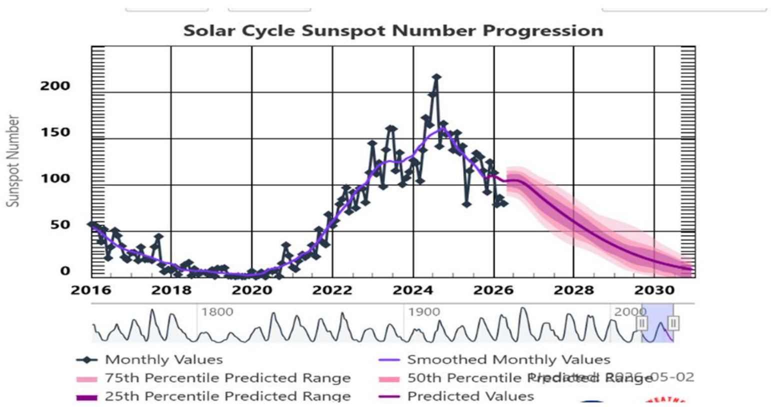

Fig.1 Solar Cycle Sunspot Number Progression.

2.1.1 Sunspot Number Progression

The study finds that the SC24 considered one of the weak solar cycle in the space age characterized by reduced sunspot numbers and weaker magnetic activity while that of SC25 has shown unexpectedly rapid growth in flare activity. SC24 produced numbers of C-class flare but cooperatively fewer intense events-class flares were mainly which occurred around 2011-2014 its maximum phase and late2017 declining phase. major active regions included NOAA AR 12192, NOAA AR 12673. As per data and research SC24 was a weaker magnetic intensity than previous cycle, reducing the number of flares overall. Now present solar cycle SC25 has increased frequency of M-class and X-class flares more magnetically complex sunspot regions, higher flare productivity earlier in the cycle. According to recent flare data 2024 recorded over 30 X-class flares (See Figure2).

The active regions AR 3663 and AR 3664 in May 2024 generated multiple strong X-class eruptions, contributing to severe geomagnetic storms. Major X-class flare for SC24(X9.3) Sep 6,2027 is the largest flare of SC24. SC24 X(11.88/X13.37) estimates AR 12673 is extremely energetic events. While in SC25 X8.7 may 14,2024 is the largest flare so for in SC25. SC25 multiple X5+ flares occur in May 2024 an intense geomagnetic impact.

As per NASA's Solar dynamic observatory, the X9.3 flare of Sep 2017 remains the strongest event of SC24.SC25's strongest event to date is the X8.7 flare observed on May 14, 2024.Sunspot region (SSR) for SC24 were generally smaller and less magnetically complex. SSR occurred at AR 12192 is the largest sunspot region of SC24 producing 6 X-class flares .AR 12673 produced 4 X-class flare and 27 M-class flares generating the powerful X9.3flare in 2017.SC25 active region (AR) appear dynamically unstable and flare productive. AR 3663 and AR 3664 of May 2024 produced numerous X-class flares in short interval. Studies indicates SC25 active regions may exhibit faster magnetic flux emergence, greater rotational shear, increased magnetic reconnection rates. This factor contributes to higher flare occurrence.

2.1.2 Number of C, M and X-Class Solar Flares Per Year

The graph below shows us the number of C, M and X-class solar flares that occur for any given year. It gives us a nice idea of the number of solar flares in relation to the sunspot number. It is thus another way of seeing how a solar cycle evolved over time. This data comes from the NOAA SWPC and is updated daily.

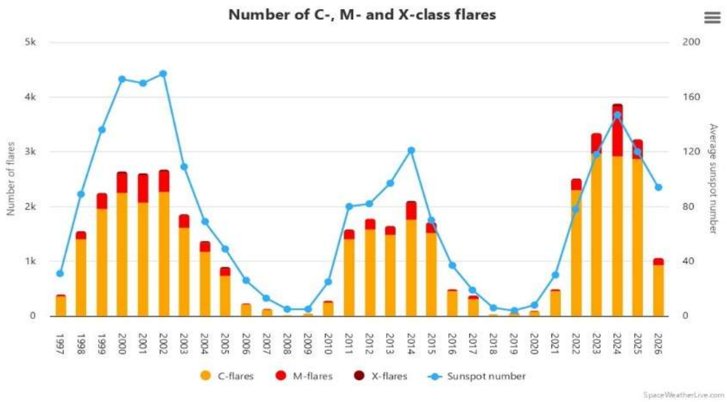

Fig.2 Number of C-, M- and X-class flares.

The graph below shows you the number of C, M and X-class solar flares that were produced during past month together with the sunspot number of each day. This gives you an idea of the solar activity during the past month. This data comes from the NOAA SWPC and is updated daily.

Number of C-, M- and X-class flares of last month (See Figure3).

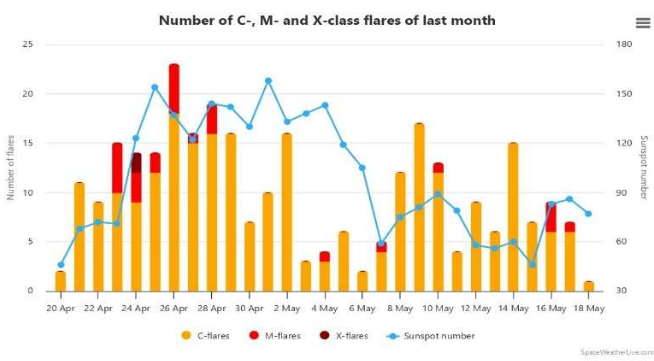

Fig.3 Number of C-, M- and X-class flares (20 Apr-18)

2.1.3 Current Scientific Understanding

As per the research, currently researcher believes that SC24 represented a relatively weak magnetic cycle while SC25 is undergoing stronger magnetic amplification than predicted. SC25 may continue producing major X-class flares through 2026.The occurrence of extreme flares is linked to complex delta sunspot regions and magnetic helicity accumulation. Recent studies indicate that SC25's maximum phase occurred roughly between August 2024 and January 2025, accompanied by heightened flare and CME activity.

3. Results

3.1 Parameter Comparison

A direct comparison of key solar cycle parameters between SC24 and SC25 is summarized in Table-1.

Table 1: Comparative Summary of Parameters in Solar Cycle 24 and Solar Cycle 25

Parameter	Solar Cycle 24 (2008–2019)	Solar Cycle 25 (2019–Present)
Start Date	December 2008	December 2019
Peak Phase	Double Peak (2012 & 2014)	Broad Maximum Plateau (Late2024 – 2025)
Peak Sunspot Number	116.4 (April 2014)	>160.0 (Monthly smoothedvalue)
Cycle Amplitude	Weak (lowest in 100 years)	Moderate–Strong (ExceedsSC24)
Strongest Solar Flare	X9.3 (September 6, 2017)	X8.7 (May 14, 2024)
Dominant Active Regions	NOAA AR 12192, AR 12673	NOAA AR 13663, AR 13664
Magnetic Complexity	Low-to-Moderate ($\beta\gamma$ dominant)	High (Frequent complex $\beta\gamma\delta$ groups)
Max Geomagnetic Disturbance	$Dst_{min}= -223$ nT (March 2015)	$Dst_{min} = -412$ nT (May2024)

3.2 Sunspot Number Progression

Solar Cycle 24 exhibited a distinct double-peak structure in 2012 and 2014, with a maximum smoothed sunspot number of 116.4. Solar Cycle 25 grew rapidly after late 2021, bypassing SC24 values at similar cycle phases and exceeding a smoothed sunspot number of 160 during its peak phase between late 2024 and 2025.

3.3 Flare Distribution and Frequency Analysis

During Solar Cycle 24, major flare activity concentrated around its peak phase (2011–2014) and during a late-cycle phase in September 2017. SC24 produced a total of 49 X-class flares. In contrast, Solar Cycle 25 recorded over 30 X-class flares in 2024 alone.

3.4 Active Region Energetics and Case Studies

NOAA AR 12673 (September 2017 - SC24): This region emerged rapidly in late SC24, producing the strongest flare of SC24—an X9.3 flare on September 6, 2017. The event triggered intense ionospheric absorption, sharp total electron content (TEC) increases, and geomagnetic storms analyzed in studies of upper atmospheric responses (Meena & Endla, 2026; Meena & Gour, 2024). NOAA AR 13664 (May 2024 - SC25): This active region produced multiple X-class eruptions, including an X8.7 flare on May 14, 2024. The series of halo CMEs produced a historic G5 geomagnetic storm (Dst = −412 nT, Kp = 9), demonstrating higher cumulative flare productivity than AR 12673.

4. Discussion

The observational differences between SC24 and SC25 stem from underlying solar magnetic dynamo processes. The weak polar field strengths observed during the SC23/SC24 solar minimum limited toroidal magnetic field buildup, leading to weaker flux emergence and lower sunspot numbers in SC24. In SC25, stronger differential rotation shear and increased magnetic helicity accumulation led to frequent formation of complex βγδ magnetic topologies. Active regions in SC25 exhibited rapid flux emergence along steep polarity inversion lines (PIL), generating continuous magnetic reconnection sequences. These eruptive solar flares release extreme ultraviolet (EUV) and X-ray radiation, driving high photoionization rates in Earth's lower ionosphere. Strong solar flares disrupt low- latitude ionospheric plasma density, perturb ionic compositions, and produce large-scale Total Electron Content (TEC) variations (Meena et al., 2024; Meena, Sharma, & Gour, 2024a, 2024b). Solar flares accompanied by fast CMEs generate major geomagnetic disturbances when interacting with Earth's magnetosphere (Gour et al., 2024; Vaswani et al., 2022).

5. Conclusion

Solar Cycle 24 and Solar Cycle 25 present notable contrasts in magnetic activity, flare frequency, and space weather severity:

1. Cycle Amplitude: Solar Cycle 24 was a weak solar cycle (Rz ≈ 116.4) with a double-peaked maximum. Solar Cycle 25 has exceeded SC24 in amplitude, sunspot numbers (Rz > 160), and overall flare occurrence.

2. Flare Distribution: SC24 generated isolated energetic events late in its cycle (such as the X9.3 flare of September 2017). SC25 displays sustained, high-frequency M- and X-class flare production earlier in its progression.
3. Space Weather Impacts: Active regions in SC25 (e.g., AR 13664) show fast flux emergence and high magnetic complexity (βγδ), generating severe geomagnetic storms

Solar cycle 24 and solar cycle 25 exhibit significant differences in flare behavior and magnetic activity.SC24 was relatively weak, with fewer extreme events and lower overall magnetic intensity.SC25 has emerged more flare-productivity and magnetically active cycle producing numerous strong M-class and X-class flares earlier than expected. Although SC24 generated some remarkable events such as the X9.3 flare of 2017, SC25 appears more consistently active and capable of stronger space-weather impacts. Current observations suggest that SC25 may become one of the most significant solar cycles since solar cycle 23 if elevated activity continues through the remainder of the decade.

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Declaration of Conflict of Interest

The author declares no conflict of interest.

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Author Contribution Statement

A. K. Pandey Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing original draft, Dr. J. D. Prajapati – Review.

Data Availability Statement

The data used in this study are publicly available. Dst index data were obtained from the Kyoto World Data Centre via the NASA/GSFC OMNI Web database https://omniweb.gsfc.nasa.gov/html/omni_min_data.html Solar wind plasma and IMF data were retrieved from the same database. CME data were sourced from the SOHO/LASCO CME catalog and the Heliospheric Shock Database maintained by the University of Helsinki.

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