

STATISTICAL ANALYSIS OF SOLAR ACTIVITY VARIATIONS USING SUNSPOT NUMBER DURING THE RISING PHASE OF SOLAR CYCLE 25

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ABSTRACT

The 25th since 1755, Solar Cycle 25 is the current solar cycle when vast recording of solar sunspot activity began. Solar Cycle 25 began at the December 2019 solar minimum and subsequently developed into a substantially stronger cycle than the initial 2019 prediction. Our study quantifies the temporal evolution of solar activity using the International Sunspot Number (SSN) distributed by the World Data Centre–Sunspot Index and Long-term Solar Observations (WDC-SILSO) at the Royal Observatory of Belgium. Monthly mean, 13-month smoothed monthly, and yearly mean SSN Version 2.0 data are analysed. The cycle minimum is represented by a 13-month smoothed SSN of 1.8 in December 2019. The smoothed series rises from 1.8 in December 2019 to a confirmed maximum of 160.9 in October 2024,

after which it declines to 99.8 by February 2026, the latest cantered smoothed value available in the SILSO series at the time of analysis. The annual mean SSN increases from 3.6 in 2019 to 154.7 in 2024 and decreases to 123.2 in 2025. Linear regression over 2019–2024 gives a slope of 33.12 SSN units yr⁻¹ and $r = 0.975$ ($p = 0.0009$), indicating a strong monotonic rise in annual activity during the minimum-to-maximum interval. The Cycle 25 smoothed maximum is 38.2% higher than the Cycle 24 maximum of 116.4. The results demonstrate that Cycle 25 was not a simple repeat of the weak Cycle 24 pattern: its rise was rapid after 2021 and its maximum was considerably stronger. The study also emphasizes the difference

between short-term monthly variability and the physically meaningful smoothed cycle envelope.

KEYWORDS: Solar Cycle 25, Sunspot number, Solar Activity, Solar Maximum.

1. INTRODUCTION

The Sun is magnetically active star whose activity varies periodically and approximately 11-year cycle variation during which the number of sunspots increases from minimum to maximum and subsequently decline. These changes are because of solar magnetic field variation and strongly influence the heliosphere environment and space weather conditions near the earth. Such variation of solar activity needs to study solar cycle 25.

The study of Solar cycle 25 is important because it started unusually quiet minimum and then develop more strongly than the initial consensus forecast. SC25 provides to examine characteristics of recent cycle and compare with the previous cycles. We can find similarities and differences in solar activity and improve our understanding of solar cycle variability.

Statistical analysis of sunspot numbers and related geomagnetic parameters help us to find out relationship between solar surface activity, solar eruption and their effect near the earth.

According to NASA-NOAA solar cycle prediction centre identified December 2019 as the cycle minimum and placed the peak 115 but the later observations showed that the cycle exceeded this level substantially. WDC-SILSO now identify October 2024 as the smoothed maximum with SSN 160.9.^{[1][2][3][4]}

The main objective of this research paper is the statistical analysis of SC25 using sunspot number data maintained by Solar Influences Data Analysis Center (SILSO) version 2.0 of the Royal observatory of Belgium. The analysis is based on following questions (i) how activity increased after 2019 minimum. (ii) when cycle reached to its maximum. (iii) monthly fluctuations (iv) how does the maximum of SC25 is compare with SC24 and (v) statistically trends in annual mean. These all observation and characteristics variations are the base and documented record to study future comparison with SC26.^{[5][6]}

2. Data Analysis and Methods

We used WDC-SILSO, version 2.0 Royal observatory of Belgium for data sources. The data contains daily, monthly, 13 month smoothed monthly total sunspot number and yearly mean total sunspot number.

2.1. Definition of Sunspot number SSN is a daily index called Wolf number calculated using the formula

$$R=k(10g+S)$$

Where g =Number of sunspot groups

S =total number of individual spots

k =correction factor used to adjust difference in telescope/observer.

2.2. Monthly and annual means It is a daily total sunspot number in a calendar month defined as

$$R_m=(1/N_m) \sum R_d$$

Where, N_m is number daily contributing observation. The yearly mean is calculated over the daily values in the year.

2.3. 13-month smoothing SILSO defines the smoothed monthly sunspot number using 13 month running mean. The central month has full weight, the five months on each side have full weight and two end points have half weight.

$$S_t = [0.5R_{(t-6)} + \sum_{i=-5 \text{ to } +5} R_{(t+i)} + 0.5R_{(t+6)}]/12$$

The short-term fluctuations and standard basis to define solar cycle minima and maxima.

2.4. Statistical analysis The annual trend can be calculated using ordinary least squares linear regression $R_y=a+by$, where y is calendar year and b will be slope.

The Pearsons correlation coefficient was calculated as,

$$r=\sum [(x-\bar{x})(y-\bar{y})]/\sqrt{[\sum (x-\bar{x})^2 \sum (y-\bar{y})^2]}$$

3. RESULTS AND DISCUSSION

3.1 Annual evolution of Solar Cycle 25

Annual mean sunspot number for 2019-2025

Table 1: Annual mean sunspot no. for SC25 (2019-2025).

Year	Annual mean SSN	SD	N	YoY change %	Phase
2019	3.6	0.5	12884	none	Min.
2020	8.8	4.1	14440	144.4	Rising

2021	29.6	7.9	15233	236.4	Rising
2022	83.2	14.2	15258	181.1	Rising
2023	125.5	19.2	13286	50.8	Rising
2024	154.7	22.0	12265	23.3	Max.
2025	123.2	17.8	12473	-20.4	Decline

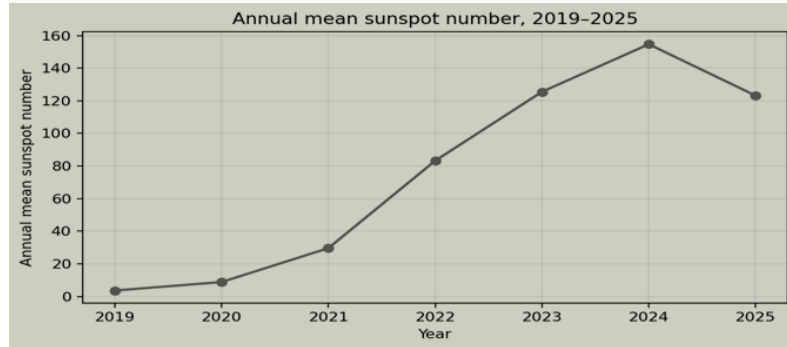


Fig.1: Annual mean sunspot number min. (2019) of SC25.

The annual mean sunspot number minimum (2019) clearly shown in fig. 1. The minimum rise from 3.6(2019) to 8.8(2020), 29.6 in 2021, 83.2 in 2022, 125.5 in 2023, and 154.7 in 2024 respectively.

From the observation, here we see that for 2019-2024, the mean annual SSN was 67.57 with the standard deviation 63.53. The fitted linear slope was 33.12 SSN and pearson $r=0.975$, the associated two-sided p value is 0.0009. The positive slope here provides strong statistical proof for systematic increase in annual activity over the minimum to maximum interval.

The annual mean then down from 154.7 in 2024 to 123.2 in 2025 (Table 1) that is decline of 20.4%. This shows decrease with smoothed maximum in October 2024 and then subsequent downward phase of the cycle.^{[7][8][9][10]}

3.2. Monthly variability and smoothed cycle envelope

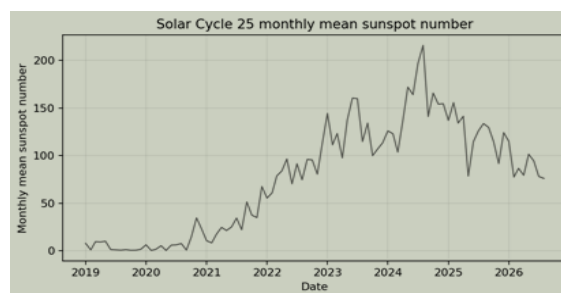


Fig. 2: Monthly mean sunspot number (Jan.2019-Aug.2026).

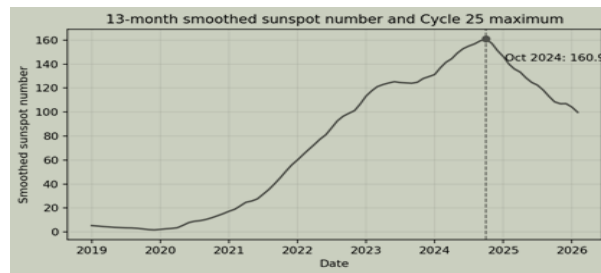


Fig. 3: 13-month smoothed sunspot number and Max.

Monthly variability is shown on the cycle scale rise (fig. 2), during 2019-2020 most monthly means were below 10, but occasionally short lived increased occurred.

But activity became higher in 2021 with monthly means 67.5 in December. During 2022 monthly means were mostly between 55 and 113. While in 2023 above 100 and two consecutive months near 160. The largest monthly mean analyzed interval is 216.0 in August 2024. This monthly maximum not to be confused with the cycle maximum because individual months are sensitive to transient active regions. The conventional cycle maximum is based on the 13-months smoothed series which peaks at 160.9 in October 2024.

The smoothed curve provides clear representation of the cycle envelope. It rose from 1.8 in December 2019 to 125.3 in June 2023 remained near a broad plateau during the latter half of 2023, and then increase further through 2024. The smoothed sequence reaches 159.4 in September 2024, 160.9 in October 2024 (Fig.3) and then falls to 157.2 in November and 151.2 in December. By February 2026 it has declined to 99.8.

3.3. Statistical analysis of Solar cycle 25

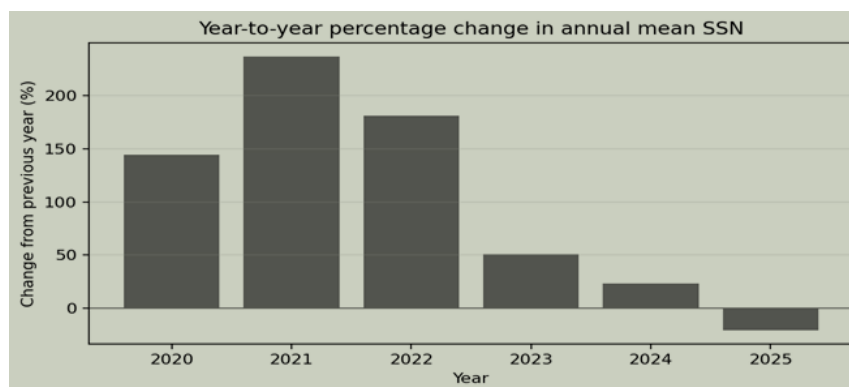


Fig. 4: Year to year percentage change in annual mean SSN.

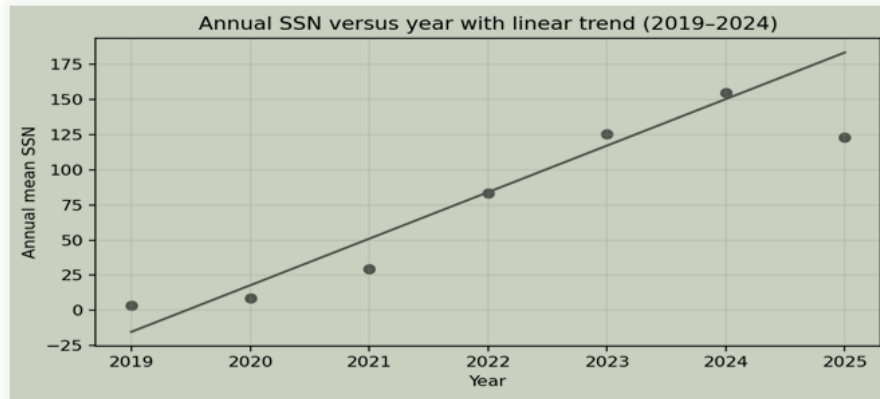


Fig. 5: Annual mean SSN vs linear regression line.

3.4. Maximum comparison with Solar Cycle 24

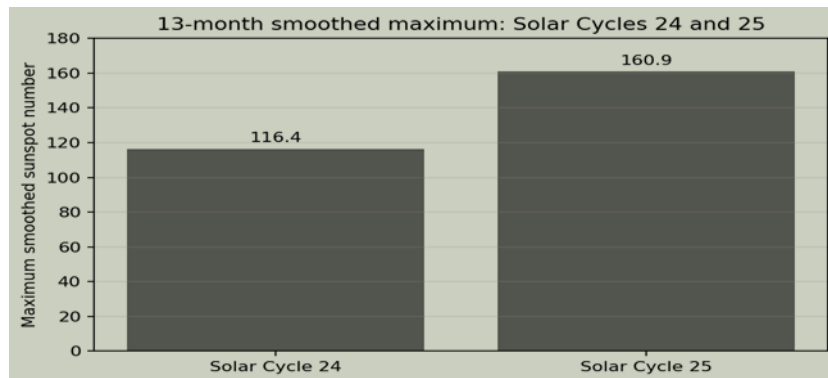


Fig. 6: 13-month smoothed maxima of Solar cycle 24 and 25.

Table 2: Cycle to Cycle comparison.

S. No.	Metric	Values
01.	SC25 minimum	1.8 (Dec. 2019)
02.	SC25 smoothed maximum	160.9 (Oct. 2024)
03.	SC24 smoothed maximum	116.4 (Apr. 2014)
04.	SC25/SC24 maximum increase	38.2%
05.	2019-2024 slope	33.12 SSN
06.	2019-2024 r value	0.975

The comparison shown clearly in table 2 that SC25 is stronger than SC24 when standard smoothed maximum is used. The increase from 116.4 to 160.9 corresponds to 38.2%. The result is important because SC24 was relatively weak maximum, whereas SC25 developed a higher activity envelope.^{[7][8]}

The year-to-year growth rate is highest in the early rising phase because the denominator is small, the annual mean increase by 144.4% from 2019 to 2020, 236.4% from 2020 to 2021 and 181.1% from 2021 to 2022. The relative growth rate then decreases as the absolute SSN became large reaching 23.3% from 2023 to 2024 shown in fig.4.

DISCUSSION

In the present study, the SC25 was initially slow and then became fast and clear after 2020. The smoothed SSN remained below 10 during 2019-2020 with deep minimum associated with the transition for SC4 to SC25. During 2021-2022 the smoothed curve developed a sustained upward gradient. By early 2023 the cycle has already reached a smooth level above 110, and first broad high activity interval approached 125. This behavior exhibit is consistent with NASA's observation that solar activity was increasing after the December 2019 minimum and by 2022 was already exceeding the early predictions.

Solar cycle exhibits a perfectly symmetric single peak. The SC25 smoothed series shows a broad maximum rather than a sharply isolated peak. A first high plateau developed around mid 2023 followed by renewed rise during 2024. The final conventional maximum of 160.9 occurred in October 2024. This broad structure explain why the cycle maximum can not be identified reliably from one exceptionally high monthly mean. The distinction between monthly and smoothed maxima is especially clear 2024. The monthly mean reached 216.0 in August, but the smoothed maximum occurred two months later at 160.9.

Now comparing with solar cycle 24 we find that SC25 smoothed maximum of 160.9 is 38.2% above SC24's 116.4. The two cycle also began from similarly low minima. 2.2 for SC24 minimum in December 2008 and 1.8 for SC25 minimum in December 2019. Thus, the stronger SC25 maximum can not be explained simply by a much higher starting minimum.

4. CONCLUSION

In the present study we find following main conclusions, (i) Solar cycle 25 began at December 2019, solar minimum with 13- month smoothed SSN 1.8 (ii) The annual mean SSN increased continuously from 3.6 in 2019 to 154.7 in 2024, demonstrating a strong minimum to maximum rise. (iii) The 2019-2024 annual trend has a slope 33.12 SSN and $r=0.975$ with $p=0.0009$. (iv) SC25, 13-month smoothed maximum occurred in October 2024 at SSN=160.9 (v) The SC25 maximum is 38.2% higher than SC24 maximum. (vi) After the maximum annual mean SSN decreased to 123.2 in 2025 while the latest is 99.8 in February 2026. (vii) Finally, SC25 is stronger than SC24 and provides a useful observational benchmark for future investigation of solar eruption, geomagnetic storms and solar terrestrial coupling.

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Data Availability Statement

The data used in this study are publicly available freely. The result presented in this paper are based on version 2.0 monthly, 13-months smoothed monthly and yearly total sunspot number of the international sunspot number from the world data center (WDC-SILSO), Royal observatory of Belgium (<http://www.sidc.be/silso>).

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