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# Analyzing Solar Cycle Behavior Through Neutron Monitor Data: Insights from Inflection Points

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Neutron monitor (NM) count rates provide a reliable, ground-based proxy of solar modulation of galactic cosmic rays (GCRs), exhibiting an inverse correlation with solar activity. In this study, we analyze NM data from the OULU station during Solar Cycles (SCs) 20 to 25 using an inflection-point methodology previously applied to sunspot number (SSN) data. We model the NM count rate time series using a modified empirical function and extract the value of the count rate at the inflection point, $C_i(t_{\mathrm{IP}})$, corresponding to the steepest decrease in GCR intensity due to rising solar activity.

We find that $C_i(t_{\mathrm{IP}})$, calculated using only the first 1800 days of each solar cycle, strongly correlates with key solar activity metrics. For the OULU station, a linear regression between $C_i(t_{\mathrm{IP}})$ and the average SSN ($SSN_{\mathrm{av}}$) across SC 20–24 yields a coefficient of determination of $R^2 \approx 0.98$. Similarly, the correlation with the maximum SSN ($SSN_{\mathrm{max}}$) gives $R^2 \approx 0.91$. These results indicate that $C_i(t_{\mathrm{IP}})$ may serve as a robust early-cycle predictor of solar cycle strength.

Applying this method to the ongoing SC 25, we obtain $C_{25}(t_{\mathrm{IP}}) = 103.1821$ counts (OULU), which predicts an average SSN of $81.1 \pm 5.9$. These findings demonstrate the potential of NM data, and in particular inflection-point analysis, as a predictive tool for characterizing solar cycle evolution based on cosmic ray modulation.

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## 1. Introduction

The solar cycle is an ~11-year modulation of solar magnetic activity, marked by variations in sunspot number (SSN). Solar Cycle 25 (SC25), which began in December 2019, reached its maximum around August 2024 with a peak smoothed monthly SSN of approximately 156—exceeding earlier forecasts from the Solar Cycle Prediction Panel and NOAA.

A number of studies have shown that the slope at the inflection point during the rising phase of a solar cycle correlates with its amplitude [1]. This approach, applied to sunspot data by [2], [3], and others, has yielded predictions consistent with observed values, reinforcing the value of early-cycle dynamics as predictors of solar activity.

In this work, we extend the inflection point methodology to ground-based cosmic ray observations, specifically neutron monitor (NM) count rates. These rates are inversely related to solar activity, decreasing as the heliospheric magnetic field strengthens. We define $C_i(t_{\mathrm{IP}})$ as the NM count rate at the inflection point during the descending NM phase, and $C_i(t_{\mathrm{min}})$ as the minimum count rate, which typically occurs several months after the SSN peak due to heliospheric transport delays.

We investigate linear correlations between these NM-based indicators and solar cycle strength metrics, such as the average and maximum SSN, to assess their potential as early proxies of solar activity. To our knowledge, this is the first systematic application of inflection point analysis to NM data, offering a novel approach for forecasting solar cycle strength using cosmic ray proxies.

## 2. Data and Methods

### 2.1 Data Sources

This study uses pressure-corrected daily neutron monitor (NM) count rates from the NMDB database (http://www01.nmdb.eu/) and http://cr0.izmiran.ru/common/links.htm, along with daily sunspot number (SSN) data from NOAA's repository (https://www.ngdc.noaa.gov/stp/SOLAR/). The NM data from the Oulu station (OULU), which has a low geomagnetic cutoff rigidity of approximately 0.8 GV, were selected due to their long-term reliability and high data completeness. This station provides more than 95% valid daily values from October 1, 1964, to April 30, 2025, making it especially suitable for studying solar modulation of cosmic rays during solar cycle transitions.

Solar cycles (SCs) 20 through 25 are defined using fixed time intervals based on SSN minima. The SSN serves as a proxy for solar activity and is used to classify cycles as stronger or weaker than average. These classifications are later compared against neutron monitor-derived parameters.

### 2.2 Modeling NM Count Rates

To analyze the long-term modulation of galactic cosmic rays (GCRs), we model the NM count rate $C_i(t)$ for each station $i$ (In this proceeding, we focus exclusively on the OULU NM station.) during each solar cycle using a modified function inspired by empirical sunspot number models:

$$C_i(t) = A\left(1 - \frac{t^3}{e^{(t/b)^2} + c}\right), \tag{1}$$

where $A$ is the average count rate during the first 200 days of the cycle (normalized amplitude), and $b$, $c$ are fitted shape parameters. This function captures the typical inverted bell-shaped evolution of NM count rates, which are anti-correlated with solar activity.

To ensure the model serves as an early-cycle predictor, we restrict the fitting procedure to the first 1800 days of each solar cycle. This allows the estimated parameters and derived quantities (e.g., the maximum slope) to act as early indicators of the cycle's overall behavior.

### 2.3 Inflection Point Detection

The primary quantity of interest is the NM count rate value at the inflection point $t_{IP}$ of $C_i(t)$, defined as the moment when the second derivative vanishes:

$$\left.\frac{d^2 C_i(t)}{dt^2}\right|_{t=t_{IP}} = 0.$$

This point corresponds to the most rapid modulation of GCRs due to increasing solar activity and typically aligns with the rising phase of the SSN. We calculate $t_{IP}$ numerically and evaluate the count rate at that time, $C_i(t_{IP})$, as a potential predictor of solar activity metrics (e.g., SSN average or maximum).

### 2.4 Error Estimation and Model Evaluation

Uncertainty in $C_i(t_{IP})$ is estimated via standard error propagation, accounting for uncertainties in $A$, $b$, $c$, and $t_{IP}$. The latter is assumed to have an uncertainty of ±365 days, consistent with variability in SSN rise times across solar cycles.

Model performance is quantified using the reduced chi-square statistic:

$$\chi^2_\nu = \frac{1}{\nu} \sum_{t=1}^{T} \left( \frac{C_i^{\mathrm{data}}(t) - C_i^{\mathrm{fit}}(t)}{\sigma_t} \right)^2 ,$$

where $C_i^{\mathrm{data}}(t)$ and $C_i^{\mathrm{fit}}(t)$ denote the observed and fitted NM count rates, $\sigma_t$ is the standard deviation of the daily NM counts, and $\nu$ is the number of degrees of freedom.

## 3. Results and Discussion

### 3.1 Cycle Comparison and Predictive Analysis

After extracting $C_i(t_{IP})$ for each cycle, we explore its statistical correlation with SSN-based metrics, such as the average and peak sunspot numbers of the corresponding solar cycle. The goal is to evaluate whether this parameter can serve as a proxy for forecasting solar modulation intensity from neutron monitor count rates data.

Figure 1 illustrates the methodology applied to OULU NM data during Solar Cycle 21. A cubic smoothing spline is used to suppress short-term fluctuations and reveal the general trend of the NM count rates. The resulting smoothed curve is fitted with Equation 1, allowing the determination of the inflection point $t_{IP}$, where the NM count rate decreases most rapidly.

This inflection point reflects the peak modulation rate of galactic cosmic rays due to solar activity, making it a meaningful proxy for heliospheric conditions near the solar maximum. Figures 2–3



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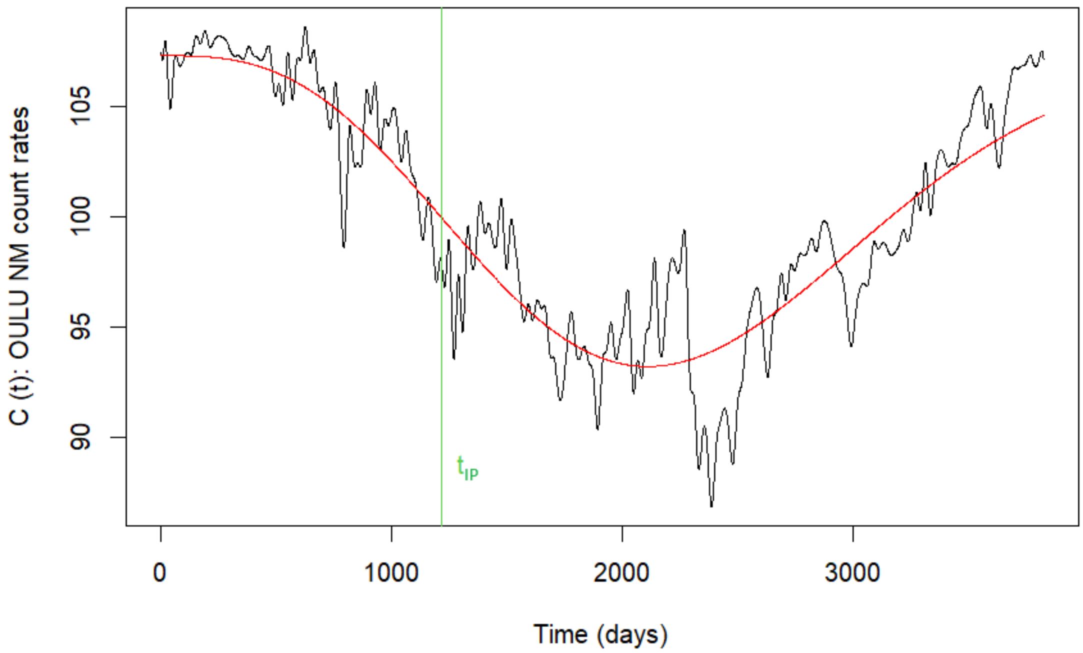


**Figure 1:** Temporal evolution of the OULU neutron monitor count rates, smoothed using a cubic spline during Solar Cycle 21. The time is expressed in days from the beginning of the solar cycle ($t$ = 0 days). The black curve represents the smoothed NM count rates in OULU during Solar Cycle 21, and the red curve illustrates the fit of this time series according to Equation 1. The green vertical line indicates the day $t_{IP}$ where the inflection point occurs.

show correlations between $C_i(t_{IP})$ and solar activity metrics ($SSN_{\text{av}}$, $SSN_{\text{max}}$. Despite the small sample size, the linear relationships exhibit high $R^2$ values across all stations, suggesting a robust and physically meaningful connection. These findings support the potential of NM-based inflection point analysis as a tool for forecasting solar cycle characteristics.

In this study, we focus primarily on the OULU neutron monitor (NM), located in Finland, which has a low geomagnetic cutoff rigidity of approximately 0.8 GV. This low-rigidity station is particularly suitable for our analysis because it is sensitive to a broader range of galactic cosmic ray (GCR) energies, especially lower-energy particles that are more strongly modulated by solar activity and heliospheric conditions.

The inflection-point method used in this work relies on detecting the moment of steepest decline in NM count rates during the rising phase of a solar cycle. This rapid decrease corresponds to the period of strongest solar modulation, when the heliospheric magnetic field intensifies and the solar wind becomes more efficient at shielding the Earth from GCRs. Since low-rigidity stations like OULU detect lower-energy cosmic rays that are more susceptible to solar modulation, they provide a more pronounced and clearer signal of this process.

Consequently, the use of OULU—and by extension, other low-rigidity NM stations—is es-

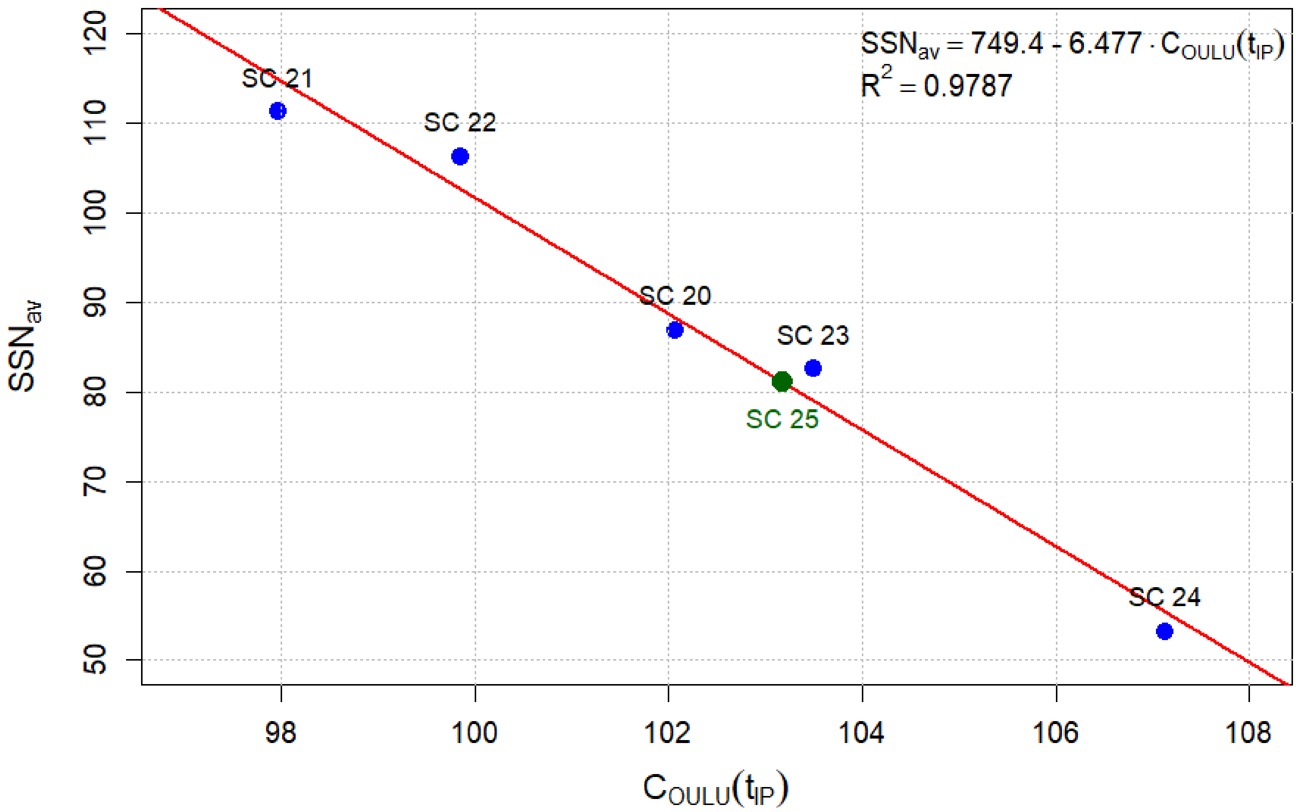


**Figure 2:** Scatter plot showing the average sunspot number ($\mathrm{SSN_{av}}$) versus the count value $C_i(t_{\mathrm{IP}})$ obtained during the first 1800 days of Solar Cycles 20 to 24 from the OULU neutron monitor. A linear fit (red line) is applied to these five points (blue dots), with the resulting regression equation and $R^2$ displayed in the upper-right corner. The green dot represents the prediction for Solar Cycle 25 using the observed value of $C_i(t_{\mathrm{IP}})$ during its first 1800 days. Labels above each point identify the corresponding solar cycle.

sential for accurately capturing the features needed to identify the inflection point. High-rigidity stations, on the other hand, primarily detect higher-energy particles that are less affected by solar modulation, resulting in smaller variations in count rates and reduced sensitivity to the changes we aim to measure. For this reason, our analysis is restricted to low-cutoff NM stations (rigidity $< 1$ GV) to ensure the reliability and physical relevance of the derived parameters.

### 3.4. Linear Relationship Between $C_i(t_{\mathbf{IP}})$ and $SSN_{\mathbf{av}}$

In order to investigate the relationship between cosmic ray measurements from neutron monitors and the average solar activity in each solar cycle, we fitted a linear regression model between $C_i(t_{\mathrm{IP}})$ — the value of the neutron monitor count rate at the inflection point of the solar cycle, estimated from the first 1800 days of the cycle — and the average sunspot number smoothed over 13 months, denoted as $SSN_{\mathrm{av}}$.

The linear model is of the form:

$$SSN_{\text{av}} = \beta_0 + \beta_1 \cdot C_i(t_{\text{IP}})$$

where the estimated coefficients are:

$$\beta_0 = 749.39 \pm 56.32,$$
$$\beta_1 = -6.48 \pm 0.55.$$

This model was fitted using data from Solar Cycles 20 to 24, comprising only five data points. Despite the small sample size, the regression is statistically significant:

- The coefficient of determination is $R^2 = 0.9787$, indicating that 97.87% of the variability in $SSN_{\text{av}}$ is explained by $C_i(t_{\text{IP}})$.
- The F-statistic for the model is 138 with a p-value of 0.0013, indicating strong overall significance.
- The slope coefficient $\beta_1$ is significantly different from zero ($t = -11.75$, $p = 0.0013$), confirming a robust negative linear relationship.

These results confirm the existence of a strong and statistically significant linear relationship between $C_i(t_{\text{IP}})$ and $SSN_{\text{av}}$. The negative slope is physically consistent: higher NM count rates during the ascending phase of a solar cycle (indicating lower solar activity) are associated with lower average sunspot numbers throughout the cycle.

**Prediction for Solar Cycle 25.** Using the value

$$C_i(t_{\text{IP}}) = 103.1821$$

computed during the first 1800 days of Solar Cycle 25, we predict $SSN_{\text{av}}^{(25)} = 81.1$.

To estimate the uncertainty, we compute a 95% confidence interval (CI) using the standard error of the regression and the t-distribution with 3 degrees of freedom. The standard error of the estimate is approximately 3.87. Taking into account the residual variance and leverage of the new point, the 95% CI for $SSN_{\text{av}}^{(25)}$ is:

$$\boxed{SSN_{\text{av}}^{(25)} = 81.1 \pm 5.9 \quad \text{(95\% CI: [75.2, 86.9])}}.$$

This prediction supports a relatively low average solar activity for Cycle 25, consistent with the relatively high neutron monitor count observed at the inflection point.

The variation of $C_i(t_{IP})$ with the maximum sunspot number is also observed.

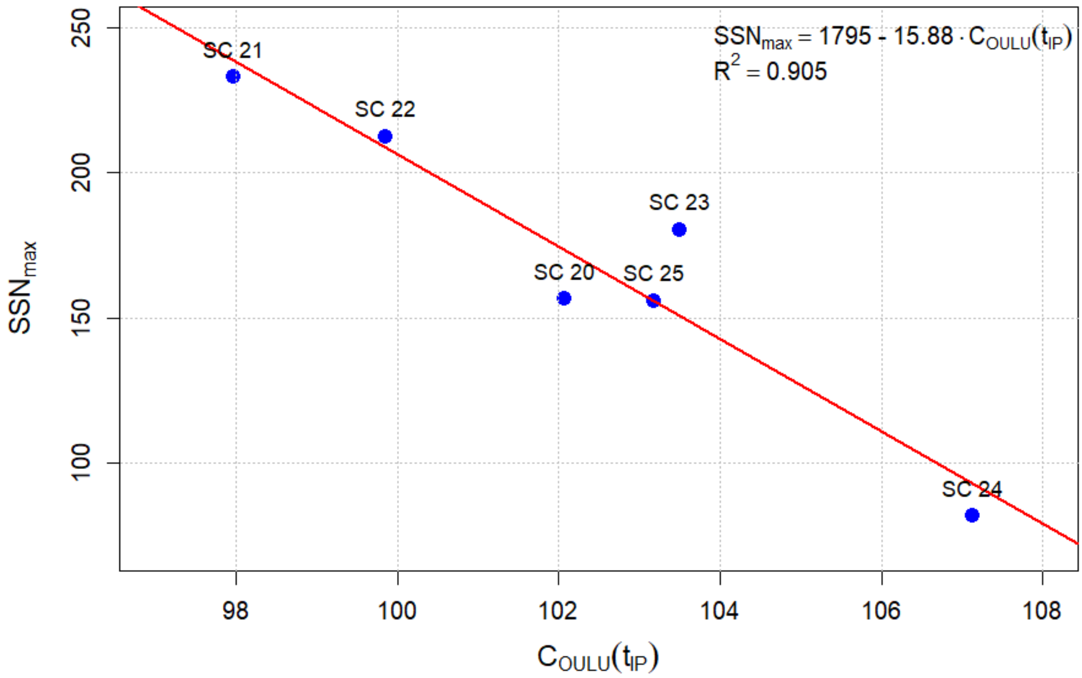


**Figure 3:** Maximum sunspot number ($SSN_{max}$) vs. $C_i(t_{IP})$ from OULU for SCs 20–25, with linear fit (red), $R^2$, and SC25 prediction (green).

## 4. Conclusions

In this study, we introduced a novel application of the inflection point methodology—originally developed for sunspot number analysis—to neutron monitor (NM) count rate data, focusing on the OULU station across Solar Cycles (SCs) 20 to 25. By modeling the NM count rate time series with an empirical function and restricting the fit to the first 1800 days of each cycle, we extracted the NM value at the inflection point, $C_i(t_{IP})$, as an early-cycle diagnostic of solar modulation.

Our results show that $C_i(t_{IP})$ exhibits a strong inverse linear correlation with key solar cycle metrics such as the average and maximum sunspot number. In particular, for SCs 20–24, we find $R^2 \approx 0.98$ for the correlation between $C_i(t_{IP})$ and average SSN, and $R^2 \approx 0.91$ for the correlation with maximum SSN. These high coefficients of determination highlight the predictive potential of this NM-based parameter.

Applying the methodology to Solar Cycle 25 yields a predicted average SSN of 81.1 ± 5.9, consistent with the moderately strong activity observed to date. This demonstrates that the inflection point of NM count rates can serve as a practical, ground-based tool for early forecasting of solar cycle strength, based solely on cosmic ray modulation during the initial rising phase of a cycle.

Future work will extend this analysis to additional neutron monitor stations, test its robustness across different energy sensitivities and geomagnetic cutoff conditions, and explore possible physical mechanisms underpinning the observed correlations.

## Acknowledgments

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