

C-Class Solar Flares and the Ionosphere: Decoding Temperature–TEC–Solar Activity Correlations (Jan–Mar 2025)



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Abstract

This study presents a comprehensive statistical analysis of 624 C-class solar flares observed between 1 January and 18 March 2025, examining their temporal characteristics, associated ion and electron temperatures (Ti, Te), total electron content (TEC), solar zenith angle (SZA), sunspot number (SSN), and 10.7 cm solar radio flux (F10.7). The mean flare magnitude was C3.87, with a mean duration of approximately 20 minutes. Daily flare occurrence averaged 8.3 events, peaking at 21 flares on 12 March 2025. Pearson correlation analysis revealed a moderate positive correlation between flare magnitude and F10.7 ($r = 0.331$) and a weak positive correlation with SZA ($r = 0.227$). TEC exhibited only a very weak relationship with flare magnitude ($r = 0.032$), suggesting that moderate C-class flares produce limited immediate enhancements in ionospheric electron density under the prevailing solar activity conditions. Ion temperatures averaged 1168 K while electron temperatures averaged 1694 K, yielding a mean Ti/Te ratio of 0.70. These findings provide new observational constraints on the ionospheric response to moderate solar flares during the ascending phase of Solar Cycle 25 and complement earlier investigations of stronger flare events. The results have implications for space weather forecasting models that currently under-represent the cumulative effects of frequent C-class activity.

1. Introduction

Solar flares are sudden, intense releases of energy in the solar atmosphere that emit radiation across the electromagnetic spectrum, particularly in soft X-rays and extreme ultraviolet (EUV). These emissions enhance ionization in Earth's upper atmosphere, leading to rapid increases in ionospheric electron density that can disrupt high-frequency (HF) radio communications, degrade Global Navigation Satellite System (GNSS) accuracy, and affect satellite operations (Meena et al., 2022; Meena & Gour, 2024). While X-class and M-class flares have been extensively studied because of their dramatic geoeffectiveness, the more frequent C-class flares (peak soft X-ray flux between 10^{-6} and 10^{-5} W m⁻²) have received comparatively less systematic attention, especially regarding their cumulative impact on the ionosphere during periods of moderate solar activity.

Previous investigations have demonstrated clear ionospheric responses to major solar flares. Meena et al. (2024) examined ion composition changes during moderately high solar activity in January 2023, while Meena, Sharma, and Gour (2024) documented TEC variations associated with moderate flare activity in August 2023. Comparative studies of strong versus weak flares during the 2011 solar maximum further highlighted the non-linear nature of the ionospheric response (Meena, Gour, & Soni, 2024). More recently, Meena and Endla (2026) performed a comparative analysis of the X9.3 flare of 6 September 2017 on both Earth and Mars, underscoring the importance of multi-parameter diagnostics including density, temperature, and plasma dynamics.

The present work focuses exclusively on C-class flares recorded during the first 2.5 months of 2025 a period corresponding to the ascending phase of Solar Cycle 25. By analyzing a large homogeneous sample of 624 events, we quantify relationships among flare magnitude, duration, ion and electron temperatures, TEC, solar zenith angle, sunspot number, and F10.7 flux. The primary objectives are: (1) to characterize the statistical distribution of C-class flare parameters; (2) to evaluate correlations between flare strength and ionospheric/solar indices; and (3) to assess whether moderate flares produce measurable TEC enhancements under the solar activity levels prevailing in early 2025.

2. Data and Methodology

2.1 Data Sources

The dataset comprises 624 C-class solar flares observed from 1 January 2025 to 18 March 2025. For each event the following parameters were recorded: flare classification (e.g., C5.1), start, maximum, and end times (UT), ion temperature T_i (K), electron temperature T_e (K), total electron content (TEC in units of 10^{16} electrons m⁻²), solar zenith angle (degrees), sunspot number, and the 10.7 cm solar radio flux (F10.7 in solar flux units, sfu). The first recorded TEC value was flagged as missing and excluded from correlation analyses involving TEC.

2.2 Derived Parameters

Flare magnitude was extracted as the numerical coefficient following the letter “C” (range 1.0–9.9). Flare duration was computed as the difference between end and start times, accounting for day-boundary crossings, and expressed in minutes. The ion-to-electron temperature ratio T_i/T_e was calculated for each event. Daily occurrence rates and daily mean values of TEC, F10.7, SSN, and magnitude were also derived.

2.3 Statistical Analysis

Descriptive statistics (mean, median, standard deviation, quartiles) were computed for all continuous variables. Pearson product-moment correlation coefficients were calculated among magnitude, duration, T_i , T_e , TEC, SZA, SSN, and F10.7. Linear regression trends were fitted where appropriate. Visualizations included histograms, time-series plots of daily counts and daily means, scatter plots colored by secondary variables, boxplots stratified by magnitude bins, and a correlation heatmap.

3. Results

3.1 Overall Characteristics of the Flare Population

A total of 624 C-class flares were identified over 75 observing days, corresponding to a mean daily rate of 8.32 events (median 7; maximum 21 on 12 March 2025). The magnitude distribution was skewed toward weaker events: the mean magnitude was C3.87 (median C3.35), with C2–C4 flares constituting the majority (see Figure 1a). Only 14 events exceeded C9.0. Mean flare duration was 19.9 minutes (median 16 min), although a small number of long-duration events exceeded 100 minutes.

Ion temperatures ranged from 980 K to 1506 K (mean 1168 K), while electron temperatures spanned 1319–2260 K (mean 1694 K). The resulting mean T_i/T_e ratio of 0.70 is consistent with typical mid-latitude daytime ionospheric conditions under moderate solar activity. TEC values ranged from 4.3 to 32.1 TECU (mean 13.6 TECU).



Fig.1 Overview of C-class solar flare statistics (1 January–18 March 2025). (a) Magnitude distribution; (b) daily occurrence rate; (c) TEC versus magnitude colored by F10.7; (d) boxplots of Ti and Te stratified by magnitude bins.

3.2 Correlation Structure

The Pearson correlation matrix (Figure 2a) reveals several notable relationships. Flare magnitude correlates most strongly with F10.7 ($r = 0.331$), followed by SZA ($r = 0.227$) and SSN ($r = 0.146$). The correlation between magnitude and TEC is essentially negligible ($r = 0.032$), indicating that individual C-class flares do not produce a systematic, immediate TEC enhancement detectable in the present dataset. Electron temperature shows a moderate negative correlation with SZA ($r = -0.573$) and a weaker negative correlation with magnitude ($r = -0.185$). Ion temperature correlates positively with electron temperature ($r = 0.372$) and with F10.7 ($r = 0.276$).

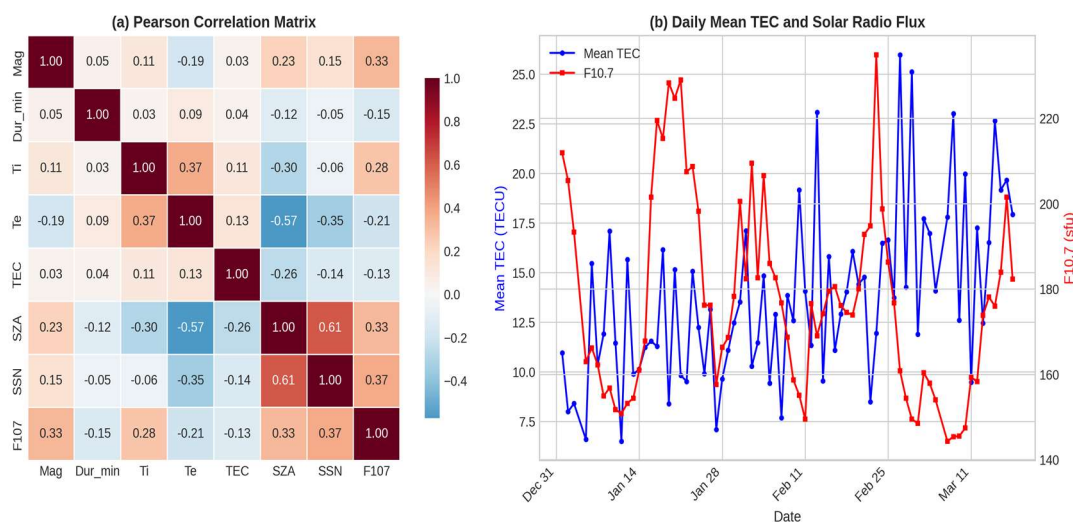


Fig.2 (a) Pearson correlation matrix of key parameters; (b) daily mean TEC and concurrent F10.7 flux.

3.3 Temporal Evolution and Duration Characteristics

Daily mean TEC and F10.7 exhibit only modest co-variation (Figure 2b). Periods of elevated F10.7 do not consistently coincide with elevated TEC, reinforcing the weak magnitude–TEC relationship. Flare duration shows almost no correlation with magnitude ($r = 0.052$) and only a weak negative correlation with F10.7 ($r = -0.150$). The distribution of the Ti/Te ratio is approximately Gaussian about a mean of 0.70 (Figure 3b), with the bulk of events lying between 0.55 and 0.85.

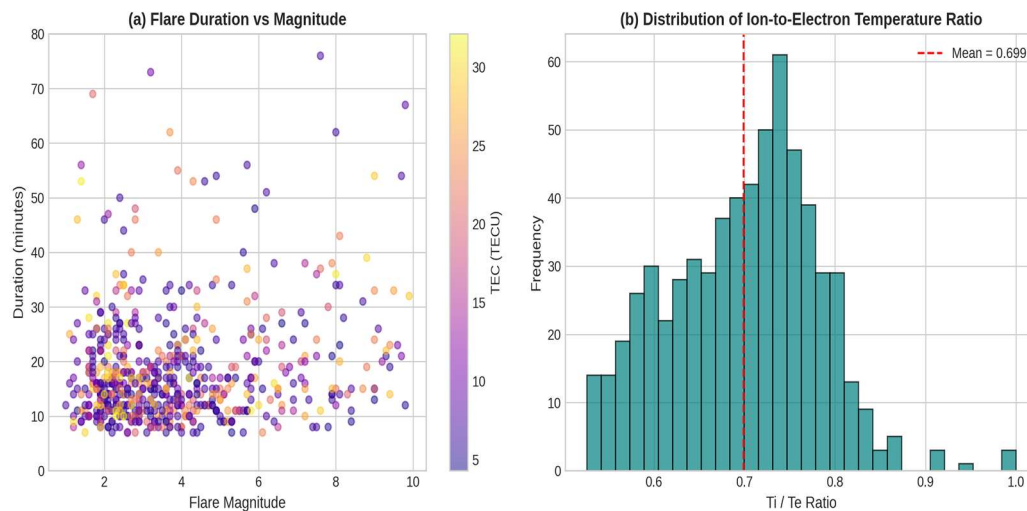


Fig.3 (a) Flare duration versus magnitude (colored by TEC); (b) histogram of the ion-to-electron temperature ratio.

4. Discussion

The near-absence of a correlation between C-class flare magnitude and TEC is the most striking result of this analysis. Earlier studies focusing on M- and X-class flares have routinely reported clear TEC enhancements of several TECU, often with a pronounced dependence on solar zenith angle (Meena et al., 2024; Meena, Sharma, & Gour, 2024). The present findings suggest that the energy deposited by typical C-class events is insufficient to drive a detectable, systematic increase in column electron density when averaged over the observing conditions of early 2025. Local time, geomagnetic activity, and the pre-existing ionospheric state likely dominate the TEC variance.

The moderate positive correlation of magnitude with F10.7 is expected: higher solar radio flux generally accompanies a more active corona capable of producing stronger flares. The positive correlation with SZA may reflect a selection effect flare occurring when the observing site is at higher zenith angles (near sunrise/sunset or higher latitudes) may be preferentially reported, or it may indicate a genuine geometric dependence of soft X-ray illumination.

Temperature diagnostics provide additional insight. Electron temperatures are systematically higher than ion temperatures, as expected from the preferential heating of the electron gas by solar EUV. The weak negative correlation between T_e and magnitude may indicate that stronger C-class flares are associated with slightly cooler electron populations, possibly because they occur preferentially in denser plasma where collisional cooling is more efficient. The stability of the Ti/Te ratio around 0.70 suggests that the thermal structure of the ionosphere remained relatively undisturbed by the C-class population as a whole.

These results complement the broader literature on solar–terrestrial coupling. While individual C-class flares appear modest in their ionospheric impact, their high frequency (average >8 per day) implies a non-negligible cumulative energy input. Future modeling efforts should therefore incorporate the statistical properties of C-class populations rather than focusing exclusively on extreme events. The dataset also provides a valuable baseline for comparison with periods of higher solar activity later in Cycle 25.

5. Conclusions

From the analysis of 624 C-class solar flares observed between January and mid-March 2025, the following conclusions are drawn:

1. C-class flares occurred at a mean rate of 8.3 events per day, with magnitudes concentrated between C2 and C5 and a mean duration of ~20 minutes.
2. Flare magnitude correlates moderately with F10.7 ($r = 0.331$) and weakly with SZA and SSN, but shows essentially no correlation with TEC ($r = 0.032$).
3. Mean ion and electron temperatures were 1168 K and 1694 K, respectively, yielding a stable Ti/Te ratio of approximately 0.70.

4. Individual C-class flares under the solar activity conditions of early 2025 do not produce systematic, detectable TEC enhancements, in contrast to the well-documented responses of M- and X-class events.
5. The high occurrence rate of C-class flares nonetheless implies a potentially important cumulative contribution to the ionospheric energy budget that warrants inclusion in next-generation space-weather models.

Continued monitoring through the remainder of Solar Cycle 25 will be essential to determine how these relationships evolve with increasing solar activity.

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Conflict of Interest

The authors declare that there are no conflicts of interest associated with this research. The authors have no financial, personal, or professional relationships that could have influenced the design, analysis, interpretation, or presentation of the findings reported in this manuscript.

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Authors' Contributions

Preetam Singh Gour: Conceptualization, methodology, data collection, data analysis, investigation, and drafting of the manuscript.

Ashish Kumar Meena: Conceptualization, data analysis, interpretation of results, visualization, and critical revision of the manuscript.

Shiva Soni: Supervision, scientific guidance, interpretation of results, and critical review and editing of the manuscript.

All authors contributed to the discussion of the results, reviewed the manuscript critically, approved the final version, and agreed to be accountable for all aspects of the work.

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