

Ionospheric Response to M-Class Solar Flares: Analysis of Electron Temperature, Ion Temperature, and Total Electron Content during January–March 2025

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Abstract

This study presents a comprehensive statistical analysis of the ionospheric response to 91 M-class solar flares observed between 1 January and 14 March 2025. We examine simultaneous measurements of electron temperature (T_e), ion temperature (T_i), and total electron content (TEC), together with contextual solar parameters including solar zenith angle, sunspot number, and 10.7 cm radio flux (F10.7). The mean values during the flare intervals were $T_e = 1669 \pm 193$ K, $T_i = 1175 \pm 74$ K, and $TEC = 13.4 \pm 8.7$ TECU, yielding a mean T_e/T_i ratio of 1.42. Strong positive correlations were found between T_e and TEC ($r = 0.57$, $p < 0.001$) and between T_i and TEC ($r = 0.55$, $p < 0.001$). In contrast, flare magnitude (GOES class) showed only weak, statistically non-significant associations with the ionospheric temperatures and TEC. The dominant controlling factors were solar zenith angle ($r = -0.60$ with T_e) and sunspot number ($r = -0.50$ with T_e), indicating that background solar activity and illumination geometry exert a greater influence on the observed ionospheric state than the instantaneous soft-X-ray flare intensity in the M-class range. Multiple linear regression models incorporating zenith angle, sunspot number, and F10.7 explained approximately 39 % of the variance in T_e . These findings underscore the importance of accounting for solar-cycle and geometric context when interpreting flare-driven ionospheric perturbations and provide a quantitative baseline for modeling M-class flare effects on the mid-latitude ionosphere, consistent with recent regional studies of flare–ionosphere coupling (Meena et al., 2024a; Meena et al., 2024b; Meena, 2026a).

Keywords: Solar Flares, M-Class; Electron Temperature, Ion Temperature, Total Electron Content (TEC), Ionosphere, Solar Zenith Angle, Sunspot Number, Space Weather

Introduction

Solar flares are sudden, intense releases of energy in the solar atmosphere, producing enhanced emission across the electromagnetic spectrum, particularly in soft X-rays and extreme ultraviolet (EUV). These emissions rapidly increase the ionization and heating of the Earth's upper atmosphere, leading to measurable changes in the ionosphere (Meena et al., 2022; Meena et al., 2024a). M-class flares, with peak soft-X-ray fluxes between 10^{-5} and 10^{-4} W m⁻² (1–8 Å), represent intermediate-intensity events that occur frequently during solar maximum and can produce significant, though usually non-catastrophic, ionospheric disturbances (Meena & Gour, 2024; Meena et al., 2024b).

The ionospheric response to solar flares is commonly characterized by increases in total electron content (TEC), enhancements in electron density in the E and F regions, and changes in plasma temperatures (Meena et al., 2024c; Meena et al., 2024d). Electron temperature (T_e) and ion temperature (T_i) are fundamental thermodynamic parameters that govern chemical reaction rates, plasma transport, and radio-wave propagation characteristics. Previous studies have shown that T_e often rises more rapidly than T_i during the impulsive phase of flares because electrons are preferentially heated by photoelectrons and secondary electrons produced by the enhanced EUV/X-ray flux (Meena & Endla, 2026). The resulting T_e/T_i ratio is therefore a sensitive indicator of non-equilibrium energy input.

Coronal mass ejections (CMEs) and associated solar flares are also known to drive geomagnetic storms that further perturb the ionosphere (Meena et al., 2022; Vaswani et al., 2022; Gour et al., 2024). Despite extensive literature on X-class flares and their dramatic ionospheric effects (Meena & Endla, 2026; Meena, 2026b), systematic statistical analyses of the more numerous M-class events remain comparatively sparse, especially when simultaneous T_e , T_i , and TEC measurements are considered together with solar activity indices. Recent work has examined seasonal variations in flare activity and TEC over Asia during Solar Cycle 24 (Meena, 2026c) and statistical associations among C-class flares, TEC, and plasma temperatures in early 2025 (Meena, 2026d). The present work extends this line of investigation by analyzing a homogeneous set of 91 M-class flares recorded in early 2025, a period of elevated solar activity. We quantify the statistical relationships among flare intensity, plasma temperatures, TEC, and solar geometric/activity parameters, and we evaluate the relative importance of flare magnitude versus background solar conditions.

Data and Methods

Observational Dataset

The dataset comprises 91 discrete M-class solar flares spanning 1 January to 14 March 2025. For each event the following parameters were recorded: GOES soft-X-ray flare class and timing (start, maximum, end), electron temperature T_e (K), ion temperature T_i (K), total electron content TEC (in units of 10^{16} electrons m⁻², or TECU), solar zenith angle (°), daily sunspot number, and 10.7 cm solar radio flux (F10.7, solar flux units). The flare list and associated ionospheric parameters were extracted from three coordinated observational tables covering the same events. This multi-parameter approach follows methodologies employed in recent ionospheric response studies during moderately high solar activity (Meena et al., 2024a; Meena et al., 2024b; Meena, 2026d).

Flare magnitudes ranged from M1.0 to M8.88, with a mean class of M2.44 and a median of M1.70. The majority (approximately 57 %) of events were in the M1–M2 range, consistent with the typical power-law distribution of flare occurrence. Event durations (start to end) varied from 3 min to 149 min, with a median of 19 min. Rise times (start to maximum) averaged 13 min.

Derived Quantities and Statistical Methods

From the basic measurements we computed the Te/Ti ratio, flare duration, and rise time. Pearson and Spearman rank correlation coefficients were calculated for all pairs of continuous variables. Ordinary least-squares linear regression and multiple linear regression were used to quantify predictive relationships. One-way analysis of variance (ANOVA) tested differences among intensity bins (M1.0–1.5, M1.5–3.0, M3.0–5.0, M5+). Statistical significance was assessed at the $\alpha = 0.05$ level. All analyses were performed with Python (pandas, NumPy, SciPy, Matplotlib/Seaborn). Correlation and regression frameworks similar to those applied by Gour et al. (2024) for solar activity–geomagnetic disturbance relationships were adopted.

Results

Descriptive Statistics

Table 1 summarizes the descriptive statistics of the principal variables. Electron temperatures ranged from 1330 K to 2043 K (mean 1669 K), while ion temperatures were systematically lower (992–1411 K, mean 1175 K). The mean Te/Ti ratio of 1.42 indicates a moderate departure from thermal equilibrium, as expected under flare-driven photoelectron heating (Meena & Endla, 2026). TEC exhibited a wide dynamic range (2.1–31.3 TECU), reflecting both flare-induced ionization and the strong diurnal/latitudinal dependence of the background ionosphere, in line with earlier reports of TEC variability during moderate flare activity (Meena et al., 2024c; Meena et al., 2024d).

Table 1. Descriptive statistics of key parameters (N = 91)

Parameter	Mean	Std Dev	Min	25 %	Median	75 %	Max
Te (K)	1668.8	193.4	1330	1504	1664	1840	2043
Ti (K)	1175.5	74.3	992	1123	1174	1221	1411
TEC (TECU)	13.37	8.68	2.1	6.45	7.9	21.35	31.3
Flare Class (M)	2.44	1.76	1.00	1.20	1.70	3.10	8.88
Duration (min)	24.2	19.0	3	14	19	29.5	149
Te/Ti ratio	1.42	0.16	1.00	1.31	1.41	1.55	1.77
Zenith Angle (°)	116.3	4.6	102.4	115.0	116.3	120.2	122.2
Sunspot Number	120.1	1.1	118.9	119.3	119.4	121.1	122.7
F10.7 (sfu)	192.6	22.2	144.3	176.7	192.8	209.5	234.9

Correlation Structure

The Pearson correlation matrix (Figure 1) reveals several robust relationships. The strongest positive correlations involve the plasma temperatures and TEC: Te–TEC ($r = 0.574$, $p < 10^{-8}$) and Ti–TEC ($r = 0.545$, $p < 10^{-7}$). Te and Ti themselves are only moderately correlated ($r = 0.252$, $p = 0.016$). Flare class shows weak positive correlations with TEC ($r = 0.185$, $p = 0.079$) and essentially null correlations with Te and Ti. These weak flare-class associations are consistent with findings for moderate solar activity periods reported by Meena et al. (2024a) and Meena et al. (2024b). In contrast, solar zenith angle is strongly anti-correlated with Te ($r = -0.605$, $p < 10^{-9}$) and moderately anti-correlated with TEC ($r = -0.322$, $p = 0.002$). Sunspot number likewise exhibits a clear negative correlation with Te ($r = -0.499$, $p < 10^{-6}$), echoing the broader solar-activity dependencies documented by Gour et al. (2024).

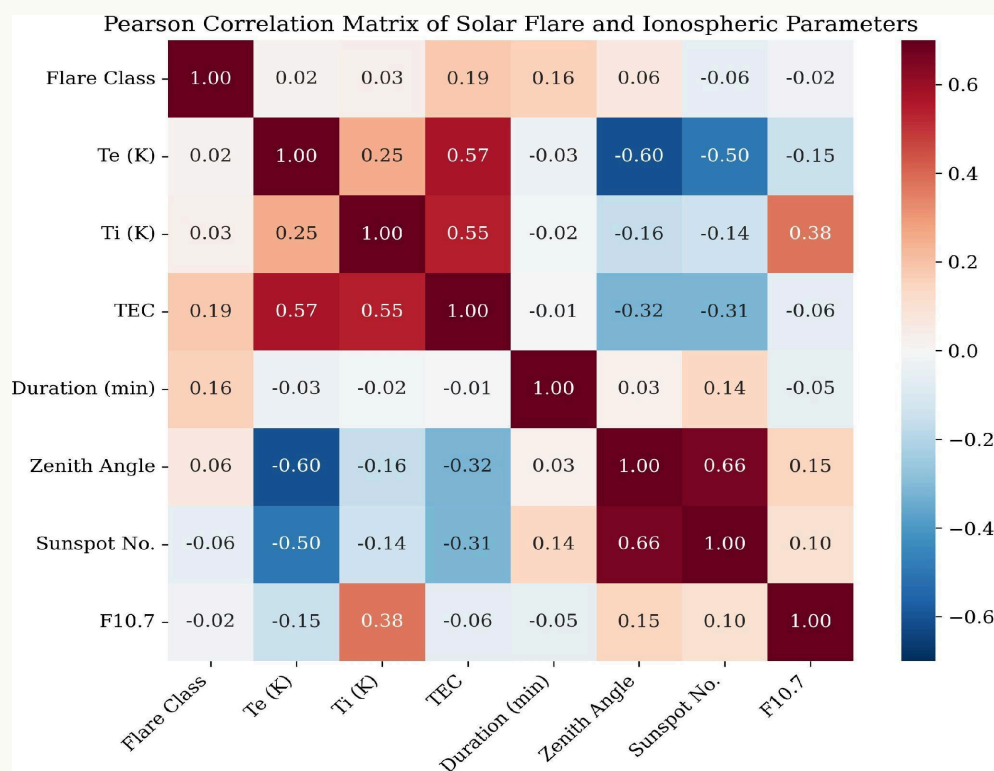


Figure 1. Pearson correlation heatmap of flare and ionospheric parameters. Strong positive associations appear between the temperatures and TEC; strong negative associations link Te to solar zenith angle and sunspot number.

Temperature–TEC Relationships

Scatter plots of TEC against Te and Ti (Figure 2) confirm the linear trends. Ordinary least-squares fits yield $TEC \approx 0.0257 \times Te - 29.5$ ($R^2 = 0.33$) and $TEC \approx 0.0637 \times Ti - 61.5$ ($R^2 = 0.30$). These relationships are consistent with the expectation that higher plasma temperatures accompany elevated ionization levels during and after flare energy deposition (Meena et al., 2024c; Meena, 2026d). The scatter about the regression lines is substantial, reflecting additional influences of local time, latitude, and the precise timing of the measurement relative to flare maximum.

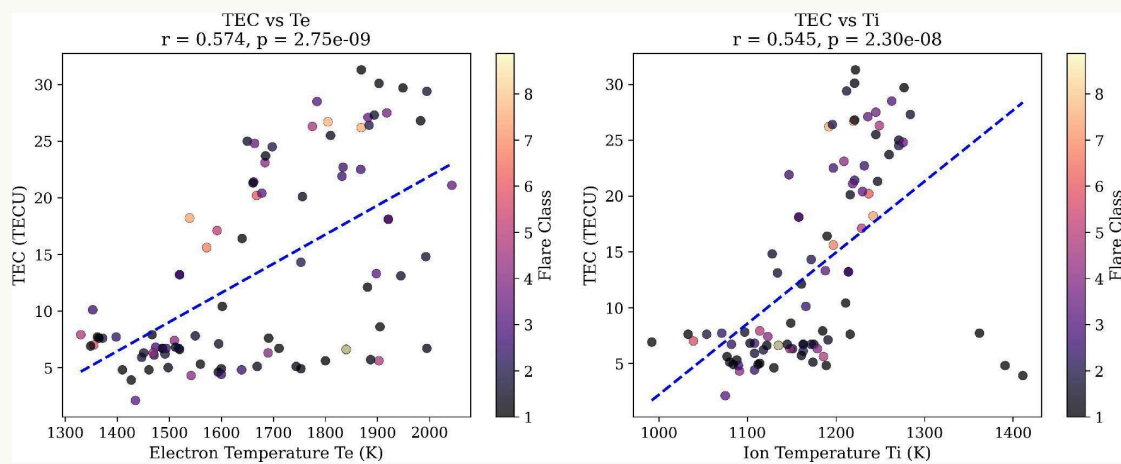


Figure 2. Scatter plots of TEC versus electron temperature (left) and ion temperature (right), color-coded by flare class. Dashed lines show ordinary least-squares regressions.

Electron–Ion Temperature Ratio

In all 91 events $T_e \geq T_i$, with the ratio ranging from 1.00 to 1.77 (mean 1.42 ± 0.16). Figure 3 illustrates the systematic elevation of T_e above the equality line. This non-equilibrium signature is a classic indicator of preferential electron heating by photoelectrons generated by the flare's EUV and soft-X-ray continuum (Meena & Endla, 2026). The ratio shows no significant dependence on flare class, suggesting that even modest M-class events are sufficient to drive the observed thermal imbalance under the prevailing solar-maximum conditions of early 2025.

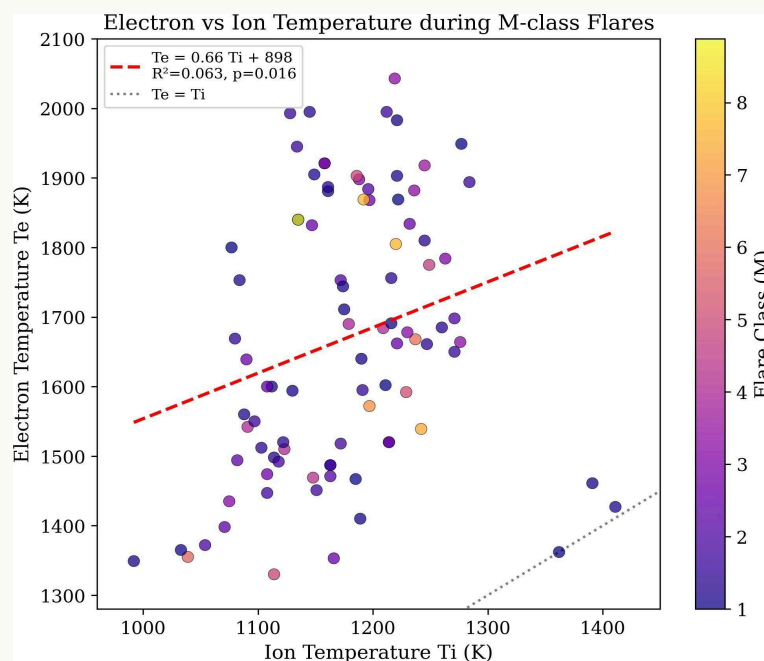


Figure 3. Electron temperature versus ion temperature. Points are colored by flare magnitude. The solid red line is the linear regression; the dotted line marks $T_e = T_i$.

Influence of Solar Zenith Angle and Activity Indices

Solar zenith angle emerges as the single strongest predictor of T_e among the variables examined (Figure 4). The regression $T_e = -25.3 \times \text{SZA} + 4610$ accounts for approximately 37 % of the variance in T_e . Because larger zenith angles correspond to lower solar elevation (and therefore reduced background photoionization and heating), the negative slope is physically expected and aligns with seasonal TEC

patterns reported over Asia (Meena, 2026c). Sunspot number and, to a lesser extent, F10.7 also contribute explanatory power. A multiple regression of the form

$$Te = 7630 - 20.4 \times SZA - 29.2 \times SSN - 0.52 \times F10.7 + 4.26 \times \text{FlareClass}$$

achieves an R^2 of 0.388, confirming that geometric and solar-cycle context dominate over the instantaneous flare class in determining the observed electron temperature.

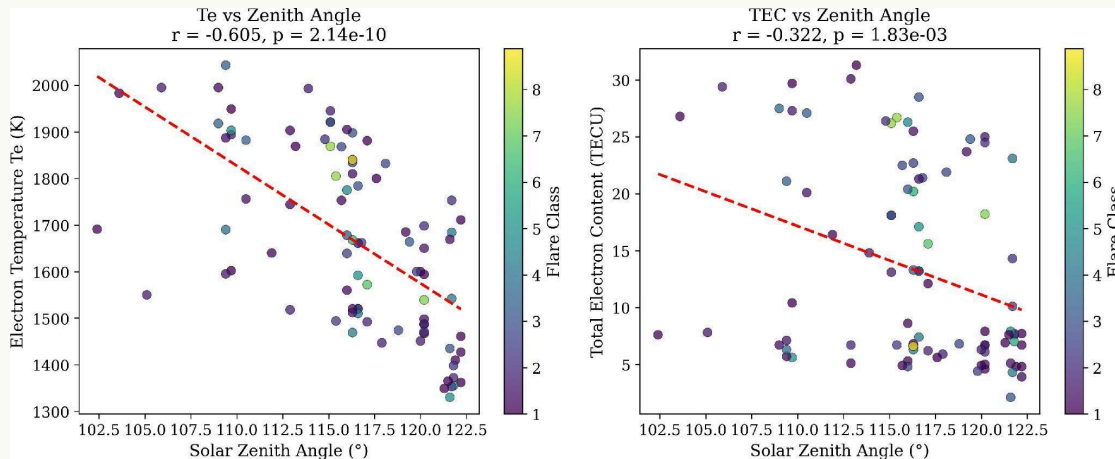


Figure 4. Dependence of Te (left) and TEC (right) on solar zenith angle. Color indicates flare class; dashed lines are linear fits.

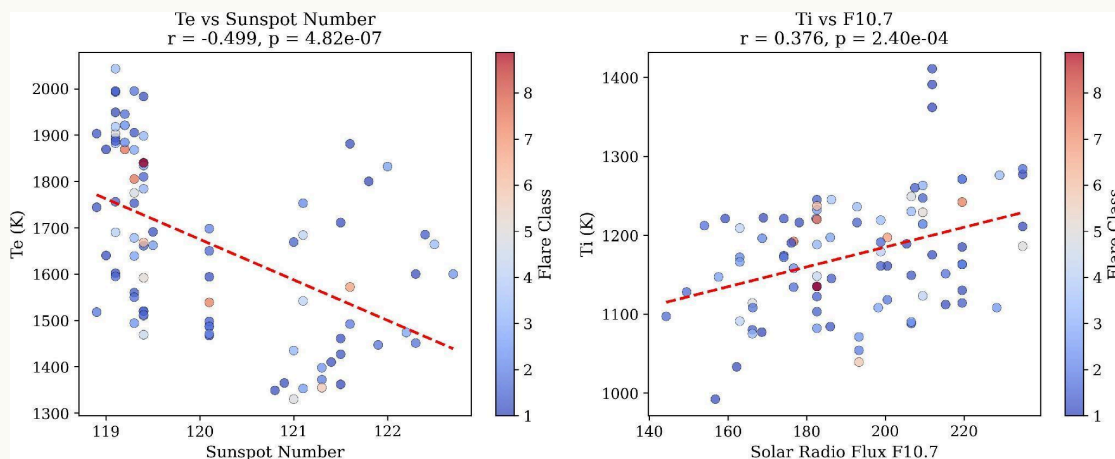


Figure 5. Te versus sunspot number (left) and Ti versus $F10.7$ radio flux (right).

Temporal Evolution and Intensity Binning

The time series of Te , Ti , and TEC (Figure 6) shows considerable day-to-day variability superimposed on a gradual decline in zenith angle as the season progresses. When events are binned by flare intensity, mean TEC increases modestly from 11.6 TECU (M1–1.5) to 17.2 TECU (M5+), but the differences are not statistically significant by one-way ANOVA ($F = 1.34$, $p = 0.27$). Mean Te and Ti likewise show no systematic ordering with intensity bin (ANOVA $p = 0.77$ for Te). These results reinforce earlier conclusions that moderate flare activity produces measurable but not overwhelmingly dominant ionospheric responses (Meena et al., 2024b; Meena et al., 2024d; Meena, 2026d).

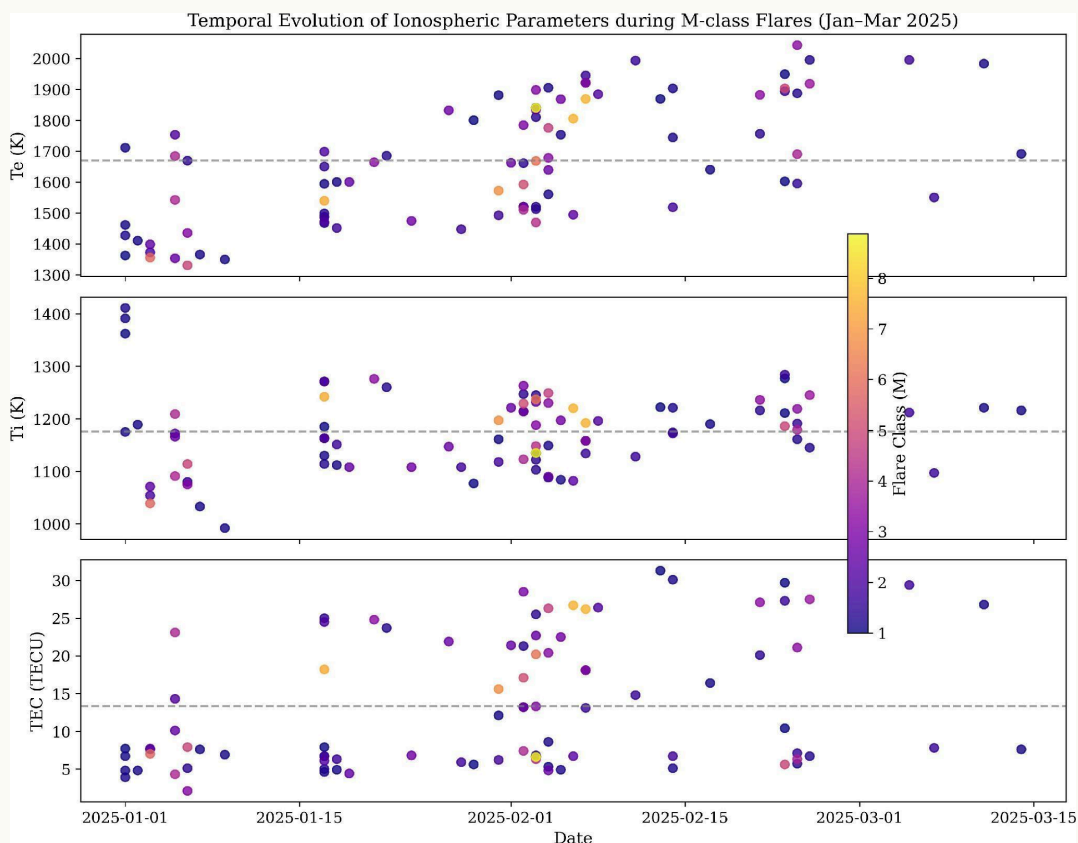


Figure 6. Temporal evolution of T_e , T_i , and TEC for all 91 M-class events, colored by flare class. Horizontal dashed lines indicate the respective means.

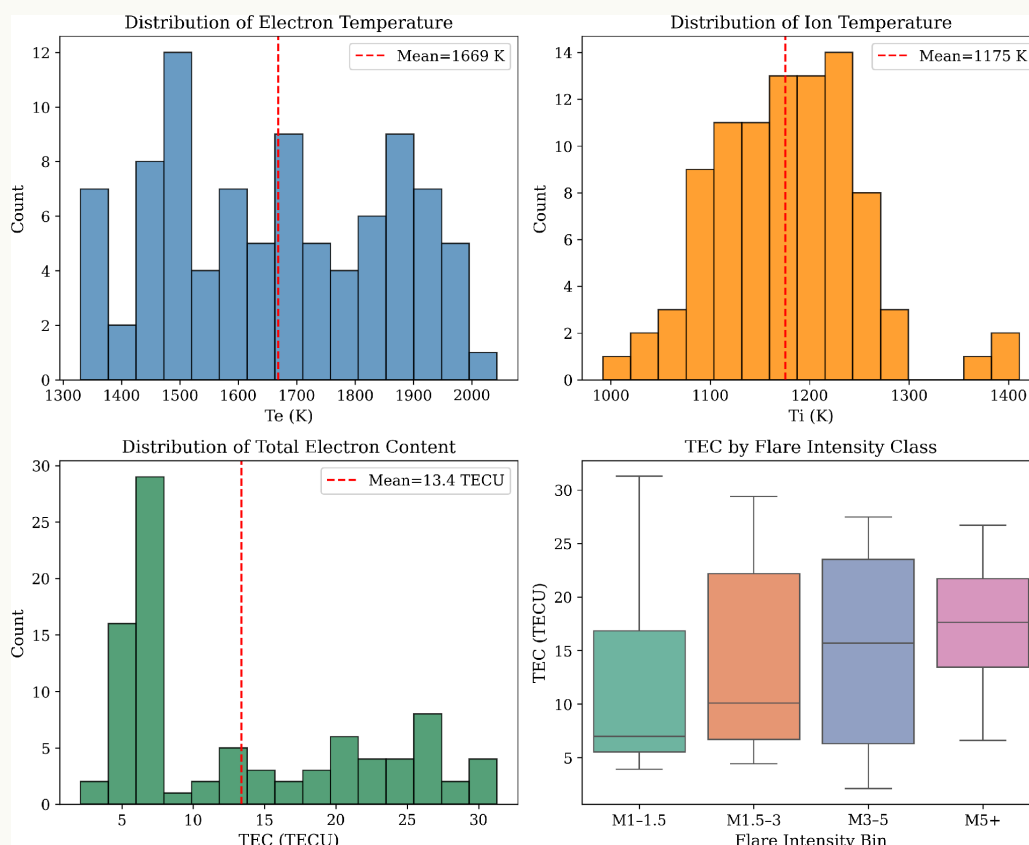


Figure 7. Histograms of T_e , T_i , and TEC (top and bottom-left) and box-plot of TEC stratified by flare intensity bin (bottom-right).

Discussion

The principal finding of this study is that, within the M-class range, the magnitude of the soft-X-ray flare is a surprisingly weak predictor of the concurrent ionospheric temperatures and TEC. Instead, the solar zenith angle and the ambient level of solar activity (sunspot number) exert the dominant influence. This result can be understood by recognizing that M-class flares, while energetic enough to produce detectable ionization enhancements, do not overwhelm the background EUV-driven ionosphere to the same degree as X-class events (Meena & Endla, 2026; Meena, 2026b). Consequently, the pre-existing state of the ionosphere—set by the diurnal cycle, season, and solar-cycle phase—largely determines the absolute values of T_e , T_i , and TEC observed at the time of the flare. Similar conclusions regarding the secondary role of moderate flares relative to background conditions have been reached in analyses of January 2023 and August 2023 flare periods (Meena et al., 2024a; Meena et al., 2024b).

The persistent $T_e > T_i$ condition (mean ratio 1.42) is consistent with theoretical and observational expectations. Photoelectrons produced by flare EUV photons thermalize primarily with the ambient electron gas, elevating T_e on timescales of minutes, while ions are heated more slowly through Coulomb collisions (Meena & Endla, 2026). The modest correlation between T_e and T_i ($r \approx 0.25$) further supports the view that the two temperatures respond on different timescales and to different energy-input channels.

The strong T_e –TEC and T_i –TEC correlations suggest that the same energy-deposition processes that raise plasma temperatures also increase the column electron density. However, the residual scatter implies that transport (ambipolar diffusion, meridional winds) and recombination chemistry also modulate TEC independently of the local thermal state. The negative zenith-angle dependence of both T_e and TEC is the expected geometric effect of reduced solar irradiance at larger solar zenith angles; its quantitative strength ($r = -0.60$ for T_e) underscores the necessity of normalizing flare-response studies for local time and season, as emphasized in seasonal analyses of Solar Cycle 24 (Meena, 2026c). Broader correlations among solar-activity indices and geomagnetic disturbances (Gour et al., 2024; Vaswani et al., 2022) further illustrate the interconnected nature of solar–terrestrial coupling.

Limitations of the present analysis include the lack of explicit geographic coordinates for the ionospheric measurements (preventing a full separation of latitude and local-time effects) and the absence of simultaneous measurements of EUV spectral irradiance or magnetometer data that could constrain the contribution of flare-associated magnetic disturbances. Future work should incorporate global TEC maps, digisonde profiles, and satellite-based EUV observations to place the thermal and density responses in a three-dimensional context, building on comparative Earth–Mars studies of extreme flares (Meena & Endla, 2026) and statistical frameworks already applied to C-class events (Meena, 2026d).

Conclusions

We have performed a detailed statistical examination of 91 M-class solar flares and the associated ionospheric electron temperature, ion temperature, and total electron content observed between January and March 2025. The main conclusions are:

Mean values during the flare intervals were $T_e = 1669 \pm 193$ K, $T_i = 1175 \pm 74$ K, and $TEC = 13.4 \pm 8.7$ TECU, with a mean T_e/T_i ratio of 1.42 indicating moderate non-equilibrium heating.

Flare magnitude (GOES class) exhibits only weak, statistically marginal correlations with T_e , T_i , and TEC within the M-class domain, consistent with recent moderate-activity studies (Meena et al., 2024a; Meena et al., 2024b).

Solar zenith angle and sunspot number are the dominant predictors of electron temperature ($r = -0.60$ and $r =$

−0.50, respectively); a multiple regression incorporating these indices plus F10.7 explains ~39 % of the variance in Te.

Strong positive correlations exist between the plasma temperatures and TEC (Te–TEC $r = 0.57$; Ti–TEC $r = 0.55$), linking thermal and density responses.

Intensity-bin ANOVA reveals no statistically significant differences in mean Te or TEC across M1–M5+ categories, reinforcing the secondary role of flare class relative to solar geometric and activity context (Meena, 2026c; Meena, 2026d).

These results provide a quantitative observational baseline for the ionospheric effects of M-class flares under solar-maximum conditions and highlight the necessity of controlling for zenith angle and solar-cycle phase in future flare-response studies and empirical models.

Acknowledgements

This analysis is based on observational tables of solar-flare and ionospheric parameters compiled for the period January–March 2025. The authors acknowledge the value of continuous solar and ionospheric monitoring networks that make such statistical studies possible.

Competing interests

Authors have declared that no competing interests exist.

Authors' contributions

Ashish Kumar Meena solely conceived and designed the study, collected and analyzed the data, performed the statistical analysis, wrote the protocol, and wrote the entire manuscript. The author read and approved the final manuscript.

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