Dear Editor,

Thank you for sending us the report on "Ionospheric Plasma Irregularities During Intense geomagnetic storms of Solar Cycle 25" manuscript No. egusphere-2025-86 submitted to Annales Geophysicae. We are very grateful to the Editor and anonymous referee for the time and efforts invested in reviewing our work. We have incorporated the general comment provided by one reviewer in this round.

Response to Reviewer:

Major comments:

The authors present ROTI plots in Universal Time (UT), which makes it difficult to interpret the local time dependence of irregularities. Since ionospheric phenomena like post-sunset irregularities are strongly influenced by local time, this choice limits the interpretability of the results. Local time (LT) plots would better visualize the storm-time impact and allow comparisons across different longitude sectors. Therefore, the authors should replot their ROTI in Local Time (LT), even though they provided LT information in table 1, to better capture the local time dependence of irregularities. This would allow them to identify whether irregularities are enhanced or suppressed during specific local times (e.g., post-sunset, post-midnight) and also correlate storm impacts with the local time of SSC and main phase onset. The authors also mention plasma irregularity suppression during certain geomagnetic storms (e.g., November 2023), this would be good in terms of local time discussions. Several studies identified the importance of the local time at which geomagnetic storms happen to explain their impact on the ionosphere. Please review these documents to gain a better understanding of the

above, including discussions related to DDEF, PPEF, and the suppression of irregularities.

1. **Liu, J., Zhao, B., & Liu, L. (2010, March). Time delay and duration of ionospheric total electron content responses to geomagnetic disturbances. In Annales Geophysicae (Vol. 28, No. 3, pp. 795-805). Copernicus GmbH.**
2. **Amaechi, P. O., Oyeyemi, E. O., & Akala, A. O. (2018). Geomagnetic storm effects on the occurrences of ionospheric irregularities over the African equatorial/low-latitude region. Advances in Space Research, 61(8), 2074-2090.**
3. **Araujo-Pradere, E. A., Fuller-Rowell, T. J., Codrescu, M. V., & Bilitza, D. (2005). Characteristics of the ionospheric variability as a function of season, latitude, local time, and geomagnetic activity. Radio Science, 40(05), 1-15.**
4. **Seba, E. B., & Nigussie, M. (2016). Investigating the effect of geomagnetic storm and equatorial electrojet on equatorial ionospheric irregularity over East African sector. Advances in space Research, 58(9), 1708-1719.**

Reply: Following to the Referee's report, we have plotted ROTI in Local Time (LT) to identify whether irregularities are enhanced or suppressed during specific local times (e.g., post-sunset, post-midnight) and also correlated storm impacts with the local time of SSC and main phase onset. Please see the revised version of Figures 8-10 and Table 3. For better understanding, the discussion on the basis of above literature has been added in the revised manuscript. Following discussion regarding local time dependence of the post-sunset ionospheric plasma irregularities during the storms have been added in the Results and Discussion section.

The storm-time ring current is critical for both the development and suppression of equatorial ionospheric plasma irregularities. For instance, ionospheric plasma irregularities are generated if the greatest excursion of the ring current (minimum SYM-H index) occurs between midnight and postmidnight. However, the plasma irregularities are suppressed when the maximum excursion of the ring current occurs in the early afternoon (Aarons, 1991). Table 3 shows the LT of maximum excursion of ring current or MPE at each GNSS location. During geomagnetic storms in March, April, and May, the ring current has the greatest excursion after midnight in American sector, indicating the highest likelihood of plasma irregularities in the evenings following the storms' main phases in this sector. For instance, the maximum ring current excursions at the GNSS stations BOGT, RIOP, and SANT (LT = UTC-5) occurred at approximately 00:21, 23:03, 11:54, and 21:14 LTs on March 24, April 24, November 5, and May 11, respectively. On the same days, the CORD station (LT= UTC-4) reported the highest excursions at 01:21, 00:03, 12:54, and 22:14 LT. Notably, the highest excursions during the storms of March, April, and May occurred predominantly during the night to midnight which is the most ideal time for the growth of post-sunset ionospheric plasma irregularities. During November storm, the maximum ring current excursion occurred at approximately 11:54, and 12:54 LTs which is the least favorable time for ionospheric plasma irregularities to occur. However, the intensity of post-sunset plasma irregularities varies between these storms due to complex interaction of important factors such as storm-time electric fields, meridional winds, background ionospheric conditions, local time and seasons. The largest excursion of the ring current in the November storm

occurred before dusk, indicating that post-sunset plasma irregularities were unlikely during the main phase of this storm.

The authors attempt to link high-latitude Joule Heating (JH) with the Equatorial Ionization Anomaly (EIA), which is a low-latitude phenomenon (lines 240-250). While this is an interesting approach, the connection between these two regions is not clearly explained in the paper. The paper shows correlations between JH and EIA structures, but it does not establish a causal relationship. The authors should provide more evidence or references to support their claim that JH directly influences EIA and explicitly state the mechanism by which high-latitude JH influences low-latitude EIA. Do the authors propose that JH-driven thermospheric winds transport plasma or alter neutral composition, thereby affecting EIA structures? The authors observe interhemispheric asymmetries in JH (e.g., stronger JH in the northern hemisphere during the May 2024 storm). How do these asymmetries translate to differences in EIA structures or irregularities at low latitudes?

Reply: Joule heating has a considerable and primarily indirect effect on the post-sunset EIA during the main phase of a geomagnetic storms, which is mediated by storm-time neutral winds, thermospheric upwelling, and electric field modulation. Following to the Referee's suggestions, we have improved the Results and Discussion section.

The authors' discussion on the relationship between EIA structures and ionospheric irregularities is a good starting point, but it lacks several critical elements that would make their findings more robust, insightful, and convincing. That is, the authors do not provide a detailed mechanistic explanation of how specific EIA structures (e.g., double crest, single crest, or merged) influence the formation or suppression of irregularities. For example: How do density gradients in the EIA directly affect the night time

growth of Rayleigh-Taylor instabilities? Please review the followings for further understanding:

• Luan, X. (2021). Equatorial ionization anomaly variations during geomagnetic storms. Ionosphere dynamics and applications, 301-312.

• Balan, N., Liu, L., & Le, H. (2018). A brief review of equatorial ionization anomaly and ionospheric irregularities. Earth and Planetary Physics, 2(4), 257-275.

• Seba, E. B., Nigussie, M., & Moldwin, M. B. (2018). The relationship between equatorial ionization anomaly and nighttime equatorial spread F in East Africa. Advances in Space Research, 62(7), 1737-1752.

• Aa, E., Chen, Y., & Luo, B. (2024). Dynamic expansion and merging of the equatorial ionization anomaly during the 10–11 May 2024 super geomagnetic storm. Remote Sensing, 16(22), 4290.

Reply: Following to the Referee's suggestion, we have added detailed discussion about EIA structures, density gradients in EIAs and their connection with ionospheric plasma irregularities. Please see Section 3.3.2 of the revised manuscript.

Suggestion on the conclusion section:

Here are my suggested potential findings that should be included in the conclusion section and summarized in the abstract, along with clear physical explanations (the physical explanations in discussion and conclusion).

Reply: Following to the Referee's report, we have improved the conclusion section as:

- The distribution and intensity of Joule heating during geomagnetic storms varied significantly with the storm's magnitude, local time of occurrence, duration, and seasons. Among the four storms examined, the May storm (near the June solstice) exhibited the most intense post-sunset Joule heating, followed by the March (equinox),

April (post-equinox), and November (fall transition) storms, with the latter showing the weakest activity. Nearly symmetric heating patterns were observed during equinoctial storms, whereas solstice storms led to marked asymmetries between hemispheres.

- **Each storm produced distinct equatorial ionization anomaly (EIA) structures, ranging from single crests with filled troughs to uneven double crests with deep troughs. These configurations were generated by the interaction between storm-induced electric fields and equatorward neutral winds, both of which are modulated by the spatial and temporal characteristics of Joule heating. After sunset, equatorward meridional winds (southward in the Northern Hemisphere and northward in the Southern Hemisphere) can lift low-latitude plasma upward along magnetic field lines, resulting in pronounced double-crest EIAs. In contrast, hemispherically asymmetric winds may amplify the EIA in one hemisphere while suppressing it in the other, forming a single crest. When poleward winds dominate in both hemispheres, plasma uplift is inhibited, leading to weaker EIA development.**
- **The combined influence of storm-time electric fields and thermospheric winds plays a key role in shaping the EIA, elevating plasma to higher altitudes, and redistributing electron density across trough and crest regions. During the main phase of storms, frequent North/South flipping in the interplanetary magnetic field (IMF Bz) can generate both eastward and westward prompt penetration electric fields (PPEFs), resulting from undershielding and overshielding effects. These alternating electric fields drive upward and downward vertical plasma drifts, further altering EIA structure.**
- **In particular, EIAs with filled or deep troughs and steep vertical gradients in plasma density can create favorable conditions for the development of Rayleigh-Taylor instabilities, which in turn promote post-sunset ionospheric irregularities. The occurrence and intensity of these irregularities varied spatially and temporally across the storms. For example, greater irregularity activity was observed in the Northern Hemisphere during equinoctial storms, while Southern**

Hemisphere dominance was seen during the solstice storm. In contrast, suppression of post-sunset irregularities was evident over the American sector during the intense storm in the winter season. Overall, the evolution and strength of post-sunset ionospheric irregularities at equatorial and low latitudes are governed by the combined influence of EIA density gradients, vertical plasma drifts, Local Time of maximum ring current development, and seasons.

These insights not only enhance our understanding of low-latitude ionospheric behavior but also provide valuable foundation for improving predictive models and mitigation strategies for satellite communication, navigation systems, and other technologies sensitive to ionospheric disturbances. Future research may focus on integrating multi-instrument observations with advanced model simulations to further unravel the complex electrodynamic processes governing storm-time ionospheric variability.

Sincerely,

Dr. Nadia Imtiaz.