General comments:

This study presents the characteristics of equatorial and low latitude ionosphere during four intense geomagnetic storms that occurred on March 23–25, 2023, April 23–25, 2023, November 4–7, 2023 and May 10–13, 2024 in the ascending phase of Solar Cycle 25 based Joule Heating (JH) rates at high latitudes. For this purpose, authors have utilized the Weimer 2005 Model simulations to analyse the JH patterns along with Madrigal TEC maps to identify the changes in the intensity, location, and symmetry of the equatorial ionization anomaly (EIA) during these intense geomagnetic storms. Equatorial/low-latitude ionospheric plasma irregularities at different longitudes under geomagnetically disturbed conditions are studied using the TEC derived ROTI measurements. While a strong JH is observed during the May 2024 storm in the main phase, the other storms have the following order from strong to weak: March 2023, April 2023, and November 2023. The authors have investigated especially the role of asymmetric Joule heating in the structuring of the EIA like double crest, single crest or merged. Authors have utilized these features to investigate the formation or suppression of equatorial plasma irregularities. It is suggested that the generation of these ionospheric plasma irregularities and their latitudinal distribution strongly dependent on EIA's density gradients and latitudinal density structure. For instance, while the double crest EIA structures with strong plasma density gradients playing an important role in the generation of post sunset ionospheric plasma irregularities during the main phases of these four geomagnetic storms, single crest or merged EIA structure didn't favour the generation of ionospheric plasma irregularities. In addition, the role of storm-time penetration electric field in the structuring and seeding of ionospheric plasma irregularities have been investigated. Analysis of these storms by authors suggest that solar wind parameters, geomagnetic activity, JH, and PPEFs significantly influence ionospheric TEC variations, EIA crest formations, and post-sunset plasma irregularities. These investigations revealed that these storms highlighted the importance of inter-hemispheric asymmetries in JH that affected the distribution and magnitude of ionospheric irregularities. Finally, the paper concludes that the resulting change in the thermospheric winds and electric fields due to storm conditions can alter the EIA structures which will impact the plasma irregularities at equatorial and low latitudes.

While many of the results presented here are already reported, I believe discussions like role of single EIA, double or Merged EIA on plasma irregularities looks to be interesting though it is known that asymmetry of EIA can suppress the plasma bubbles due to thermospheric meridional winds. I am providing the comments to the authors. The manuscript may be considered for publication only after implementing the comments made in this review report by incorporating appropriate changes.

Specific comments

It is mentioned that JH is strong in May 2024 Mother's Day storm during main phase. Then it followed like this: March 2023>April 2023>November 2023. Cause of variation proposed: Change in thermosphere winds and electric fields due to storm conditions alter EIA structures. What is the role of thermospheric neutral density such as O/N2 ratio on the EIA single crest, double crests?

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 advice, we have improved the Results and Discussion section.

Whether authors have investigated positive/negative storms on the plasma irregularities.

Reply: We agree with the referee suggestion. The present analysis primarily focused on storm-time electrodynamic drivers of plasma irregularities. The distinction between positive (density enhancement) and negative (density depletion) storm phases has not been explicitly separated in this study. Previous investigations have shown that positive storms can enhance background density and steepen the EIA crests, thereby favoring Rayleigh–Taylor growth, while negative storms tend to suppress irregularity development by reducing ambient plasma density. Incorporating such a classification in future case studies would strengthen the understanding of storm-phase-specific impacts on irregularity development.

How the symmetry/asymmetry of EIA with single, double crests can influence the EPBs are not discussed. Please provide discussions.

Reply: In the revised manuscript, we have added discussion on the structure of EIA and its influence on the EPBs. 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 southward/northward flipping in the interplanetary magnetic field (IMF Bz) can generate both eastward and westward prompt penetration electric fields (PPEFs), resulting from overshielding and undershielding effects. These alternating electric fields drive upward and downward vertical plasma drifts, further modifying EIA structures. 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, post-sunset plasma irregularities are more likely to occur 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 the maximum ring current development, and seasons.

What is the role of electric fields on the generation/suppression of plasma irregularities?
Reply: During geomagnetic storms, equatorial ionospheric plasma density distribution is influenced by electric fields, including DDEF from storm-time neutral winds and PPEF of magnetospheric origin astafyeva2018. According to (abdu1997, abdu2009), the presence of eastward/westward PPEF after sunset during the main phase of a storm can affect the vertical drift of plasma over the equatorial region either strengthening or disturbing the favorable conditions for plasma irregularities. During a storm's recovery phase, the westward DDEF in the sunset terminator may cause the plasma to move downward, and the normal PRE is reversed, reducing plasma irregularities (abdu1997).

Why authors have chosen TEC maps between 18:00-00:00 UT for all the storm events in Figure-6? Since different storms have main phases at different UT times, why authors have chosen this time interval to study the plasma irregularities and their connection to EIA.
Reply: We are interested to study the behavior of post-sunset ionospheric plasma irregularities during the main phase of different storms. For this reason we focused on time between 18:00-00:00 UT.

The plots shown in Figure-6 can be plotted as a line plots to show clear asymmetry in EIA. Also in the plot, map for 23:00 UT is not shown. Whether it is plotted like this only, please clarify.
Reply: We agree with the referee that line plots provide useful temporal variations at individual stations; however, TEC maps offer a significant advantage by showing the two-dimensional spatial distribution of the ionosphere. In particular, during storm-time conditions, TEC maps make it easier to visualize enhancements, and depletions across a wide region, providing a more comprehensive picture of the ionospheric response. We revised Figure 6 according to the referee suggestions with good colors and also included 23 UT.

Role of geomagnetic storms on plasma irregularities in the following papers: S. Sripathi and Ram Singh, A study on the response of the ionosphere to the three major space weather events of 2015 using meridional chain of ionosondes and GPS receivers over India, journal of Sun and Geosphere, DOI: 10.31401/SunGeo.2018.02.08, 2020. Similarly, the following paper discusses the role of geomagnetic storms and role of Es layers on the plasma irregularities. Please go through it. Singh, R., & Sripathi, S. (2020). A statistical study on the local time dependence of equatorial spread *F* (ESF) irregularities and their relation to low-latitude Es layers under geomagnetic storms.

***Journal of Geophysical Research: Space Physics*, *125*, e2019JA027212. https://doi.org/10.1029/2019JA027212. It is said that the generation of ionospheric plasma irregularities and geographical distribution strongly dependent on EIA density gradients and general density structure. Please include the physics of their dependency.**

Reply: Following paragraph has been added in the Results and Discussion section:

As reported in previous studies, both positive and negative storm phases have an impact on the latitudinal density gradients at the EIA crests and the background ionospheric density, both of which are essential for the growth of equatorial spread F (ESF) through the Rayleigh-Taylor instability Sripathi and Singh (2020); Singh and Sripathi (2020). These gradients are modified by storm-time electric fields such as PPEF and DDEF, which change the positions and intensities of ESF events. The ESF formation can also be further shaped by low-latitude sporadic E (Es) layers, which can locally increase densities and initiate localized irregularities Singh and Sripathi (2020). The observed dependency of plasma irregularities on the storm phase and the underlying ionospheric structures can be explained by these mechanisms.

It is mentioned that the storm-time Joule heating in high-latitude can cause atmospheric gravity waves (AGWs) to move equatorward, thus providing favorable conditions for formation equatorial/low-latitude ionospheric plasma irregularities. But it is under recovery phase mostly. But here authors are describing plasma irregularities in the main phase. Please clarify.

Reply: We agreed with referee that the storm-time Joule heating at high-latitudes can cause AGWs that can affect low-latitude ionosphere during the recovery phase of the storm. However, during intense geomagnetic storms, strong Joule heating during the main phase can also generate fast propagating traveling atmospheric disturbances (TADs). The combined effect of fast TADs atmospheric disturbances can also be seen in the form of EIA modification and ionospheric plasma irregularities during the main phase of the storms.

Double crest EIA structures with strong plasma density gradient play an important role in generation of post sunset plasma irregularities. Single crest or merged EIA does not favor the generation of irregularity. Please provide brief explanation for this. How the plasma irregularity generation is associated with EIA crest need to be mentioned clearly in the manuscript.

Reply: The necessary explanation has been added in the revised manuscript.

3.1 Structure of Equatorial Ionization Anomaly (EIA): “This merging and subsequent increase in TEC were driven by enhanced JH and geomagnetic activity”. The claim can be elaborated by explaining the variation of JH with EIA structure.

Reply: Please see 3.1 section of the revised manuscript.

In general, PPEFs will affect the equatorial and low latitudes in the main phase of the storm, while Joule heating will affect the equatorial and low latitudes in the recovery phase of the storm through thermospheric wind circulation. However, here, authors are discussing the role of Joule heating during Main phase which I am not able to understand. Please clarify how the Joule Heating can impact the EIA crest in the main phase.

Reply: We agreed with the respected referee. The strong Joule heating during the main phase of the storm can affect the low-latitude ionosphere through thermospheric disturbances. Depending on the storm intensity and timing, these thermospheric disturbances along with PPEF lead to significant modification in EIA structure. We added relevant description in the mansucript.

The EIA trends are visually explained in table-3 with JH values where pattern can be observed. However, there is no mention of physics of their connection with the JH. What is the relation between JH and EIA dynamics are not clearly mentioned. Please explain. Similarly, Table-3 doesn't show any location where EIA crest is strong/weak. It has to be clearly mentioned.

Reply: Following discussion has been added: Joule heating has a considerable and primarily indirect effect on the post-sunset EIA during the main phase of geomagnetic storms, which is mediated by storm-time neutral winds, thermospheric upwelling, and electric field modulation. The strong JH causes an equatorward wind surge, which uses neutral drag to drive plasma along magnetic field lines to higher altitudes. This decreases the downward plasma diffusion and elevates ionospheric heights, reducing chemical loss and supporting positive ionospheric storm effects, which strengthen the EIA intensity. However, the EIA's structure typically undergoes the most significant changes in the evening, around the local sunset. After sunset, the equatorial ionosphere experiences PRE and vertical plasma drifts because of enormous Cowling conductivities and rapid changes in zonal winds. The combination of PPEF and PRE can significantly increase ambipolar diffusion and upward EXB drift, resulting in poleward extension of EIA crests. In contrast to poleward expansion, geomagnetically quiet or disturbed conditions may lead EIA crests to merge into a single peak across the geomagnetic equator. The electrodynamic effect, downward equatorial plasma drift, equatorward neutral winds, and an increase in the low-latitude O/N2 ratio all contribute to the structuring of EIA crests {balan2018, luan2021}. In the caption of Table 3, we have now added the location of EIA crests that is over the American longitudes.

3.2 Ionospheric Plasma Irregularities: The observations presented here under PPEFs and DDEFs and claims to have plasma irregularities. The proof/data/evidence/observation of the irregularities are needed to be included.

Reply: Following referee's suggestions, we have revised this section. Please see section 3.2 of the revised manuscript.

What is the role of atmospheric waves and tides on the variability of the PRE, EIA and plasma irregularities. It is known that equatorial electrodynamics plays significant role in day-to-day variability of the E X B drift and RT instability triggered plasma irregularities. So, this point needs to be addressed.

Reply: Following paragraph has been added:

Furthermore, the atmospheric waves and tides play a crucial role in the diurnal variability of the PRE, EIA, and the generation of plasma irregularities. Tidal and gravity wave perturbations originating in the lower atmosphere modify neutral winds, which in turn influence the equatorial dynamo and the vertical E × B drift Sripathi and Singh (2020). This variability alters the magnitude and timing of the PRE, modifies the EIA density gradients, and sustains the Rayleigh–Taylor instability, thereby controlling the occurrence and intensity of equatorial spread F (ESF) Singh and Sripathi (2020). Even under geomagnetically disturbed conditions, these processes highlight the importance of lower atmosphere–ionosphere coupling in regulating plasma irregularities.

Authors have chosen these four storms without looking into the role of seasons on the EIA. Usually, it is standard practice to choose storms that fall in equinox. Please address this point.

Reply: We thank to the referee for pointing this out. It should be noted that the four storms analyzed (March 23–25, 2023; April 23–25, 2023; November 4–7, 2023; and May 10–13, 2024) were selected primarily for their intensity and data availability rather than seasonal occurrence; while equinox storms are commonly emphasized in EIA studies, a systematic seasonal comparison is beyond the scope of this work and will be addressed in future investigations. Also, 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 the two hemispheres.

If you want to study only 18:00-00:00 UT, please show this period with yellow highlight in the Figures-1-4 so that it is easy for the readers to follow it. Currently, authors have highlighted the main phase of the storm with ‘red’ rectangle box. In fact, in these figures, AE/AU/AL is missing.

Reply: In the revised manuscript, we have added the auroral indices and also highlighted the period of interest between 18:00-00:00 UT.

In the introduction, the sentence starts with ‘Ionospheric effects on applications are generally minor in mid-latitudes…’ may be replaced with ‘Ionospheric effects are generally minor in mid-latitudes…’ as the sentence is not conveying message correctly.

Reply: Correction has been made.

"It is generally said that during storm time, it increases the daytime eastward electric field". E_{total} (t)=E_{quiet} (t)+E_{PPEF} (t). It can either increase or decrease the equatorial zonal electric field, depending on IMF Bz polarity and whether you are on the dayside or nightside. This equation can be included.

Reply: We thank to the referee for suggesting this. Following text has been added in the revised version: During geomagnetic storms, the zonal electric field can be expressed as $E(t)=E_Q(t)+E_{PPEF}(t)$, where $E_Q(t)$ is the quiet-time background field and $E_{PPEF}(t)$ is the prompt-penetration electric field. Depending on the IMF B_z polarity and local time, the PPEF can either enhance the eastward daytime field or reduce (and sometimes reverse) the zonal field, leading to significant storm-time variability.

Correct ‘Disturbed Dynamo (DD)’ to ‘Disturbance Dynamo (DD)’

Reply: Correction has been made.