General comments:

The manuscript is well-structured and addresses a timely and relevant topic in space weather and ionospheric physics. The use of multiple data sources enhances the reliability of the findings, and the interpretation is generally sound and supported by the data. The study contributes valuable insights into the behavior of ionospheric irregularities during geomagnetic storms in the early phase of Solar Cycle 25. The paper is suitable for publication in Annales Geophysicae after revisions. Below are some suggestions to improve clarity, scientific rigor, and presentation.

Methodology and presentation:

> **The methodology is appropriate, but more detail on the ROTI calculation parameters (e.g. time resolution, thresholding) would improve reproducibility. Additionally, the criteria used to define the "intensity" of the selected storms beyond Dst values would worth being clarified.**
>
> **Reply: ISEE ROTI data are derived from over 9300 GNSS phase observations acquired at 30-second intervals and transformed into 5-minute ROTI values at ionospheric pierce locations. The 2D ROTI maps are updated every 5 minutes with a 0.25° × 0.25° grid resolution. ROTI ≥ 0.5 TECU/min indicates ionospheric disturbances, while ROTI ≥ 1.0 TECU/min indicates significant irregularities.**
>
> **We have used the SYM-H index rather than the disturbance storm time (Dst) index to characterize geomagnetic storms because SYM-H offers a 1-minute cadence, in contrast to the hourly resolution of Dst. While both indices represent the symmetric component of the ring current and thus share the same physical interpretation, the higher temporal resolution of SYM-H enables a more accurate depiction of the rapid variations and short-term dynamics of geomagnetic storms.**
>
> **On the other hand, figures are generally clear and informative. Some color scales (e.g. in ROTI maps) could be better annotated for readability. Also please consider highlighting the storm periods in figures for better visual context. Figure 6 could include a 23:00 UT map or authors could clarify its absence.**

Reply: Following referee's suggestion we have revised the Figures.

And Table 3 should be accompanied by a discussion of the physics behind the observed JH patterns and their relation to EIA dynamics.

Reply: Following discussion has been added as suggested by the referee: 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. 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 due to enormous Cowling conductivities and rapid changes in zonal winds. The combination of PPEF and PRE can significantly increase ambipolar diffusion and upward E × B 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 (Balan et al., 2018; Luan, 2021).

Please explain how PPEF vs. DD electric fields interact with EIA structures and influence RT instability and PRE (pre-reversal enhancement).

Reply: Following discussion has been added as suggested by the referee: 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 (Astafyeva et al., 2018). According to (Abdu, 1997; Abdu et al., 2009), 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 (Abdu, 1997).

Results:

The interpretation of EPB suppression during the April 2023 storm is compelling. It would be useful to compare this with similar events in previous solar cycles, if available and through this comparison, the selection of these specific storms could be justified. The discussion of hemispheric asymmetry is also interesting. Could the authors elaborate on possible seasonal or longitudinal effects that might contribute to this asymmetry?Please consider discussing the potential implications of these findings for GNSS signal degradation or navigation systems.

Reply: Following discussion has been added as suggested by the referee: The seasonal behavior of ionospheric plasma irregularities depends on magnetic declination (alignment of the Earth's magnetic field with the solar terminator) and trans-equatorial meridional winds (Seba and Nigussie, 2016; Tsunoda, 1985). Lloyd's season classification includes winter (January, February, November, December), summer (May to August), and equinox (March, April, September, and October) (Liu et al., 2010). During equinotical months, the sun's greater elevation and minimal transequatorial thermospheric winds can result in significant ionization and steeper plasma gradients, which can sustain plasma irregularities (Rastogi, 1980; Maruyama, 1988). Intense plasma irregularities can significantly disturb GNSS-based navigation and communication systems by causing amplitude and phase scintillations. These scintillations cause fast fluctuations in signal power and carrier phase, which reduces positioning precision and reliability. During

seasons conducive to the formation of plasma irregularities, notably around the equinoxes, GNSS receivers may encounter large range errors, cycle slipping, or even loss of lock, particularly for single-frequency users.As a result, understanding the seasonal and regional variability of irregularities is crucial for forecasting scintillation impacts and creating mitigation solutions, including the use of multi-frequency receivers, real-time monitoring, and augmentation systems (Aaron 1997, Basu et al., 1999).

References:

The references are appropriate and up to date. Consider adding a few recent studies on EPB dynamics during geomagnetic storms for broader context and also the following:

Tahir, A., Wu, F., Shah, M., et al. (2024) Multi-Instrument Observation of the Ionospheric Irregularities and Disturbances during the 23–24 March 2023 Geomagnetic Storm Remote Sensing, 16(9), 1594. https://doi.org/10.3390/rs16091594. This study uses GNSS, Swarm, Formosat-7/COSMIC-2, and Fabry-Perot data to analyse EPB dynamics and electric field variations during the March 2023 storm, offering a complementary perspective to the manuscript Zakharenkova, I., Astafyeva, E., et al. (2023) Development of the Storm-Induced Ionospheric Irregularities at Low and Mid-Latitudes Space Weather, 21(3), e2021SW002891. https://doi.org/10.1029/2021SW002891,

Focuses on the latitudinal expansion of irregularities during geomagnetic storms, relevant for comparing with the inter-hemispheric asymmetries discussed in the manuscript Imtiaz, N., Calabia, A., et al. (2025) Ionospheric Plasma Irregularities During Intense Geomagnetic Storms of Solar Cycle 25 EGUspherePreprinthttps://egusphere.copernicus.org/preprints/2025/egusphere-2025-86/.

The manuscript under review itself, for citation within future work or cross-referencing.

Reply: References have been added as suggested by the referee:

Language and style: The manuscript is generally well-written. A few minor grammatical issues and awkward phrasings should be corrected. For example,

- on page 2: "Storm-related variations in thermosphere/ionosphere parameters can dramatically" → "Storm-related variations in thermosphere/ionosphere coupling/conditions can dramatically"

Reply: The rephrasing is incorporated according to the Referee's suggestion.

on page 2: "The EPF, the EIA, and the density gradients in the EIA should all be affected" → "The EPF, the EIA, and the density gradients in the EIA are affected"

Reply: The rephrasing is incorporated according to the Referee's suggestion.

on page 2: "Disturbed Dynamo (DD)" → "Disturbance Dynamo (DD)".

Reply: The rephrasing is incorporated according to the Referee's suggestion.

on page 3: "Huang et al. (2013) studied that the single onset in the TEC" → "Huang et al. (2013) showed that the single onset in the TEC"

Reply: The rephrasing is incorporated according to the Referee's suggestion.

- on page 5: "This article is organized as follows:" → "This paper is organized as follows:" - on page 7: "In order to achieve this, we investigate four geomagnetic storms" → "In order to gain these insights, we investigate four geomagnetic storms". Citation: https://doi.org/10.5194/egusphere-2025-86-RC3

Reply: The rephrasing is incorporated according to the Referee's suggestion.