General comments:The topic is relevant and timely. However, the manuscript requires substantial improvements in clarity, organization, methodological description, and scientific justification. Several statements lack quantitative support, key definitions are missing, and the linkage between results and conclusions needs to be strengthened.

Specific Comments

Abstract

1. Statements such as "strong JH" and ranking of storms by JH strength (Lines 9–12) are qualitative. Please provide quantitative estimates of JH and define thresholds used to classify JH as strong or weak.

Response: We thank the referee for this suggestion. In this study, the following J_H thresholds are used for the classification of storms: weak (20-30 mW/m^2, November), moderate (30-50 mV/m^2, March/April) and strong (> 50 mW/m^2, May).

2. The conclusion in Line 13 regarding thermospheric winds and electric fields appears premature, as supporting results (e.g., JH, EIA evolution, and ionospheric irregularities) are not sufficiently presented in the abstract.

Response: Following modification has been done in the revised version: These results suggest that, during geomagnetic storms, the combined effects of storm-driven electrodynamics and neutral winds modulate low-latitude ionospheric variability, influencing EIA dynamics and the formation of plasma irregularities.

3. The abstract lacks key findings related to EIA morphology and ionospheric irregularities (e.g., ROTI behavior), as well as how JH influences these processes. These should be clearly summarized.

Response: The revised version of abstract: This study examines the low-latitude ionospheric response to four intense geomagnetic storms during Solar Cycle 25 (March, April, November 2023, and May 2024), focusing on Equatorial Ionization Anomaly (EIA) variations and post-sunset plasma irregularities. We used the Weimer (2005) model for Joule Heating (J_H), Madrigal total electron content (TEC) maps, and GNSS-derived ROTI to analyze storm-time changes in EIA structure and equatorial plasma

bubbles (EPBs). The May 2024 storm exhibited the strongest post-sunset JH, particularly near the June solstice, while March and April storms showed moderate J_H and November the lowest. Equinox storms produced nearly symmetric J_H patterns, while solstice storms revealed interhemispheric asymmetries. The following J_H thresholds are used for the classification of storms: weak (20-30 mW/m^2, November), moderate (30-50 mW/m^2, March/April) and strong (> 50 mW/m^2, May). J_H, together with storm-time electric fields and equatorial meridional winds, influence the location, strength, hemispheric asymmetry, and the generation or suppression of plasma irregularities of the EIA crest. It has been found that the generation of ionospheric plasma irregularities and their geographical distribution strongly depend on EIA's density gradients and general structure. Well-developed double-crest EIAs with steep density gradients favor post-sunset irregularities, while single-crest or merged EIAs are less favorable. Fluctuations in the IMF B_z drive east-west prompt penetration electric fields that dynamically modulate the F-region, altering the plasma fountain effect, the EIA structure, and the distribution of irregularities after sunset. These results suggest that during geomagnetic storms, the combined effects of storm-driven electrodynamics and neutral winds modulate low-latitude ionospheric variability, influencing EIA dynamics and the formation of plasma irregularities.

Introduction

4. In Lines 29, the term "ionospheric parameters" is vague. Please specify which parameters are being referred to.

Response: In the revised version, following modification has been made: During magnetic storms, thermospheric and ionospheric parameters such as neutral wind, composition, and electric fields deviate from their normal patterns.

5. Define the IMF Bz component when first introduced.

Response: In the revised version, we have used 'Interplanetary Magnetic Field (IMF) B_z component'.

6. Lines 27–46 contain several general statements that require appropriate references. Some of these can be moved to the Discussion section. The introduction should focus more on the study's objectives rather than well-established concepts.

Response: In the revised version, we have modified the introduction section according to the respected referee's suggestions.

7. The statement in Line 31 regarding minor ionospheric effects at mid-latitudes requires supporting references.

Response: In the revised version, the statement regarding minor effects at mid-latitudes has been removed.

8. In Lines 43–44, references are needed for PPEF and dynamo-related electric fields. Also, clarify whether "disrupted dynamo" refers to the disturbance dynamo.

Response: In the revised version, following modification has been done: 'Storm-time electric fields can emerge from either a short-lived prompt penetration electric field (PPEF) or a disturbance dynamo electric field (DDEF).' References has been added.

9. Define IMF Bz clearly at its first occurrence (Line 44).

Response: In the revised version, we have defined 'Interplanetary Magnetic Field (IMF) B_z component' at its first occurrence.

10.Ensure proper formatting of chemical species (e.g., N2) using subscripts throughout the manuscript.

Response: In the revised version, we have used subscript notation for N2.
11.Lines 65–73 are repetitive and may be removed or condensed.

Response: In the revised version, repetition has been removed.
12.TEC should be defined at first use (Line 78).

Response: In the revised version, we have used the definition of TEC as total electron content at first place it is used.

13.The statement in Lines 81–83 describing the use of Madrigal TEC is misplaced and should be moved to the final paragraph of the Introduction.

Response: In the revised version, we have moved the lines related to madrigal TEC to the final paragraph of the Introduction section.
14.The term EPIs (Line 94) is not defined prior to use.

Response: In the revised version, we have replaced EPIs by equatorial plasma bubbles (EPBs) throughout the manuscript.
15.The statement in Lines 135–136 regarding PPEF observations is unclear. Please clarify whether actual observations or model outputs are used. Overall, the Introduction lacks coherence, contains redundant statements, misses key references, and does not clearly articulate the research gap.

Response: In the revised version, we have improved introduction section as suggested by the respected referees.

Datasets and Methodology

16. Justify the use of both 1-minute and hourly averaged solar wind parameters. Consider using a consistent temporal resolution.

Response: It depends upon the availability of the data. For instance, we have used the high resolution or 1-minute data-sets including: IMF B_z, the solar wind speed (V_{sw}), the eastward zonal component E_y of the interplanetary electric field (IEF), and the ring current proxy index SYM-H. Low resolution (1-hour averaged) data-sets include: Sunspot number (R), the geomagnetic activity index (Kp), and the solar radio flux at 10.7 cm (F10.7).
17.Provide the source/link for CCMC data.

Response: In the revised version, we added link to the model: CCMC-hosted Weimer-2005 model available at (https://ccmc.gsfc.nasa.gov/models/Weimer~2005/).

18.Although ROTI derived from ground-based GNSS is presented (Figures 6–10), the data sources, station details, and processing methods are not described in this section.

Response: In the revised version, we have added necessary details about ground-based GNSS.

19.The methodology for analyzing global TEC maps (from the CEDAR Madrigal database) is insufficient. Please clarify how EIA structures (single crest, double crest, merged crest) are identified and quantified.

Response: In the revised version, we have added the following information: The Madrigal TEC maps, commonly utilized in ionospheric studies, are developed from a comprehensive, global, and distributed geodetic receiver data (Rideout and Coster, 2006). The CEDAR Madrigal database provides worldwide TEC maps with 1° × 1° resolution that are updated every 5 minutes, available at (http://cedar.openmadrigal.org/). From Madrigal TEC maps, the EIA structures can be characterized by analyzing the latitudinal spread of plasma density around ±10°- 20° magnetic equator. These structures appear as double crests (two peaks with a central trough), single crests (one peak dominant, the other weak/missing), or merged crests (a broad, blended enhancement lacking distinct sides).

20.In Line 164, explain how geomagnetic coordinates were obtained (e.g., model used) and provide appropriate references.

Response: In the revised manuscript, we have added the following 'Geomagnetic coordinates are determined using model calculations provided by British Geological Survey–Geomagnetism available at https://geomag.bgs.ac.uk/data_service/models_compass/coord_calc.html.

21.In Table 1, simplify the "Instrument" column to "GNSS" and revise formatting in the "Sector" column for clarity.

Response: In the revised version, we have replaced instrument with GNSS.

22.In Table 2, revise “Sun spots (R)” to “Sunspot (R)”. Also, explain the criteria used to select quiet days (Dst, Kp, AE, etc.).

Response: In the revised version, “Sun spots (R)” has been replaced to “Sunspot (R)”. The quiet days of the months are selected on the basis of Kp index that is Kp≤3 categorized as quiet day.

23.The classification of weak and strong ionospheric irregularities based on ROTI (Lines 165–169) should be supported with references.

Suggestion: Clearly separate this section into Data Sources (Madrigal TEC, GNSS TEC, CCMC, PPEF model) and Method of Analysis.

Response: In the revised version, we have added references for the categorization of ROTI. Also, we have clearly introduced breaks in the Data sources and details as suggested by the referee.

Results

24.The time interval 18:00–00:00 UT does not necessarily correspond to “after sunset” across all longitudes. Please clarify this.

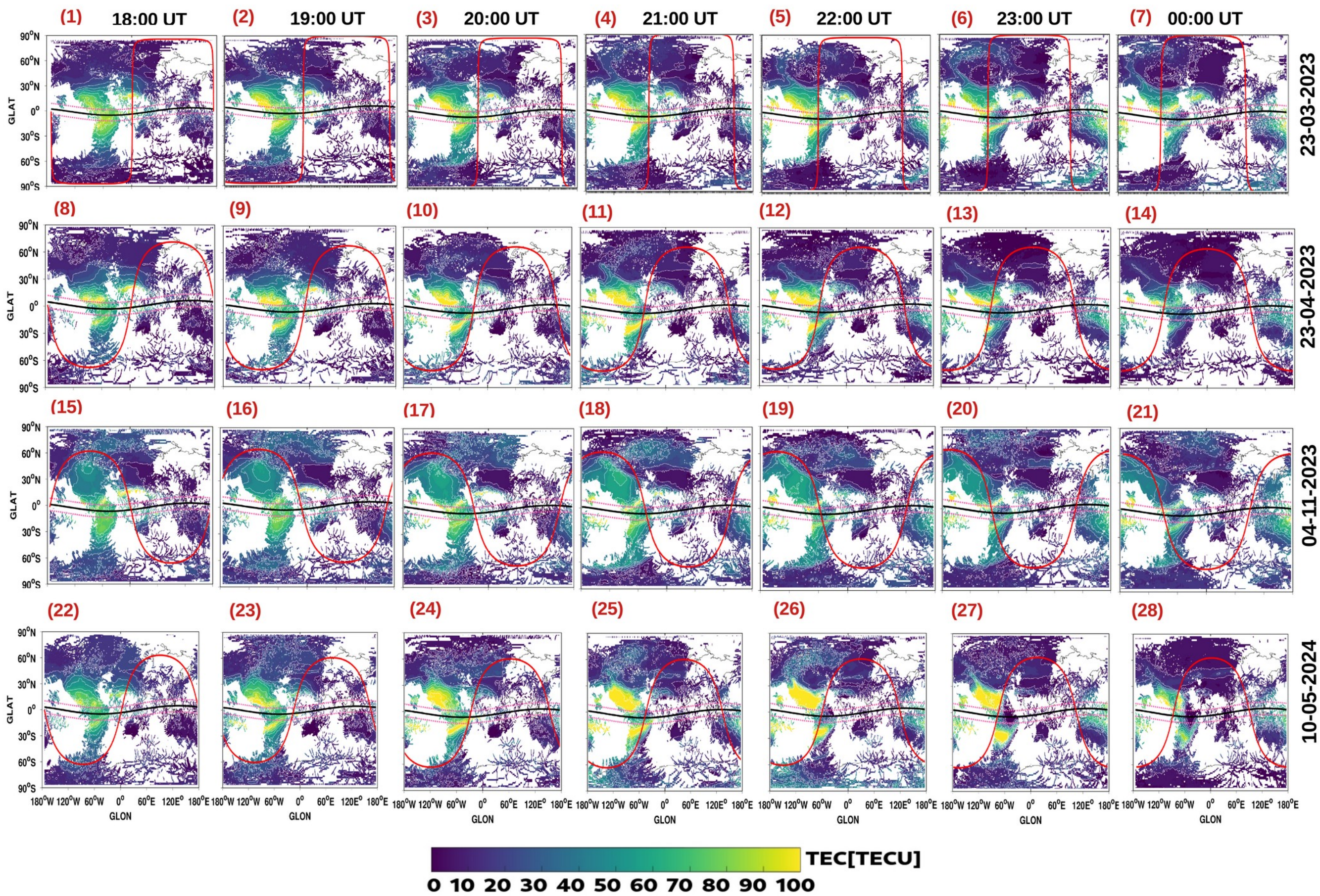
Response: We agreed with the referee’s point. In the revised version, we have removed unnecessary ‘after sunset’.

25.In Figure 6:

- **Clarify whether the solid lines represent the magnetic equator and provide references.**
- **Consider including ±15° magnetic latitude lines to better illustrate EIA structure.**
- **Adding a solar terminator would improve interpretation.**
- **Quantify statements such as “higher TEC values”.**

Instead of relying solely on global maps, consider including latitudinal TEC profiles (preferably in geomagnetic coordinates) to better illustrate EIA morphology and hemispheric asymmetry.

Response: We have revised the TEC maps and included the following: In each plot, the two pink dashed lines represent the northern and southern crests of the EIA, the black solid line represents the magnetic equator, and the red outlined region denotes a solar terminator to highlight the longitude sector associated with the post-sunset ionospheric response. Discussion on TEC has been added.



26.The claim that TEC enhancement is driven by JH (Line 69) is not sufficiently supported. Provide quantitative comparisons or correlations between TEC and JH.

Response: Following description has been added: 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 J_H 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 conductivity 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/N_2 ratio all contribute to the structuring of EIA crests (Balan et al., 2018; Luan, 2021).

27.In Line 281, clarify how the extension of TEC anomalies to mid-latitudes is determined.

Response: We have focused our discussion on low-latitudes. Therefore, we have omitted our discussion about mid-latitudes.

28.Figures 6–10 require clearer labeling. The red box annotations should be explained in the captions, and sectors should be indicated.

Response: Figures 7-10 have been revised for clear labeling. Following text has been added in the captions: The red rectangle highlight the main phase of the storm.

29.The discussion of plasma irregularities (Lines 315–318) would benefit from time series plots showing JH and ROTI together for each storm.

Response: We are thankful to the respected referee. It is now clearly mentioned in the revised manuscript that J_H does not affect ROTI directly, rather, its effects mediated through modification of trans-equatorial winds, which can alter EIA structures and provide favorable conditions for plasma irregularities through ROTI enhancements. Since we already have J_H maps at representative storm times, which can more effectively demonstrate the timing and spatial evolution of spatial distribution of enhanced high-latitude energy input than additional time-series panels that will make Figures over crowded because we already have multiple panels. However, we have revised Results and discussion section to better explain indirect connection between J_H, EIA structuring, and ROTI enhancements.

30.Figures 7–10 are not clearly labeled or described.

Response: Figures 7-10 have been revised.

Discussion

31.The manuscript lacks a dedicated Discussion section. The results are not interpreted in the context of underlying physical mechanisms or compared with previous studies. A comprehensive discussion is necessary.

Response: We have added more comprehensive discussion about our results. Please see the Results and discussion section of the revised manuscript.