

## Review Comments on Manuscript

**Title:** *Equatorial Ionospheric Plasma Bubbles During Intense Geomagnetic Storms of Solar Cycle 25*

The manuscript aims to investigate the behavior of the ionosphere during four intense geomagnetic storms (March 23–25, 2023; April 23–25, 2023; November 4–7, 2023; and May 10–13, 2024). The study emphasizes the role of asymmetric Joule Heating (JH) in modulating the Equatorial Ionization Anomaly (EIA) and its influence on the formation or suppression of post-sunset ionospheric plasma irregularities. The authors employ the Weimer (2005) model to simulate JH patterns and utilize Madrigal TEC data to examine variations in the intensity, spatial distribution, and symmetry of the EIA during these storm periods.

### 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.
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.
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.

#### Introduction

4. In Lines 29, the term “*ionospheric parameters*” is vague. Please specify which parameters are being referred to.
5. Define the IMF Bz component when first introduced.
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.
7. The statement in Line 31 regarding minor ionospheric effects at mid-latitudes requires supporting references.

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*.
9. Define IMF Bz clearly at its first occurrence (Line 44).
10. Ensure proper formatting of chemical species (e.g., N<sub>2</sub>) using subscripts throughout the manuscript.
11. Lines 65–73 are repetitive and may be removed or condensed.
12. TEC should be defined at first use (Line 78).
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.
14. The term *EPIs* (Line 94) is not defined prior to use.
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.

## Datasets and Methodology

16. Justify the use of both 1-minute and hourly averaged solar wind parameters. Consider using a consistent temporal resolution.
17. Provide the source/link for CCMC data.
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.
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.
20. In Line 164, explain how geomagnetic coordinates were obtained (e.g., model used) and provide appropriate references.
21. In Table 1, simplify the “Instrument” column to “GNSS” and revise formatting in the “Sector” column for clarity.
22. In Table 2, revise “*Sun spots (R)*” to “*Sunspot (R)*”. Also, explain the criteria used to select quiet days (Dst, Kp, AE, etc.).
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*.

## Results

24. The time interval 18:00–00:00 UT does not necessarily correspond to “after sunset” across all longitudes. Please clarify this.
25. In Figure 6:

- Clarify whether the solid lines represent the magnetic equator and provide references.
- Consider including  $\pm 15^\circ$  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.

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.

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

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

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

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

## **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.