Response to Reviewer Comment

We sincerely thank reviewer for the thorough and constructive review. The detailed feedback and technical suggestions have greatly improved the clarity, accuracy, and presentation of our manuscript. We have carefully addressed all eight points, including clarifying the averaging window size, refining methodological descriptions, correcting terminology, and enhancing figure readability. The reviewer's careful attention to detail has strengthened the rigor and transparency of our study. We believe these revisions significantly improve the manuscript's quality and reader comprehension. Below is our detailed point-by-point response and description of the changes made.

1. Line 173: There is still no information about the size of the averaging windows. This is an important information for the reader.

We have added the following sentence in Lines 173-174 :"Both smoothing steps use a window size of 45 data points."

2. Line 214: "A commonly used model for the collision frequency v at reflection height z is (Gołkowski et al., 2018)". It shows the collision frequency as a function of altitude, not at the reflection height.

We thank the reviewer for this important terminological correction. The reviewer is absolutely correct that the equation describes how collision frequency varies with altitude rather than specifying the collision frequency at a particular reflection height. "A commonly used model for the collision frequency ν as a function of altitude z is (Gołkowski et al., 2018) :" We have revised the text in Line 216.

3. Line 223-225: z and reflection height are mixed up in the text. "In this formulation, $Ne(z)$ represents the electron density (in cm^{-3}) at reflection height z, obtained from PyGPI5 simulations." Ne(z) only represents the vertical density profile. In general, this section remains quite confusing. Did I understand the following right?

Inserting equation (4) and (5) into equation (3) + using the Ne(z) from PyGPI5 simulations and the cutoff frequency from the ELF data (derived in section 2.3)

obtains equation (6), which can be solved for z. Where the computed z is then the reflection height for the cutoff frequency f1,- Please rephrase the description of method 2 for better legibility.

We sincerely thank the reviewer for identifying this confusion and providing a more clear interpretation of the methodology. The reviewer's understanding is absolutely correct, and we acknowledge that our original description was poorly organized and contained terminological inconsistencies.

"By substituting Eq.(4) and Eq.(5) into Eq.(3), we derive the condition that must be satisfied among the wave frequency, height, and electron density for electromagnetic wave reflection to occur in the D region." We have revised the text in Lines 221-222.

"In this formulation, $Ne(z)$ represents the vertical electron density profile (in cm^{-3}) obtained from PyGPI5 simulations. It describes how the electron density varies with altitude, rather than providing a single value at a specific height. To determine the reflection height corresponding to a specific wave frequency f_1, we substitute the observed cutoff frequency f_1 (derived from CSES EFD data as described in Section 2.3) into equation (6). We then perform a numerical iteration over different altitudes z until the calculated cutoff frequency from equation (6) matches the observed f_1. The altitude z that satisfies this condition is defined as the effective reflection height h' for the given frequency." We have revised the text in Lines 224-229.

4. In section 2.3, the cutoff frequency is determined by ELF measurements. It is also stated in section 2.3 that f1 = c/(2h). You could easily compute h from this. Why do you apply the other two methods?

Thank you for the valuable comment. Indeed, the formula $f_1 = c/2h'$ in Section 2.3 can directly calculate the reflection height from the cutoff frequency. Our study follows a stepwise scientific approach:

Section 2.3 mainly presents observational results, where reflection heights are derived from CSES ELF data using this formula, revealing a decrease in reflection height in regions affected by energetic particle precipitation. This is an observational phenomenon requiring further physical explanation.

Section 2.4 uses the PyGPI5 model to simulate electron density profiles and applies two different methods to calculate reflection heights to verify whether the observed decrease is caused by energetic electron precipitation (EEP):

1. Method one uses WS formula fitting, commonly applied in VLF inversion studies, providing results compatible with practical applications.
2. Method two is based on the Ratcliffe relation, offering an analytical perspective on the reflection mechanism from plasma physics.

These two methods complement each other. When consistent results are obtained, it strengthens the reliability of the analysis and confirms that the observed reflection height variation is indeed caused by EEP rather than other factors. This multi-method validation elevates a simple observational correlation to a physically verified mechanism.

5. Lines 226-228: “For ELF/VLF frequencies, these waves are not reflected at a single altitude, but more likely over a range of 5- 10 km around the reflection altitude. However, as pointed out by Marshall and Cully (2020), a reflection height that is lower than typical values was found to be more consistent with energetic electron precipitation.” These sentences are out of context. The information about the reflection height could have been raised earlier. And the information about the EPP could be placed in the discussion and why “However”?.

Thank you very much for your valuable comments. We have revised the manuscript accordingly to improve the clarity and logical flow:

We added the following sentence at Lines 155–157 to introduce the concept of ELF/VLF wave reflection over a range of altitudes earlier in the text: "It should be noted that ELF/VLF waves do not reflect at a single fixed altitude, but rather over a range of about 5–10 km around the reflection height, which is important for explaining differences between observations and simulations."

The discussion related to energetic electron precipitation (EPP) and its connection to a lower reflection height has been moved to Lines 310–312 within the discussion section for better contextual relevance, with the following addition: "As pointed out by Marshall and Cully (2020), a reflection height that is lower than typical values was found to be more consistent with energetic electron precipitation, which supports our observed correlations."

6. Line 278-281: It is ok if the Moran method is not explained in detail. However, a reference is then needed where the method is described in detail. The meaning of Moran's I in table 1 needs to be explained in the text. What information is provided by Moran's I (e.g., Positive/negative correlation-> cumulation, dispersion, information from the value of Moran score)?
We thank the reviewer for this important clarification regarding the Moran's I analysis. We agree that additional explanation and proper referencing are needed to help readers interpret Table 1 results.

We have included Moran (1950) as the reference in Line 281. We also have expanded the text following Lines 281-284 to explain that Moran's I quantifies spatial autocorrelation, where: " Moran's I is a spatial autocorrelation statistic that measures the degree to which similar values cluster together in space. The statistic ranges from -1 to +1, where positive values indicate positive spatial correlation, negative values suggest negative spatial correlation, and values near zero indicate random spatial distribution."

7. During the first revision, I did not notice that the color code in Figures 4e and f was reversed. For better readability and consistency, it would be very helpful to arrange the color bar as in Figures 4a-d.
We thank the reviewer for the careful attention to the color coding details and the valuable suggestion. We understand the importance of color consistency for figure interpretation.

The physical process illustrated in Figure 4 is as follows: an increase in electron flux leads to a rise in X-ray rate, which subsequently causes a decrease in reflection height. To accurately reflect this physical relationship, we intentionally reversed the color bars in Figures 4e and 4f compared to Figures 4a–d. In this way, "high reflection height" is represented by cool colors, while "low reflection height" is represented by warm colors. This ensures that regions with high electron flux and high X-ray rate (both shown with warm colors) visually correspond to regions with low reflection height (also shown with warm colors), helping readers intuitively grasp the relationship among these physical quantities. Therefore, although the color bar direction in panels e and f differs from that in panels a–d, this design choice maintains consistency in physical interpretation. We believe this arrangement enhances the overall clarity of Figure 4.
We appreciate the reviewer's detailed review and understanding.

8. Line 285: The meaning of the sentence is not clear. It also seems out of context. Are you

referring to table 1 or a figure? Isn't ITC more southwards (max. 20/30°N)? I assume 40-50°N is too high for the ITC.

Thank you very much for your careful reading and valuable comments. We agree that the original wording was inaccurate. We have revised the sentence to improve clarity and geographical correctness by changing "lies within" to "is near" regarding the Inter-Tropical Convergence Zone in Line 291: "the underlying reason is that this area is near the Inter-Tropical Convergence Zone."

References:

Gołkowski, M., Sarker, S. R., Renick, C., Moore, R. C., Cohen, M. B., Kułak, A., Młynarczyk, J., and Kubisz, J.: Ionospheric D Region Remote Sensing Using ELF Sferic Group Velocity, Geophysical Research Letters, 45, 12,739-712,748, https://doi.org/10.1029/2018GL080108, 2018.

Marshall, R. A. and Cully, C. M.: Chapter 7 - Atmospheric effects and signatures of high-energy electron precipitation, in: The Dynamic Loss of Earth's Radiation Belts, edited by: Jaynes, A. N., and Usanova, M. E., Elsevier, 199-255, https://doi.org/10.1016/B978-0-12-813371-2.00007-X, 2020.

Moran, P. A. P.: Notes on Continuous Stochastic Phenomena, Biometrika, 37, 17-23, 10.2307/2332142, 1950.