

Letter to Referee #1

We thank the referee for a thorough and thoughtful reading of our paper.

The referee has identified the noteworthy aspects of our results in a way that improves upon the original narrative, and we appreciate the many helpful comments.

The manuscript has undergone many changes. This includes the specific points raised by the referee:

- We agree that "phase fluctuations" is the more accurate term given the detrending method and the likely dominance of refraction. Following your suggestion, we have changed the terminology from "scintillation" to "phase fluctuations" throughout the revised manuscript. We have also taken the opportunity to add the valuable references you suggested (e.g., Conroy et al., 2022; Ghobadi et al., 2020; McCaffrey & Jayachandran, 2019) to properly contextualize this.
- We have revised the caption for Figure 5 to explicitly state that the Ionospheric Pierce Point (IPP) altitude was assumed to be 350 km, consistent with the F-region irregularities being studied.
- We now conservatively take 170 km as the E/F-region boundary, which follows the chemical transition from O₂⁺/NO⁺ to O⁺ dominance, as noted in the appendix.
- We have otherwise implemented all the remaining technical & clarity corrections you kindly listed.

In addition to these specific edits, we have also undertaken more substantial revisions, primarily to the Introduction and Conclusion sections. Based on the reviews it became clear that our original manuscript's narrow focus on particle precipitation, in isolation, needed nuance. Hence, we have completely re-written the Introduction to frame our study within the context of the full, multi-scale "energy cascade." The new introduction now explicitly discusses the role of unstable MHD wave energy, ULF waves, and Alfvénic turbulence as the primary drivers, placing our analysis of particle precipitation as one crucial kinetic component of this larger system.

We believe this new framing strengthens the paper. It does not change our core results but provides more accurate physical context, clarifying why the isolated kinetic processes we study are so important to the overall energy dissipation in geospace.

We are very thankful for your positive assessment and believe the manuscript is significantly stronger as a result of your precise feedback and the broader contextual revisions.

Sincerely,

Magnus F. Ivarsen

Letter to Referee #2

Rebuttal

We thank the referee for a thorough and thoughtful review. The referee has scrutinized our findings and identified the novel contributions, and clarified with greater emphasis than we did in our original manuscript which contributions are *not* novel. The referee has evaluated our discussions in a clear and systematic manner.

In so doing, the referee cites Parker, Laundal, and paints a picture of the ionosphere-magnetosphere system in terms of magnetohydrodynamics (MHD) and steady-state flowing plasma, and the referee encourages further familiarization. The referee states that our paper treats the magnetosphere-ionosphere (M-I) system as a ‘lumped element circuit model’, justifying a purely electrostatic description. We believe the argument that we rely on a ‘purely electrostatic description’ is a strawman, as we are merely describing kinetic processes in isolate, parts of the inhomogeneous distribution of free energy in the ionosphere-magnetosphere system.

As is recognized by all, the driven M-I system is never in a perfectly steady state. Rather, localized and intermittent excursions away from that steady state are in an evolving dynamic equilibrium characterized by various electrostatic and kinetic processes, at different altitudes, that are electrically connected to the greater MHD flow. This is the energy cascade necessitated by the excursions and whose effect is to restore equilibrium in the flowing plasma through linear and non-linear heating. Consequently, a “complete” model of ionospheric structuring would be a hybrid, multi-scale model that takes into account kinetic effects as well as the effects of non-linearities in the ionosphere’s highly anisotropic distribution of thermal noise.

When the referee states that electrostatic treatments are incompatible with causality they are confusing a system’s state with the sum of its parts. The steady-state MHD flow is always a description of the large-scale behaviour in the interconnected system, but individual processes that affect or are embedded in this flow are not necessarily adhering to the constraining equations of MHD in their primary description. The cumulative effects of these processes is behaviour that is otherwise not predicted by the individual processes themselves, wherein strict, overall MHD-adherence is assured by nature at all times.

The Referee writes that the “*magnetosphere-ionosphere interactions can be understood in terms of the magnetic field and the motion of plasma (the "B, v" paradigm)*”. We are thankful to the referee for clarifying the issue, pointing out the basic constraints placed on geospace. The quoted sentence holds that particle precipitation is indistinguishable from field-aligned currents, which must flow, and whose vorticity induces strong, perpendicular electric fields in the plasma. While the statement is demonstrably true, it ignores the action’s kinetic and statistical mechanical energy input, the wave-particle interactions that occur in Earth’s

radiation belts, as well as the local electrostatic effects of having polarization electric fields driving responsive and, in the E-region ionosphere, perpendicular currents of electrons and ions.

The resulting turbulent electrodynamics are known to be chaotic, with small-scale observations only rarely showing clear, coherent signatures of the macroscopic magnetohydrodynamic processes that ultimately drive their production. To compound the knowledge gap represented by these turbulent dynamics, anomalous heating is known to feed back into the greater geospace system, in ways that are under intense research.

The referee does however correctly state that unstable MHD wave energy *is* the source of the alluded-to kinetic processes in the plasma; the wave-modes that cause pitch angle scattering of the radiation belt's hot population of drifting electrons, for example, grow in tandem with the Kelvin-Helmholtz waves that drive a cascade of ULF waves in the unstable MHD plasma, itself likely highly correlated with the interchange instability and the growth of Alfvén turbulence, leading to the downward acceleration of electrons by parallel fields.

Here, we are very grateful to the referee, as our original manuscript was drastically simplifying the M-I connection through its narrow focus on particle precipitation.

On the same note, the referee criticized our simplified analysis of the particles using the 'Fang' equations' and here we concede the deficiency in largely ignoring the variation of specific chemistry, simplifying the collision frequencies, refraining from the detailed models of plasma production and loss that exists in the field. However, while such detailed models are merited when predicting the state of the ionosphere, our method of simplifying the chemistry does isolate a *specific and characteristic statistical behaviour in the core dataset*: the precipitating particle flux. A comprehensive modeling of the phenomenon is outside the scope of the present investigation. We have clarified the issue in the revised manuscript

Conclusion

While we disagree both with the sentiment and conclusion expressed by the referee, we concede that some of the criticism raised was valid and called-for, and the referee pointed out areas where our treatment of the subject could be strengthened considerably. As a result, we have made extensive revisions to the manuscript, including a complete re-writing of the Introduction.

We thank the referee for the constructive review of our paper, which has strengthened the presentation considerably. The referee's many helpful minor points have likewise been corrected in the revised manuscript.

Sincerely,
Magnus F Ivarsen

References:

Newell, P. T., Sotirelis, T., & Wing, S. (2009). Diffuse, monoenergetic, and broadband aurora: The global precipitation budget. *Journal of Geophysical Research: Space Physics*, 114(A9).

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