Title: Ionospheric signatures of Bursty Bulk Flows in the 6D Vlasiator simulations

Authors: Abiyot Bires Workayehu, +co-authors

Replies to Referee #2

We thank Referee #2 for comments and constructive suggestions on our manuscript. Below, we provide point-by-point responses to all comments. The referee's comments are presented in black, while our replies are shown in blue directly below each comment. We have carefully considered all suggestions and, where appropriate, will make corresponding revisions in the manuscript. We hope our answers and the corresponding suggested changes (where necessary) in the manuscript are satisfactory.

This paper presents numerical simulation results from the 6D hybrid-Vlasov code Vlasiator, coupled with an electrostatic ionospheric model, to investigate the ionospheric signatures of bursty bulk flows (BBFs). The study's core contribution lies in the detailed mapping of BBF-induced vortical flows to specific field-aligned current (FAC) systems and their associated ionospheric responses. These include enhancements in FACs, ionospheric conductances, and precipitating particle energies. The manuscript is well-written, and the results are clearly presented. The manuscript is clearly worth publishing, but before I could recommend publication, the authors could address a few minor comments, which are listed below.

1. Comment (1): The simulation uses steady and extreme solar wind conditions (Vsw = 750 km/s, Bz = -5 nT). How representative are these results of more typical solar wind conditions? Please justify this choice and, importantly, discuss how the results might change under more typical or variable solar wind conditions. For example, would a weaker IMF or lower solar wind velocity still produce such distinct ionospheric signatures?

   We thank the reviewer for this comment. Yes, the solar wind driving conditions used in the Vlasiator simulation correspond to a fast solar wind stream (Vsw = 750 km/s) with moderately active conditions (Bz = −5 nT). The fast solar wind was chosen to speed up the initialisation phase of the simulation run. Importantly, this kind of simulation would be significantly more expensive computationally, and the present Vlasiator runs with these solar wind driving conditions are the best that can be performed with the current supercomputers.

   To clarify our choice, we propose adding the following text in Section 2.1: "The fast solar wind was chosen to speed up the initialisation phase of the simulation run (Palmroth et al., 2023), while Bz = −5 nT represents conditions favourable for magnetic reconnection without being strongly disturbed."

   A stronger southward IMF and higher solar wind speed increase the coupling between the solar wind and Earth's magnetosphere, leading to more frequent substorms and BBFs in the magnetotail (Zhang et al., 2016), and the same processes are expected during weaker conditions but with lower amplitude and lower occurrence rates (Zhang et al., 2016). Regarding ionospheric signatures, generally, stronger solar wind driving conditions result in more significant ionospheric effects and more pronounced signatures. A weaker solar wind driving may still produce less intense signatures, but not necessarily less distinct ones.

2. Comment (2): The BBF criterion (Vx $\geq$ 400 km/s) is standard, but duration criteria are not discussed. How long does this BBF persist?

   We thank the reviewer for this comment. The BBF persists for about 350 s, after which it interacts with other BBFs and evolves into a more complex plasma flow structure.

   We propose adding the following text in Section 3.1 of the manuscript: "The BBF persists for about 350 s, after which it interacts with other BBFs and evolves into a more complex plasma flow structure. This is consistent with observational studies, which typically report BBF durations ranging from a few minutes to 10 minutes (Baumjohann et al., 1990; Angelopoulos et al., 1992)."

3. Comment (3): The study focuses on a single BBF event within the simulation. Is it a typical or ideal BBF produced by the Vlasiator model? Have the authors observed similar signatures for other BBFs in their simulations?

   The BBF analysed here is a typical BBF produced by the Vlasiator simulation. Yes, BBFs with more complex structures and comparable ionospheric signatures are also observed in the later stages of the simulation.

4. Comment (4): The duskside preference of BBFs is noted. How does this asymmetry influence the ionospheric signatures compared to dawnside BBFs?

   This paper discusses signatures of a duskside BBF, and we have not observed an isolated dawnside BBF in the simulation to make a one-to-one comparison of ionospheric signatures. Therefore, it is difficult to draw conclusions about the signature of a dawnside BBF compared to the duskside. However, as shown in the present paper, the dusk preference of BBFs causes ionospheric signatures to cluster in the pre-midnight MLT sector, where we have observed enhanced FAC, conductance, and flow channel, while the post-midnight ionosphere displays weaker and spatially and temporally smooth distributions of these variables.

5. Comment (5): The simulation assumes a 0° dipole tilt, which is a simplification. Could including a more realistic dipole tilt affect ionospheric coupling?

   Yes, including realistic dipole tilt angles can affect ionospheric coupling. Assuming a 0° tilt simplifies the geometry but neglects hemispheric and seasonal asymmetries that influence how the magnetosphere couples to the ionosphere. While using a 0° tilt angle roughly represents average equinoctial conditions, incorporating a realistic tilt changes the geometry of magnetopause reconnection, alters the mapping of field-aligned currents and convection into the ionosphere, and modifies ionospheric conductance through seasonal and diurnal variations in solar illumination.

6. Comment (6): The thin-shell approximation at 100 km altitude is justified, but how might altitude-dependent effects influence the results?

   We thank the reviewer for this comment. The thin-shell approximation effectively captures large-scale ionospheric current systems and electric fields through height-integrated Pedersen and Hall conductances. However, we do not know the influence that altitude-dependent ionospheric profiles may have on the results. High-resolution volumetric measurements of ionospheric parameters, such as those anticipated from the upcoming EISCAT3D (McCrea et al., 2015), will help to resolve this.

7. Comment (7): A recent study by Kumar et al. (2025) (https://doi.org/10.1029/2024JA032953), using THEMIS and MMS observations, reported a dawn-dusk asymmetry in flows and a significant deceleration of these flows earthward of X <-15 RE. Please comment on whether the Vlasiator simulation reproduces a comparable braking effect in the near-Earth region.

   The duskside preference and near-Earth deceleration of fast plasma flows observed in our study agree with Kumar et al. (2025), who observed significant flow braking earthward of X < -15 RE and more frequent occurrence in the premidnight region than postmidnight. However, the detailed braking effect reported by Kumar et al. is not explicitly addressed in this paper. Further study, directly comparing Vlasiator results with observations in this region, would be needed to assess whether the braking effect reported by Kumar et al. (2025) is reproduced.

8. Comment (8): On page 2, line 45, "breaking region" should likely be "braking region". Please check for this consistency throughout the manuscript. Yes, the reviewer is correct. The term will be corrected to "braking region", and the manuscript will be carefully checked for consistency throughout.

9. Comment (9): Line 199-200: At t = 450 s, a BBF is active, yet the paper says there are "no significant ionospheric signatures." What is the expected delay between BBF arrival and ionospheric response in this setup?

   Yes, at $t = 450$ s, a BBF is indeed present; however, it is too weak to generate significant vorticity, which in turn limits the strength of FACs and their manifestation as an ionospheric signature. The expected delay between the BBF and the ionospheric response at this simulation time is approximately 18s. This estimate is based on the Alfvén speed along the field line connecting the BBF location to the coupling radius at 5.6 R_E, with an additional 2 s delay from the coupling radius to the ionosphere (Ganse et al., 2025) to obtain the total delay time.

   We propose adding the following clarification to the manuscript: "At $t = 450$ s, a BBF is indeed present; however, it is too weak to generate significant vorticity, which in turn limits the strength of FACs and their manifestation as an ionospheric signature."

10. Comment (10): The use of Bz = 0 as a proxy for reconnection lines is an oversimplification, as it does not inherently confirm the presence of active reconnection. Could the authors elaborate on how additional reconnection indicators—such as flow reversals, Hall magnetic field signatures, or localised energy conversion— align with the Bz = 0 regions in their simulation?

    We thank the reviewer for highlighting the limitations of using $B_z = 0$ as a proxy for reconnection lines. We fully agree that $B_z = 0$ alone does not confirm active reconnection.

In our study, $B_z = 0$ was used in Section 3.1 as a simplified indicator of potential X-line locations. To identify actual reconnection sites, we additionally applied the method by Alho et al. (2024), which distinguishes both X- and O-lines. This approach has been used in previous publications and provides a more robust and reliable identification of reconnection points in Vlasiator simulations. As shown in Figure 3 and Supplementary Movie S1, the X-lines obtained using this method reasonably align with the flow reversal at points where active reconnections occur.

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