

Referee1 :

Review of “Magnetospheric convection in a hybrid-Vlasov simulation” by Shi et al.

This paper presents a detailed and compelling study of magnetospheric convection using a global hybrid-Vlasov simulation. Magnetospheric convection (mainly dominated by ions) is a fundamental process in understanding large-scale magnetospheric dynamics, and this work makes a significant contribution from the global-scale ion-kinetic approach. The authors validate their method for calculating reconnection rates, and then proceed to characterize the overall convection pattern and its connection to both dayside and nightside reconnection processes. The results are solid and novel, demonstrating the capability of ion-kinetic Vlasov simulations to capture key aspects of global magnetospheric evolution. I recommend this manuscript for publication and look forward to future studies on this subject from hybrid-Vlasov simulations.

Specific comments:

1. Line 21: The phrase “between two neutral points” . I think this means between the dayside neutral lines (X-line) and nightside neutral lines (X-line). Most field lines are not reconnected at the sub-solar point.
2. Lines 33–34: The statement “The whole convection process typically lasts on a timescale of approximately one hour”. A full convection cycle usually spans 2–5 hours. The 1-hour timescale is more representative of the magnetotail’s response time (Kennel, 1996).

Reference:

Kennel, C. F. Convection and Substorms – Paradigms of Magnetospheric Phenomenology, Vol. 2, Oxford University Press, 1996.

3. Lines 54–56: Suggested revision: “Dai et al (2024) presents compelling evidence of dayside-driven convection in Keogram in MHD simulations, along with ionospheric observations. This type of convection is shown to establish within 10–20 minutes across the magnetosphere. Furthermore, they argued that this type of convection is related to the equatorward and dayside-to-nightside extending of field-aligned currents (FACs), emphasizing its relation to ionospheric dynamics (Zhu et al.,2024).”

References:

Zhu, M. et al. (2024). Journal of Geophysical Research: Space Physics, 129, e2024JA032607.
<https://doi.org/10.1029/2024JA032607>

4. Line 98: If the analysis is restricted to the closed field line region, the green segment in the schematic should be drawn closer to Earth to reflect this specification.

5. Lines 112–113: The sentence could be clarified. Suggested revision:

“The radial (r) component of the electric field corresponds to clockwise convection, while the theta component of the electric field corresponds to outward convection.”

6. Equation (1) and Line 115: It would be helpful to expand on why this method of estimating the reconnection rate was chosen over direct calculation along the X-line. As mentioned in Line 65, accurately determining the reconnection electric field near the diffusion region can be challenging in global simulations, which may justify the chosen approach.

7. Lines 133–134: Specify the relevant time interval more clearly. The increase in closed magnetic flux is most evident between 800 and 1200 seconds, consistent with Figure 4, which shows that nightside reconnection dominates during this interval.

8. Lines 151–152: Convection generally converges near $MLT = 0$ and diverges around $MLT = 12$. Therefore, the average convection at these location should be close to zero. In simulations, the location of the converge point and diverge point may deviate a little. This causes the fluctuation of azimuthal convection in the simulations.
9. Lines 158–160: Given the ion-kinetic nature of the simulation, it would be worthwhile for future studies to examine the Hall electric fields or ion kinetic signatures, such as off-diagonal components of the ion pressure tensor, in the magnetotail reconnection region.
10. Line 202: Consider revising “convection events” to “convection channels.” Figure 6 suggests that convection near midnight is directly triggered by nightside reconnection.
11. Lines 205–206: The sentence about minimal sunward convection is unclear. Which figure supports this? And minimal with respect to what? If the statement cannot be clarified, it may be better to remove it.
12. Line 245–246: You might reference this observational work showing that dayside reconnection is directly influenced by IMF fluctuations, as in Dai et al. (2023):

Reference:

Dai, L. et al. (2023). Geoeffectiveness of Interplanetary Alfvén waves: I. Magnetopause Magnetic Reconnection and Directly-Driven Substorms. *The Astrophysical Journal*, 945(1), 47.
<https://doi.org/10.3847/1538-4357/acb267>

13. Lines 255–256: The findings in Figure 6 are novel and merit stronger emphasis in the abstract. Suggested addition:

“Our analysis identifies discrete azimuthal convection channels of closed field lines, clearly initiated by dayside reconnection and propagating to the nightside. These channels are even prominent during intervals of intense nightside reconnection.”

14. Line 263–265, Line 10–11. The discussion in the Line 265 are more specific and could be included for abstract. “plasma flows near reconnection sites and at the terminators deviates from isentropic behavior, suggesting the presence of non-adiabatic processes in these regions.”

15. Line 275: The 20-second cycle lacks direct support from the presented data. While potentially interesting for future research, it appears speculative in the current study.

Reply to ref1:

We sincerely appreciate the reviewer for the constructive comments and suggestions, which will help us to improve the quality and clarity of this paper. Below, we provide point-by-point response to these comments.

1-5, 12: We will revise the text/figure accordingly and add the reference based on the suggestions.

6. Equation (1) and Line 115: It would be helpful to expand on why this method of estimating the reconnection rate was chosen over direct calculation along the X-line. As mentioned in Line 65, accurately determining the reconnection electric field near the diffusion region can be challenging in global simulations, which may justify the chosen approach.

6: We will add the following sentence in the discussion: “We chose this method to estimate the reconnection rate instead of directly calculating it along the X-lines, as the latter approach is particularly challenging. It requires determining the reconnection electric field near the diffusion region, which is difficult to achieve in global simulations due to the presence of multiple X-lines contributing to opening

and closing of field lines (Alho et al., 2024). This selected method circumvents the need to identify and attribute to specific X-lines.”

Reference:

Alho, M., et al. (2024). Finding reconnection lines and flux rope axes via local coordinates in global ion-kinetic magnetospheric simulations. *Annales Geophysicae*, 42(1).

7. Lines 133–134: Specify the relevant time interval more clearly. The increase in closed magnetic flux is most evident between 800 and 1200 seconds, consistent with Figure 4, which shows that nightside reconnection dominates during this interval.

We will add the following sentences in the text: “This increase is most evident between 800s and 1200s, particularly in the night sectors, due to the large nightside reconnection voltage shown in Figure 4.”

8. Lines 151–152: Convection generally converges near $MLT = 0$ and diverges around $MLT = 12$. Therefore, the average convection at these location should be close to zero. In simulations, the location of the converge point and diverge point may deviate a little. This causes the fluctuation of azimuthal convection in the simulations.

We will add the following sentence in the text: “On average, convection converges near $MLT = 0$ and diverges near $MLT = 12$, resulting in net convection rates close to zero. As can be seen in Figure 6 panel (a), the location of the convergence and divergence time can vary during the simulation, which leads to the fluctuations of azimuthal convection rate.”

9. Lines 158–160: Given the ion-kinetic nature of the simulation, it would be worthwhile for future studies to examine the Hall electric fields or ion kinetic signatures, such as off-diagonal components of the ion pressure tensor, in the magnetotail reconnection region.

We will add the following sentence in the discussion: “ Given the ion-kinetic nature of the simulation, researchers have been focusing on exploring ion-kinetic signatures (Palmroth et al., 2023; Cozzani et al., 2025; Zaitsev et al., 2025). Building on these works, we plan to further investigate features such as Hall electric field and off-diagonal components of the ion pressure tensor in the magnetotail reconnection region.”

Reference:

Palmroth, M. et al. (2023). Magnetotail plasma eruptions driven by magnetic reconnection and kinetic instabilities. *Nature Geoscience*, 16(7), 570–576.

Cozzani, G. et al. (2025). Interplay of magnetic reconnection and current sheet kink instability in the Earth's magnetotail. *Geophysical Research Letters*, 52(2).

Zaitsev, I. et al. (2025). Ion-mediated tearing and kink instabilities in the Earth's magnetosphere: Hybrid-Vlasov simulations. *Journal of Geophysical Research: Space Physics*, 130(1).

10. Line 202: Consider revising “convection events” to “convection channels.” Figure 6 suggests that convection near midnight is directly triggered by nightside reconnection.

We agree with the reviewer since it can be seen in Figure 6 that the dense contours near $MLT = 3$ and $MLT = 21$ suggest that convection near the nightside could be triggered by nightside reconnection. We will add the following clarification in the paragraph: “Nevertheless, nightside reconnection can directly induce convection near the midnight sectors, as shown by the dense convection contours near $MLT=3$ and $MLT = 21$ in panel (b).”

11. Lines 205–206: The sentence about minimal sunward convection is unclear. Which figure supports this? And minimal with respect to what? If the statement cannot be clarified, it may be better to remove it.

We agree that the minimal sunward convection can't be seen in the figures, so we will remove this sentence.

13. Lines 255–256: The findings in Figure 6 are novel and merit stronger emphasis in the abstract. Suggested addition:

“Our analysis identifies discrete azimuthal convection channels of closed field lines, clearly initiated by dayside reconnection and propagating to the nightside. These channels are even prominent during intervals of intense nightside reconnection.”

We will revise the relevant sentence in abstract from: “Our analysis identifies azimuthal convection channels on the dawn and dusk flanks during the simulation run, modulated by dayside reconnection events.” to “Our analysis identifies discrete azimuthal convection channels of closed field lines, clearly initiated by dayside reconnection and propagating to the nightside. These channels are even prominent during intervals of intense nightside reconnection.”

14. Line 263-265, Line 10-11. The discussion in the Line 265 are more specific and could be included for abstract. “plasma flows near reconnection sites and at the terminators deviates from isentropic behavior, suggesting the presence of non-adiabatic processes in these regions.”

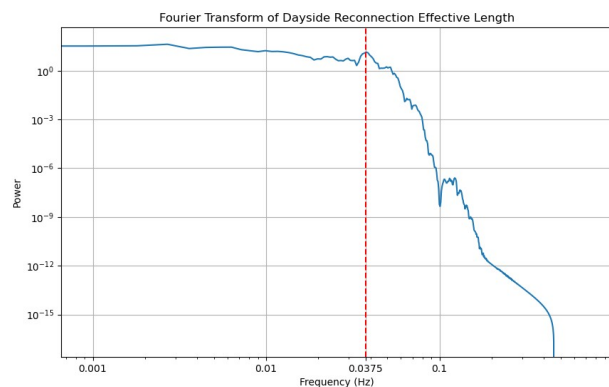
We will change the sentence in abstract from: “Instead, we demonstrate that plasma flows near reconnection sites and at the terminators exhibit more intricate patterns, deviating from earlier results.”, to “Instead, we demonstrate that plasma flows near reconnection sites and at the terminators deviates from isentropic behavior, suggesting the presence of non-adiabatic processes in these regions.”

15. Line 275: The 20-second cycle lacks direct support from the presented data. While potentially interesting for future research, it appears speculative in the current study.

We perform a Fourier transform on the dayside reconnection effective length time series, as shown in the supplement figure. The power spectral density displays a small peak at about 26.7 s, suggesting fluctuations in the dayside reconnection effective length at this period. The peak is however not very prominent, and future work is required to ascertain this periodicity. We will include this figure as an additional panel in Figure 5 in the revised manuscript. This similar periodicity can also be seen in a 2D vlsiator simulation (Hoilijoki et al., 2019, Figure 5), which we will also add as reference.

Reference:

Hoilijoki, S. et al. (2019). Properties of magnetic reconnection and FTEs on the dayside magnetopause with and without positive IMF Bx component during southward IMF. *Journal of Geophysical Research: Space Physics*, 124(6), 4037–4048.



Referee 2:

The paper consists of two pieces. The first calculates the reconnection rates as a function of MLT and UT using Faraday's Law. I have some questions about the methodology, related to the calculation of the line integral in Faraday's law. The second part discusses entropy in the context of ideal MHD, which did not seem relevant to the work. Overall the paper could be acceptable for publication, but I do have some questions that should be resolved.

Regarding the first (and primary) part of the work, the calculation of reconnection rate relies on the integral form of Faraday's Law. I found Figure 2 somewhat confusing in relation to how the segments are determined. Do points B and C end at the OCB, as a function of time? That's my assumption, that $E_r dr$ is only calculated up to the OCB in the equatorial plane, but I don't believe that was made explicit. Second, it is unclear how the AD (inner boundary) segment is dealt with. Is it set to zero and/or is it zero because it is at the inner boundary of the simulation? More explicit detail on both of these would be helpful.

Since the authors have identified the OCB in the equatorial plane, one could in principle calculate the reconnection rates directly. There must be some reason that was not done here, and some discussion of this should be included.

I am also curious why the authors did not calculate the reconnection rate directly from the ionosphere, using the knowledge of the ionospheric velocity and OCB boundary velocity as in e.g., Gasparini et al. 2024, Blanchard et al., 1996, 1997, 2001; de La Beaujardiere et al., 1991; Hubert et al., 2006; Lam et al., 2006; K. Laundal et al., 2010; Østgaard et al., 2005. Could the authors comment on why that approach was not explored?

I also suggest the term "reconnection voltage" for the data in Figure 5 (and throughout the manuscript), which are in units of kV, and reserve the term "reconnection rate" for the electric field. This is convention as discussed in the introduction of Gasparini et al. 2024.

The discussion on entropy and ideal MHD, which is under the section "azimuthal convection" seems unrelated to the reconnection work. Beyond relevance, the paper points out entropy is not conserved in certain regions of the magnetosphere, in contrast to the assumptions of ideal MHD. This is well known, and it's not clear what new insight is provided.

The phrase "Dungey cycle convection rate" is not, to my knowledge, an established terminology. Is it meant simply to describe the difference in the absolute values between the dayside and nightside reconnection rates?

Reply to ref2:

We thank the referee for taking the time to review our manuscript and for providing valuable comments. We acknowledge the referee's concerns on reconnection rate calculation and flux tube entropy in MHD framework. Here we will address these concerns in detail.

Regarding the first (and primary) part of the work, the calculation of reconnection rate relies on the integral form of Faraday's Law. I found Figure 2 somewhat confusing in relation to how the segments are determined. Do points B and C end at the OCB, as a function of time? That's my assumption, that $E_r \cdot dr$ is only calculated up to the OCB in the equatorial plane, but I don't believe that was made explicit. Second, it is unclear how the AD (inner boundary) segment is dealt with. Is it set to zero and/or is it zero because it is at the inner boundary of the simulation? More explicit detail on both of these would be helpful.

The convection rates are calculated through each boundary segment. Point B and C both end at OCB indeed. The equatorial OCB has a nontrivial geometry, which makes it more practical to assign the convection rate based on the closed flux change rate. $E_r \cdot dr$ is computed along the segments AB and CD, representing the convection rate across those boundaries. As shown by Equation 4, the reconnection voltage, which is the rate of magnetic flux transferred through segment BC, can be derived from the rate of change of the closed flux within an enclosed area(ABCD), eliminated by the closed flux entering or leaving through the other segments AB, AD and CD.

Segment AD represents the inner boundary of the magnetosphere. Ideally, this boundary should prevent any flux exchange. However, our analysis revealed a persistent, nonzero convection rate across it throughout most of the simulation. This observation suggests that the implementation of the inner boundary may contain imperfections.

We will modify the description of our methodology in the revised manuscript to clarify those points.

Since the authors have identified the OCB in the equatorial plane, one could in principle calculate the reconnection rates directly. There must be some reason that was not done here, and some discussion of this should be included.

I am also curious why the authors did not calculate the reconnection rate directly from the ionosphere, using the knowledge of the ionospheric velocity and OCB boundary velocity as in e.g., Gasparini et al. 2024, Blanchard et al., 1996, 1997, 2001; de La Beaujardiere et al., 1991; Hubert et al., 2006; Lam et al., 2006; K. Laundal et al., 2010; Østgaard et al., 2005. Could the authors comment on why that approach was not explored?

We did not calculate the reconnection voltage directly from the ionosphere for the following reasons. First, we would like to note that the major focus of this paper is on the convection rate, and not the reconnection voltage. When we compute the reconnection voltage in the different MLT sectors, as we did in our analysis, this also yields the azimuthal convection rate as a by-product, which is crucial for our study. In contrast, the method suggested by the reviewer only provides the reconnection voltage. Therefore, our selected method is more appropriate for the purpose of our study. Secondly, while it may allow validation of the obtained reconnection voltage via an independent method, determining the velocity of the OCB is difficult in the simulation because of the limited refinement level and highly dynamic nature near the reconnection sites. According to (Blanchard et al., 1997 and Gasparini et al., 2024), typical OCB velocities are on the order of a few hundred meters per second. However, the finest spatial resolution of the ionosphere is 62km in our simulation (Ganse et al., 2025), which makes the velocity of OCB unresolvable. Thirdly, one of the objectives of this work is to assess the coupling between the inner boundary and the ionosphere in the simulation, and relying on ionospheric parameters would compromise this goal. We will add a short discussion on this alternative method in the Discussion section.

Reference:

Blanchard, G. T., et al. (1997). Magnetotail reconnection rate during magnetospheric substorms. *Journal of Geophysical Research: Space Physics*, 102(A11), 24303–24312.
Gasparini, S., et al. (2024). A quantitative analysis of the uncertainties on reconnection electric field

estimates using ionospheric measurements. *Journal of Geophysical Research: Space Physics*, 129(6), e2024JA032599.

Ganse, U., et al. (2025). The Vlasiator 5.2 ionosphere—Coupling a magnetospheric hybrid-Vlasov simulation with a height-integrated ionosphere model. *Geoscientific Model Development*, 18(2), 511–527.

I also suggest the term “reconnection voltage” for the data in Figure 5 (and throughout the manuscript), which are in units of kV, and reserve the term “reconnection rate” for the electric field. This is convention as discussed in the introduction of Gasparini et al. 2024.

We will change “reconnection rate” to “reconnection voltage” where applicable in the paper.

The discussion on entropy and ideal MHD, which is under the section “azimuthal convection” seems unrelated to the reconnection work. Beyond relevance, the paper points out entropy is not conserved in certain regions of the magnetosphere, in contrast to the assumptions of ideal MHD. This is well known, and it’s not clear what new insight is provided.

The main objective of the paper is to quantify and analyze the magnetospheric convection using a hybrid-Vlasov simulation. This is also the motivation behind our calculation of the reconnection rate—to assess whether the strong azimuthal convection channels, such as those shown in Figure 6, are primarily driven by dayside or nightside reconnection.

Regarding the discussion on entropy, we agree that the breakdown of ideal MHD near reconnection sites is not unexpected. However, we include this discussion to emphasize a more surprising result: the deviation from entropy conservation near the terminator region, which is not typically associated with reconnection activity. We believe that this unexpected feature warrants attention and may motivate future studies to explore its origins and implications. We will better emphasize this novel aspect in the revised manuscript, to provide clearer motivation for the inclusion of the discussion on entropy.

The phrase “Dungey cycle convection rate” is not, to my knowledge, an established terminology. Is it meant simply to describe the difference in the absolute values between the dayside and nightside reconnection rates?

We use the “Dungey cycle convection rate” to refer to the left hand side of equation 1. We will revise the text to clarify this terminology.