General comments and changes to the manuscript:

- Both of the reviewers requested a figure showing radial profiles of the flux tube entropy and magnetic field z-components. This has been added to the manuscript, and is now Figure 5.
- During the review process, we decided to replace the figure showing interchange motion of field lines with a similar figure that we feel better shows the intended field line motion. Before the addition of the new figure with the radial profiles, this was Fig. 5, in the revised manuscript it is Fig. 6. The interpretation of the new interchange figure is the same as the original figure was. The text referring to the figure has been changed to reflect the changes in the figure, but the physical interpretation remains the same.
- Additionally, we found a small error in the calculation of the ionospheric spatial scale of the FAC structures. Previously it was reported that the scale is ~2000 km, this was changed to ~1000 km.

Changes to the text:

- Several new references have been added to the introduction, along with descriptions of the results from the referenced papers.
- A paragraph describing the interchange instability was added to the introduction, before the ballooning instability is introduced. Additionally the concept of an "interchange head" is now introduced in a way that better reflects the previous literature.
- Some repetition was removed from the introduction to make the text clearer to the reader
- Some small clarifications have been added throughout the text to address referee comments and make the interpretation of the results easier.
- Section *3.2 Signatures of the ballooning/interchange instability* has been edited to add more detail when discussing the figures that are presented there
- The *Discussion* has been largely reworked to better reflect the comments of the referees. We have added more on the novel findings of this study and clarified the similarities and differences between our study and previous literature. A paragraph describing PIC simulation results was removed, as it was not very relevant to our findings.
- The *Conclusions* have also been elaborated to better describe the novel findings of the study

Below we give our responses to the comments by the reviewers:

Response to reviewer 1, author comments given in bold text:

<u>General comment</u>

The paper presents investigations of the dipole-magnetotail transition region by means of global hybrid-Vlasov simulations of Earth's magnetosphere. The present run of the employed Vlasiator code is merged with an ionospheric solver, and the ionospheric field-aligned currents are related to the magnetospheric vorticity, as a proxy to auroral dynamics. The focus of the paper is on a wave-like density structure that appeared in the transition region after magnetotail reconnection. The wave-like structure is formed by earthward flows with ion vortices on their sides. The authors attribute the wave-like structure to ballooning/interchange activity.

-The authors thank the referee for the comments and suggestions. We have revised the paper according to the comments and have added several new references as suggested by the reviewer. We believe the quality of the paper has improved based on these changes.

The simulations clearly reveal a development of a Bz/entropy ridge at about -10 R_E (Figure 4b,f), which is apparently the source of further earthward low-entropy (bubble) intrusions (Figure 4c,g,d,h) due to an interchange process. This is indeed similar to the results of recent global high-resolution (down to ~300km) MHD simulations by Sorathia et al., 2020 (10.1029/2020GL088227). At the same, due to multiple differences (e.g. significantly larger scales and velocities of the present low-entropy intrusions), the present simulation better matches the Rice Convection Model simulations of sawtooth events by Sazykin et al., 2002 (10.1029/2001GL014416), Yang et al., 2008 (10.1029/2008JA013635) and Sun et al., 2021 (10.1029/2021GL094097), where interchange instability operates during storms or substorm, unlike quiet growth phase in simulations of Sorathia et al., 2020 (10.1029/2020GL088227). The RCM simulations show that a wide injection boundary around the geosynchronous orbit may break up into multiple injection channels with the local time separation of about 1–2 h, similarly to present simulations.

Thank you for these new references, we have added them to the manuscript and they are indeed very relevant.

There are many different forms of the ballooning/interchange instability in the literature. In many cases, regardless of the spatial/temporal scales of the phenomenon or the exact causes of the instability, the authors have considered flux tube entropy depletion as a crucial point of analysis. This is done both for the Sorathia et al. 2020 paper, the RCM studies mentioned, and many other MHD studies. We have tried to clarify that this is a general method, and added clarification on the difference between our results and those of Sorathia et al in the Discussion:

"Conversely to the previously mentioned MHD studies, the initiation of the instability in Sorathia et al. (2020) was not related to reconnection in the magnetotail, but arose from a tailward B_z gradient and a decrease in flux tube entropy. These conditions were due to the thinning of the current sheet due to magnetic flux moving to the dayside. The magnetospheric structures were mapped onto the ionospheric grid of the simulation, where the scales matched that of auroral beading. While the instability conditions (entropy and B_z gradients) are similar in our simulation, there is a key difference that possibly explains the difference in scales between the two studies. Our simulated event is driven by fast flows that result from reconnection, while their simulation focuses on the substorm growth phase and the thinning magnetotail current sheet, prior to reconnection onset."

The Discussion section of the manuscript has been largely rewritten to make the differences and similarities between our work and previous work more clear.

Even more so, the authors attribute the appearance of the interchange-unstable magnetotail configuration (Bz/entropy ridge at -10 R_E) to reconnection and loss of density via plasmoid release, which would be similar to the results of Birn et al., 2011 (10.1029/2010JA016083). This is also a different mechanism, as opposed to the mechanism that is based on flux return to the dayside (Hsieh and Otto, 2015, 10.1002/2014JA020925), which was identified to operate in the run of Sorathia et al., 2020 (10.1029/2020GL088227).

Our interpretation is that the onset of reconnection, similarly to Birn et al., 2011 and the RCM simulations by Sun et al., 2021 (https://doi.org/10.1029/2021GL094097 results in the lowering of entropy, and eventually a plasmoid release. In our simulation this low entropy region spreads over the magnetotail (as the reconnection spreads over the tail), resulting in the region becoming unstable to the ballooning/interchange

instability. This instability results in the creation of multiple BBF-like flow channels across the magnetotail.

Thus we have a combination of both BBF-like dynamics, and the ballooning/interchange instability. As we model the ion-kinetic physics of the magnetotail, we can self-consistently capture these phenomena, and go beyond the MHD and RCM descriptions.

We have clarified this point further in the Discussion, which has been largely reworked. In the final comment stage, we mentioned also a study (Tao et al., 2025) related to dayside flux depletion. As we have determined that the origin of the instability is nightside dynamics, we have left out the mention of this paper as it is not as relevant to our study.

Tao, S., Alho, M., Zaitsev, I., Turc, L., Battarbee, M., Ganse, U., Pfau-Kempf, Y., and Palmroth, M.: Magnetospheric convection in a hybrid-Vlasov simulation, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2025-1340, 2025.

The above major points need to be carefully addressed before publication of the paper. In addition to them I also list below a number of minor suggestions, which may help improve the paper.

<u>Specific comments</u>

A clarifying comment on what leads to reconnection triggering in the Vlasiator would be useful.

This point was clarified in the Discussion. For this study, the most important parameter related to this point is numerical diffusion, which leads to the onset of reconnection.

Line 31: reference to Sitnov may not be the best one here, and some auroral paper could be cited instead.

The reference was changed to Partamies et al., 2015
(https://doi.org/10.1002/2015JA021217)

Line 32: Additional reference could be added here:

Baumjohann, W., G. Paschmann, and H. Lühr (1990), Characteristics of High-Speed Ion Flows in the Plasma Sheet, J. Geophys. Res., 95, 3801–3809

Line 34: Additional references could be added here:

Baumjohann, W., Hesse, M., Kokubun, S., Mukai, T., Nagai, T., & Petrukovich, A. A. (1999). Substorm dipolarization and recovery. *Journal of Geophysical Research*, 104, 24995–25000.

Baumjohann, W. (2002), Modes of convection in the magnetotail, Phys. Plasmas, 9, 3665–3667, doi:10.1063/1.1499116

Ohtani, S., Singer, H. J., & Mukai, T. (2006). Effects of the fast plasma sheet flow on the geosynchronous magnetic configuration: Geotail and GOES coordinated study. *Journal of Geophysical Research*, 111, A01204. https://doi.org/10.1029/2005JA011383

Merkin, V. G., Panov, E. V., Sorathia, K., & Ukhorskiy, A. Y. (2019). Contribution of bursty bulk flows to the global dipolarization of the magnetotail during an isolated substorm. *Journal of Geophysical Research: Space Physics*, 124, 8647–8668. https://doi.org/10.1029/2019JA026872

Line 35: Additional references could be added here:

Angelopoulos, V., et al. (1996), Multipoint analysis of a bursty bulk flow event on April 11, 1985, J. Geophys. Res., 101, 4967–4989.

Sergeev, V. A., V. Angelopoulos, J. T. Gosling, C. A. Cattell, and C. T. Russell (1996), Detection of localized, plasma-depleted flux tubes or bubbles in the midtail plasma sheet, J. Geophys. Res., 101, 10,817– 10,826, doi:10.1029/96JA00460

Line 37: Additional reference could be added here:

Nakamura, R., Baumjohann, W., Klecker, B., Bogdanova, Y., Balogh, A., R`eme, H., Bosqued, J. M., Dandouras, I., Sauvaud, J. A., Glassmeier, K.-H., Kistler, L., Mouikis, C., Zhang, T. L., Eichelberger, H., and Runov, A. (2002). Motion of the dipolarization front during a flow burst event observed by Cluster. Geophys. Res. Lett., 29:1942

Line 39: Additional reference could be added here:

Shiokawa, K., W. Baumjohann, and G. Haerendel (1997), Braking of highspeed flows in the near-Earth tail, Geophys. Res. Lett., 24, 1179–1182, doi:10.1029/97GL01062.

Line 40: Additional reference could be added here:

Ohtani, S., Y. Miyashita, H. Singer, and T. Mukai (2009), Tailward flows with positive B Z in the near-Earth plasma sheet, J. Geophys. Res., 114, A06218, doi:10.1029/2009JA014159.

Panov, E. V., et al. (2010), Plasma sheet thickness during a bursty bulk flow reversal, J. Geophys. Res., 115, A05213,

doi:10.1029/2009JA014743.

The reference to Panov, E. V., et al. (2010) on Multiple overshoot and rebound of a bursty bulk flow (10.1029/2009GL041971) belongs together with Birn et al., 2011.

Also, the following two references could be placed next to Birn et al., 2011 in this line.

Keika, K., et al. (2009), Observations of plasma vortices in the vicinity of flow-braking: A case study, Ann. Geophys., 27, 3009–3017.

Keiling, A., et al. (2009), Substorm current wedge driven by plasma flow vortices: THEMIS observations, J. Geophys. Res., 114, A00C22,

doi:10.1029/2009JA014114.

Line 47: Additional reference could be added here:

Baumjohann, W., Pellinen, R. J., Opgenoorth, H. J., & Nielsen, E. (1981). Joint two-dimensional observations of ground magnetic and ionospheric electric fields associated with auroral zone currents—Current systems associated with local auroral break-ups. *Planetary and Space Science*, 29, 431–435.

Birn, J., & Hesse, M. (2014). The substorm current wedge: Further insights from MHD simulations. *Journal of Geophysical Research: Space Physics*, 119, 3503–3513. https://doi.org/10.1002/2014JA019863

McPherron, R. L., Nakamura, R., Kokubun, S/, Kamide, Y., Shiokawa, K., Yumoto, K, Mukai, T., Saito, Y., Hayashi, K, Nagai, T., Ables, S., Baker, D. N., Friis-Christensen, E., Fraser, B., Hughes, T., Reeves, G., & Singer, H. (1997). Fields and flows at GEOTAIL during a moderate substorm. *Advances in Space Research*, 20, 923–931.

Palin, L., Opgenoorth, H. J., Ågren, K., Zivkovic, T., Sergeev, V. A., Kubyshkina, M. V., Nikolaev, A., Kauristie, K., Kamp, M., Amm, O., Milan, S. E., Imber, S. M., Facskó, G., Palmroth, M., & Nakamura, R. (2016). Modulation of the substorm current wedge by bursty bulk flows: 8 September 2002—Revisited. *Journal of Geophysical Research: Space Physics*, 121, 4466–4482. https://doi.org/10.1002/2015JA022262

Panov, E. V., Baumjohann, W., Nakamura, R., Weygand, J. M., Giles, B. L., Russell, C. T., et al. (2019). Continent-wide R1/R2 current system and ohmic losses by broad dipolarization-injection fronts. *Journal of Geophysical Research: Space Physics*, 124, 4064–4082. https://doi.org/10.1029/2019JA026521

Sergeev, V. A., Sauvaud, J.-A., Popescu, D., Kovrazhkin, R. A., Liou, K., Newell, P. T., Brittnacher, M., Parks, G., Nakamura, R., Mukai, T., & Reeves, G. D. (2000). Multiple-spacecraft observation of a narrow transient plasma jet in the Earth's plasma sheet. *Geophysical Research Letters*, 27, 851–854.

Line 81: Additional reference could be added here:

Pritchett, P. L., F. V. Coroniti, and Y. Nishimura (2014), The kinetic ballooning/interchange instability as a source of dipolarization fronts and auroral streamers, *J. Geophys. Res. Space Physics*, 119, 4723–4739, doi:10.1002/2014JA019890.

We thank the referee for the new references, we have reviewed them and added relevant references at the appropriate lines. The manuscript benefitted from this thorough background information.

Line 222: Could specific time be indicated after "At the Earthward flows"?

A timestep was added here.

Figure 4: A plot with the time evolution of the radial profiles of Bz/PV^gamma could be shown here for the times around t=680 s. This plot would show the growth/formation of the Bz/entropy ridge.
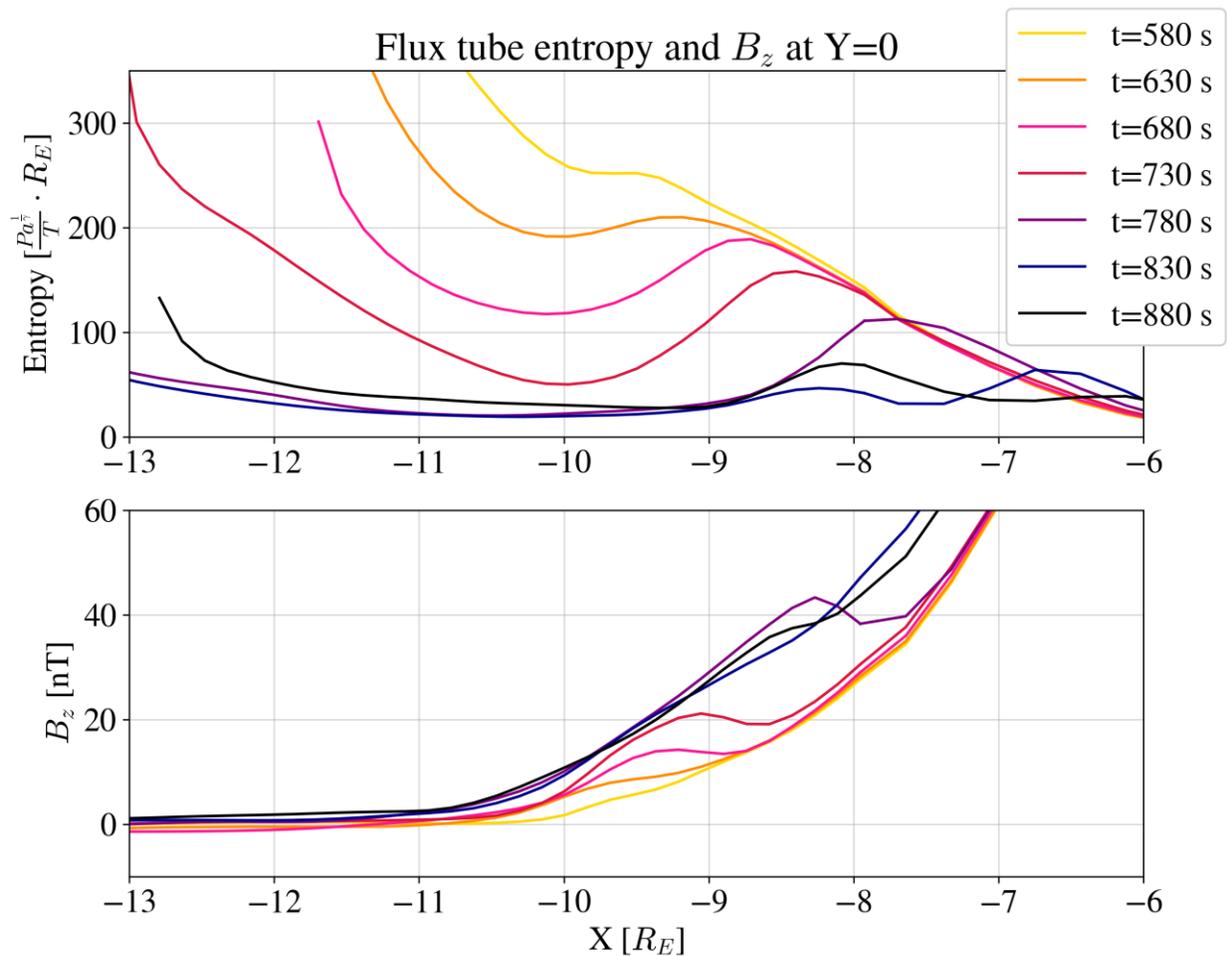
We added this type of figure to the manuscript, it is indeed useful to have. This figure was also given in the final response, but during the revision process we have updated the plotting of the lower refinement region, Earthward of –8 RE. We give the figure above, and have added a description to the manuscript in Section 3.2 *Signatures of the ballooning/interchange instability:*

"There is a clear, spatially localised, decrease in flux tube entropy at ~-10 RE as the simulation progresses, corresponding to a change in the Bz profile. At the radial

distance where entropy starts to decrease, a local minimum develops in Bz due to dipolarization further in the tail. A Bz "hump" forms in the magnetic field profiles. This is seen, for example, for t = 730 s (red curve) as an increase of Bz between at X∼ −10RE and X∼ −9RE and a minimum at∼ −8.7 RE. At this time, we see a tailward Bz gradient and an Earthward S gradient, indicating instability (Birn et al., 2018). The decrease of entropy and dipolarisation in Bz profiles are evident for the times from t = 680 to t = 780 s, as entropy in the tail decreases with time. After this, at t = 830 s the entropy in the transition region is lower than at t = 880 s. This is due to the wavy interchange structure increasing in azimuthal size, so that a higher entropy region moves to Y=0 by 880 seconds. This is seen in Fig. 4g and Fig. 4h, when looking along the Y=0 RE line. At t = 780 s Y=0 is between two regions of higher entropy at the transition region (X∼ −10RE). By 880 seconds, the maximum entropy value has decreased, but the high entropy regions have increased in size, so at Y = 0RE, X = −10RE we see a slight increase in entropy."**

Figure 6 and associated text: Could the authors explain somewhere how the FAC was obtained?

The FACs are determined from the curl of B close to the inner boundary of the simulation. This was added to the manuscript.

Line 322: Midnight may be more appropriate as mid-tail sounds ambiguous when one considers radial distance instead of azimuthal.

Midnight is indeed the better word to use here, that has been changed.

<u>Technical corrections</u>

Line 117: It seems that in is missing between done and six dimensions.

Yes, 'in' was missing from that sentence, that has been fixed.

Response to reviewer 2, author comments given in bold text:

<u>General comment</u>

This paper uses the Vlasiator code, a global hybrid-Vlasov simulation of Earth's magnetosphere with a newly included ionospheric boundary model, to study the formation, evolution, and impact of azimuthally localized fast flows through the magnetotail transition region, defined here to be between ~6-12 R_E. The author's show that reconnection first occurs on the dusk, and then dawnside, flanks before extending across the entire magnetotail as seen in the flow reversal between tailward and Earthward flow in Fig. 2f. They show that the region of fast flow that forms symmetrically in the tail at X ~ -8 R_E coincides with low flux tube entropy and increased magnetic field, which becomes unstable to the ballooning interchange instability, driving density and velocity fluctuations with wavelengths ~3.5 R_E. Braking of the fast flows causes rebound flows to form and vorticity, which drives FACs into the ionosphere. The authors state that the flows emerge in the simulation after the inclusion of the new ionospheric boundary model, highlighting the importance of magnetosphere-ionosphere coupling.

The authors compare their results to previous works and find that their results are consistent with MHD simulations of low-entropy Earthward flows driven by reconnection (e.g. Birn & Hesse 2013) rather than those where the instability is driven by magnetic flux evacuation to the dayside during substorm growth phase (Sorathia 2020). They postulate that, in the current simulation, these features, both in the magnetosphere and their auroral counterparts, are dominated by larger scales rather than kinetic-scale processes. While the comparison to previous works is extremely helpful to put the results into context, a clearer distinction on the new insights provided by this work would help set this paper apart from the others. Additional comments are below.

We thank the referee for the insightful comments. We feel the manuscript quality has improved as a result of implementing these changes.

We have elaborated further on the new insights gained by our work in the Discussion, which has been largely reworked. Our model captures the dynamics of BBF-like flows, tail-wide entropy depletions, current sheet thinning and reconnection, and the mapping of these phenomena to the ionosphere. We thus model the several different types of interconnected phenomena that have been seen in other simulations, combining the effects in a self-consistent manner. This is the first time that a similar event has been seen in a hybrid-Vlasov simulation, where the ion dynamics are captured. Our simulation offers a perspective on the development of several BBF flow channels (in the presence of ion-kinetic physics) that form from a single wide reconnection region in the close tail.

This is a possible explanation for the "wedgelet" phenomenon, where several pairs of FACs are observed in the ionosphere. In our simulation we see the transition from a the classic R1/R2 ionospheric current pattern (before the large inflow region splits into several flow channels) to a "wedgelet" type current distribution, associated with multiple magnetospheric flow channels.

Specific Comments

-Line 173: could reference Figure 3c and 4a-d when referring to the Bz enhancement as scale makes it difficult to identify in Figure2i-l.

A reference to Figure 3c has been added here.

-The reconnection starts very close to Earth despite those events being relatively rare (Beyenne & Angelopoulos 2024). Whether this is the first time reconnection occurs in the tail would be helpful to note. The initial state seems to be a dipole field and constant IMF (line 218). The reconnection shown occurs about 10 minutes into the simulation so it is unclear if this the first time reconnection is occurring in the tail as the magnetotail forms or if magnetosphere has been sufficiently preconditioned and is not significantly affected by the wave of IMF as it passes the magnetosphere for the first time.

Beyene, F., & Angelopoulos, V. (2024). Storm-time very-near-earth magnetotail reconnection: A statistical perspective. Journal of Geophysical Research: Space Physics, 129, e2024JA032434. https://doi.org/10.1029/2024JA032434

Thank you for the new reference, we added this to the Discussion when discussing reconnection in the tail. This is the first onset of reconnection we see in the simulation. We have expanded on this in the Discussion:

"The creation of the vortex flows occurs at an early stage in the simulation run, where the magnetosphere is still in its phase of global reconfiguration caused by tail reconnection. The R1 and R2 field-aligned current systems have already formed by this point in the simulation, and so we can study the current closure in the ionosphere. This marks the first large-scale reconnection event seen in the simulation run. Due to the early state of the simulation, the magneotail is very elongated. This period of initialisation is followed by rapid reconfiguration of the magnetotail due to large-scale reconnection. Such a situation could potentially arise when a period of slow solar wind is followed by very fast solar wind, triggering large-scale reconnection."

In the movie within the supplemental information, the region where Vx > 400 km/s appears to first extend in MLT across the tail before driving earthward flows. Is this region being continuously driven by reconnection? Showing radial profiles of the B_z and flux tube entropy in the tail as a function of time would be helpful to show why the region becomes unstable to the ballooning instability later in the simulation and then dissipates. 2D simulations (Zhu et al. 2004) have shown that the plasma beta can affect the growth rate of the ballooning mode for sufficiently thin current sheets. The evolving state of the tail, therefore, might be affecting when the density fluctuations occur.

Zhu, P., A. Bhattacharjee, and Z. W. Ma (2004), Finite ky ballooning instability in the near-Earth magnetotail, J. Geophys. Res., 109, A11211, doi:10.1029/2004JA010505.

The reconnection is indeed continuous throughout the event. A figure showing the Bz and flux tube entropy profiles was added to the manuscript, to Section 3.2 *Signatures of the ballooning/interchange instability*:

"There is a clear, spatially localised, decrease in flux tube entropy at ~-10 RE as the simulation progresses, corresponding to a change in the Bz profile. At the radial distance where entropy starts to decrease, a local minimum develops in Bz due to dipolarization further in the tail. A Bz "hump" forms in the magnetic field profiles. This is seen, for example, for t = 730 s (red curve) as an increase of Bz between at X~ −10RE and X~ −9RE and a minimum at~ −8.7 RE. At this time, we see a tailward Bz gradient and an Earthward S gradient, indicating instability (Birn et al., 2018). The decrease of entropy and dipolarisation in Bz profiles are evident for the times from t = 680 to t = 780 s, as entropy in the tail decreases with time. After this, at t = 830 s the entropy in the transition region is lower than at t = 880 s. This is due to the wavy interchange structure increasing in azimuthal size, so that a higher entropy region moves to Y=0 by 880 seconds. This is seen in Fig. 4g and Fig. 4h, when looking along the Y=0 RE line. At t = 780 s Y=0 is between two regions of higher entropy at the transition region (X~ −10RE). By 880 seconds, the maximum entropy value has decreased, but the high entropy regions have increased in size, so at Y = 0RE, X = −10RE we see a slight increase in entropy."

This figure was also given in the final response, but during the revision process we have updated the plotting of the lower refinement region, Earthward of –8 RE.

We observe a reconnection X-line throughout the studied interval, and see dipolarization in the Bz component as the event progresses, as is shown in the new figure. The entropy depletion and Bz dipolarization are coinciding with each other.

Flux tube entropy and B_z at Y=0
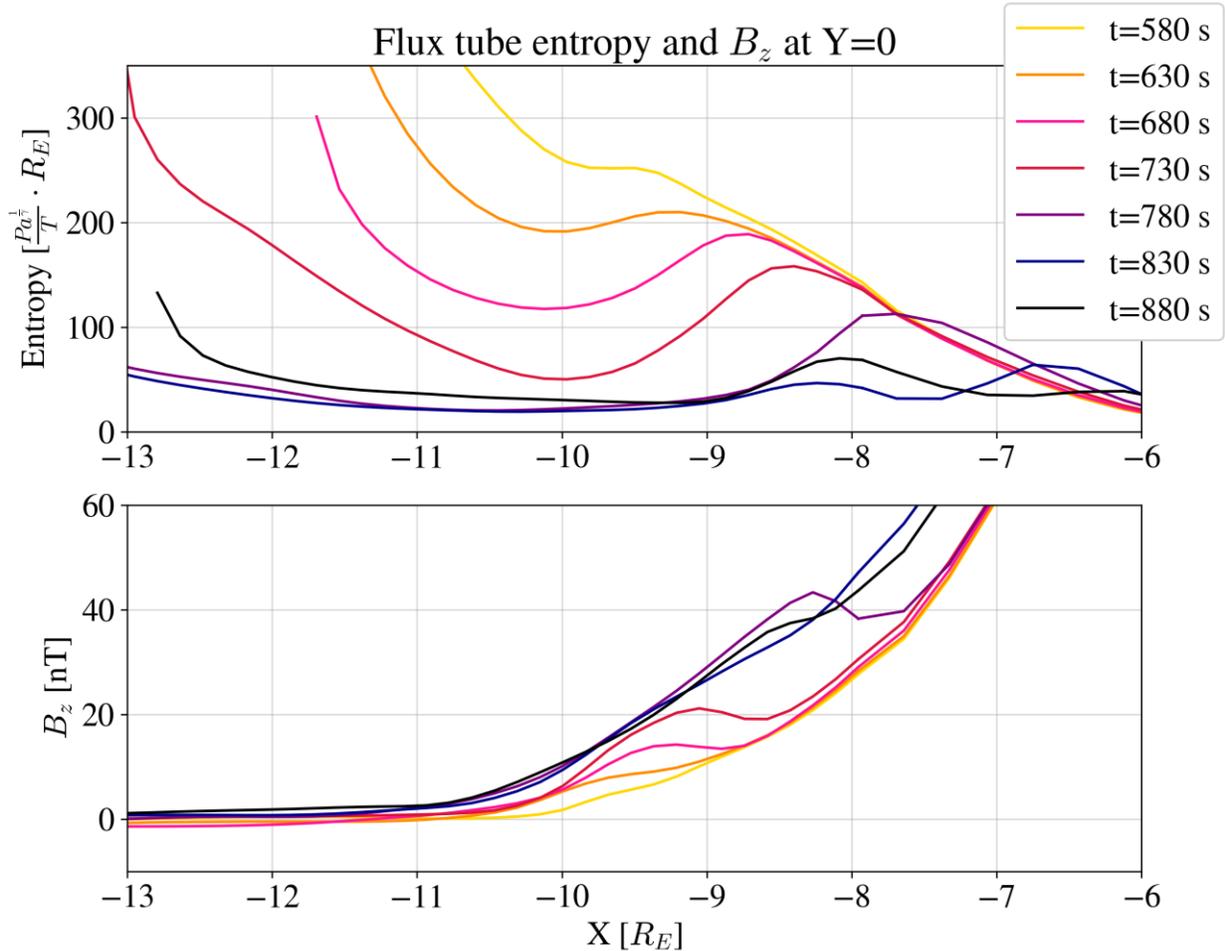
-In section 4 of the discussion, clarification on what is setting the wavelength of the density fluctuations and fast flows would be helpful to determine if it is spatially localized reconnection or the ballooning interchange instability itself. If reconnection sets the wavelength, then clarification on how it is generating that wave-like structure and whether it is bursty, or continuous would help shed light on why the flows have the widths that they do.

We now elaborate on this in the manuscript, in the Discussion. The reconnection appears to be continuous, spreading over the tail from dawn and dusk towards midnight. This results in a cross-tail X-line forming across the magnetotail, and a corresponding decrease in flux tube entropy. After this, we see signs of the ballooning/interchange instability. The wavelength is not related to bursty

reconnection that would form BBF-like structures, but rather the structures form on the Earthward side of the cross-tail X-line. The eventual wavelength of the density fluctuation is the same as the original flow channels that intrude into the transition region.

Technical Corrections

line 183: remove "along with an additional" from "an additional along with an additional upward current"

This was removed.