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2 October 2025

Viviane Pierrard
Editor
Journal of Geophysical Research: Space Physics

Re: Revision of JGR manuscript #2025JA034311 (van Irsel et al., "Current Closure and Joule Heating in Data-Driven 3-D Auroral Arc Simulations")

Dear editorial staff and reviewers,

We are grateful for the in-depth reviews and constructive comments from our reviewers and for facilitating revisions of our manuscript by the editorial staff. We have enclosed our responses with our comments in **bold** and reviewer comments in *italics*, and with our line numbers referring to the tracked-changes manuscript.

This manuscript is part of a PhD dissertation which has since undergone edits. The authors have included the relevant edits to this manuscript, listed here:

- L346 – 348: Removed incorrect comment about Ts = Ua = E0.
- L929: Changed "over" to "rather than"
- L975: Added " (at roughly 25 km east and 50 km south),"
- L1076 – 1080: Added point in L928 – 932 to conclusions list

Regards,

J. van Irsel, K. A. Lynch, A. Mule, M. D. Zettergren, J. K. Burchill, L. Lamarche, & D. L. Hampton

Encl.: Reviewer responses, tracked-changes manuscript.

Reviewer #1

Evaluations

Recommendation (Required): Return to author for minor revisions
Significant: Yes, the science is at the forefront of the discipline.
Supported: Mostly yes, but some further information and/or data are needed.
Referencing: Yes
Quality: Yes, it is well-written, logically organized, and the figures and tables are appropriate.
Data: Yes
Accurate Key Points: Yes

Summary

The paper Current closure and Joule heating in data-driven 3-D auroral arc simulations addresses the details of the field-aligned current (FAC) closure in the ionosphere by Pedersen and Hall current. The results are achieved by the multi-fluid simulation code GEMINI, with boundary conditions set by electron precipitation data inverted from multi-spectral optical observations at Poker Flat, FAC data from the Swarm mission, and background electric field from the SuperDARN and PFISR radars. The simulations address six Swarm crossings over auroral arc systems in the Poker Flat region, whose FAC closure configuration are shown to depend on the background electric field, the actual shape of the electron distribution function (in particular, non-accelerated vs. accelerated Maxwellian), and the FAC structure along the arc.

I regard the paper as remarkable, in terms of basic achievements, variety of data sources and data assimilation procedures, as well as efficient and illustrative data reduction. Regarding the basic achievements, to my knowledge, this is the first time that the ionospheric FAC closure is explored in comprehensive details, showing complexity even for 'simplest', arc-like events. Regarding the variety of data sources and assimilation procedures, besides GEMINI proper, whose 'machinery' is already quite complicated, driving it efficiently, with proper data 'fuel', is a skill in itself. Not the least, selecting appropriate events and simulations, together with organizing the results in a meaningful and compact manner, is essential too and requires further effort.

We thank the reviewer for a positive summary and for their helpful comments and questions. We have addressed them with careful consideration and hopefully to the satisfaction of the reviewer. Several suggestions require fairly extensive analysis and so have been deemed outside of the scope of this paper, but of those, we have made efforts to either make note of them in either the future work section or near relevant parts of the text. This is to ensure these thoughts are available to the reader and can be addressed in the continuing efforts and studies on auroral system science.

These being said, there are also points that can be improved, or at least discussed, as indicated below (not surprising, given the complexity and length of the paper - even if as compact as possible).

Major Comments

1. *According to the standard perspective, reasonably steady events, like often the arcs, are typically described by FAC closure with Pedersen current, local dissipation by Joule heating of the FAC Poynting flux, and divergence free electrojet. This 'well behaved' current closure might actually be less simple in practice, as suggested already by Comparison 1. Even though the PFISR data, as well as the Swarm data in Figure 17, support rather the stronger electric field (L1050-1052), and therefore the standard perspective, hints toward Hall closure are seen also in other events (like Comparison 3). I wonder to what extent such hints can really materialize, i.e., the self-consistency (L114) relies indeed on such electric fields / plasma flows that FAC closure requires also Hall current. I think this matter deserves some discussion (see also points 2 and 3), beyond just noting that Hall closure is favored by a weak electric field. How likely it is to see that actually happening? If one can argue that deviations from the standard perspective are likely enough, Hall closure could be even promoted as key point (e.g., made key point 2, while present key points 2 and 3 could be merged together).*
    - **To touch on the likelihood of one case study over another would require some form of statistical analysis, one we don't have enough conjunction events for as of yet. Our aim with this paper is to provide geophysical, self consistent solutions within the context of what GEMINI, and the data it ingests, can provide.**
    - **In Section 5, we state that "This work looks at how to determine geophysical, self-consistent solutions to current continuity in auroral arc systems, and what these systems are sensitive to, thus uncovering how important various parameters can be." Future follow up work might include statistical studies or the use of other datasets such as TII or the new EZIE mission.**
    - **L1092 – 1093: <u>Changed</u>**

        "(or other, independent flow data)"

        <u>to</u>

        "(or other, independent data such as those from the Electrojet Zeeman Imaging Explorer mission Madelaire et al. (2023))"

2. *Closely related, I note that all 6 events are rather quiet, according to Ap, though this planetary and daily index has limited relevance for arc events. The AE index (which is also not local, but closer to the matter) shows actually some activity for all 6 events, each of which appears to be associated with a small substorm (just by chance? - see also*

point 9, the item on Section 3). Intuitively, weak(er) electric fields are associated rather with quiet arcs, but equally intuitively such arcs are also pretty steady and the standard closure should be more likely. The opposite during more active times (like of the 6 events?): On one hand, one expects higher electric fields, that favor Pedersen closure, on the other hand, one expects less steadiness and more Hall closure. This may deserve some comment too.

   - **Similar to the previous comment's reply, we are deliberately avoiding statements on the likelihood of the events in this work.**
   - **The values f107a, f107, and Ap are directly input into the gemini simulation configurations to be passed through to MSIS (see https://github.com/gemini3d/gemini3d/blob/main/docs/Readme_input.md and https://ccmc.gsfc.nasa.gov/models/NRLMSIS~00/#inputs). They might be less descriptive of the events, but they are most descriptive of the simulations themselves.**

3. *Solving the apparent difficulties indicated under point 2 is related, essentially, to the Cowling mechanism, where not only the strength (L525), but also the direction of the electric field is essential, namely with a significant component parallel to the arc. Such an event is not addressed in the paper – and presumably also not trivial to find. A possible location is the Harang region, where the dusk and dawn convection cells overlap and the electric field rotates from poleward through westward to equatorward (Baumjohann, 1982, https://doi.org/10.1016/0273-1177(82)90363-5; Marghitu et a., 2009, https://doi.org/10.1029/2008JA013630). For such a (partial) Cowling channel arc, the strong electric field would likely no longer prevent the Hall closure. (See also point 9, L454).*
   - **Simulation IIIa has an eastward component of the electric field of ~13 mV/m (table 2) and hence shows a significant Cowling effect, showing an along-arc current of ~50 uA/m^2 (figure 9g). This is compared to Simulation IIIb where this peaks at around 2 uA/m^2. This comparison also addresses how this electrojet current connects to different places.**
   - **L681 – 684: <u>Added</u> "The ~13 mV/m eastward component of the Simulation IIIa electric field gives rise to a substantial display of the Cowling mechanism enhancing the auroral electrojet current (Cowling, 1932; Amm et al., 2011) as indicated by Figure 9, panels b and g."**
4. *A conceptual matter which is addressed to some extent, but perhaps could be emphasized more, is the separation of the Pedersen current in primary and secondary, polarization current. This fits as well with points 1–3 and is related to the separation of the electric field in background and 'delta' (Eqs. 2, 3 and subsequent para), whose effects are explored closely under Comparisons III and VIII of Event 3. However, even in this case, a detailed assessment of the primary and secondary Pedersen current is missing, likewise of the current closure 'branches' of Amm et al. (2011) and Fujii et al. (2011), namely how much of the FAC is closed by primary Pedersen current, how much by Hall current, and what is the weight of the closed loop in the ionosphere provided by Hall current and secondary Pedersen current (Fig. 1 of Amm et al., 2011; Figs. 2 and 3 of Fujii et al., 2011; Figs. 3 and 4 of Fujii et al., 2012). Obviously, the concept based on*

two thin layers, of Pedersen and Hall current, is less realistic than the full 3D approach. On the other hand, the inter-play between the various currents is still supported by the superposition of background and polarization (Eqs. 2 and 3). If a close exploration is beyond the scope and more appropriate for a paper in its own right (to concentrate on a Cowling channel event, point 3?), perhaps some preliminary discussion is still not too costly. Event 3 may actually provide a promising test bed for a Cowling channel study: While the FAC is closed in this case mainly by Pedersen current, there seem to be also a strong loop of Hall and polarization current, as suggested by panels l and k (or j and l) of Figure 14. Moreover, the intensity off the current in the loop, up to ~50 μA/m2, is one order of magnitude stronger than the primary FAC current, of ~4 μA/m2. This suggests indeed a strong Cowling channel, with efficiency close to 1 (Eq. 1 of Amm et al., 2011). A possible caveat is that, on the Pedersen side, the contribution made by the polarization electric field and the gradient of the Pedersen conductance is missing, though I guess this would contribute as well to balancing the Hall term (as noted also in the paper, L853).

- **Because this paper is focused on event-realistic, data-driven simulations, interpretation of primary vs. secondary responses is going to be quite complicated. Currently the manuscript concentrates on the overall responses in terms of electric fields and current—the reviewer is suggesting a more detailed decomposition into polarization vs. magnetospheric effects which is very interesting, but we argue that this would be more easily accomplished by way of a set of simpler, hypothetical simulations that hew more closely to the original theoretical papers referenced. This would make the results more readily interpretable in terms of these papers.**
- **L774 – 781: <u>Added</u> "Previous studies have looked at how the strength and direction of the ionospheric electric field alters auroral current closure by systematically dividing the field-aligned, Pedersen, and Hall currents into primary and secondary components (Amm et al., 2011; Fujii et al., 2011, 2012). In this work, we look at an undivided, 3-D current connectivity in which primary and secondary polarization currents blend into a set of individual current flux tubes. The reader is encouraged to compare and contrast these two perspectives and recognize the sub-current mechanisms within the flux tubes themselves."**

5. *One more word of caution on the sentence at L859-861: As just commented, I don't think that the touch of the Hall layer is related to the large requirements of the primary FAC, but to the Cowling channel loop in the ionosphere. This may require also some adjustment to Section 4.2.3 (and 4.1.4?).*
    - **It is difficult to partition which of the Hall currents are provided by the Cowling channel loops vs. the main FAC circuit. We can only speak to the flux tube, in this case the red one, which has more segments directed perpendicular to the electric field in simulation VIIIa vs. b. That being said, we have reworded the causal relationship that this paragraph implied.**

- **L897 – 907: <u>Changed</u>**

  > **"In all, even though Simulations VIIIa – b both have high total energy flux and strong electric field strengths, the large FAC requirements and the higher electron energy distribution peaks mean that these systems do touch on the Hall layer in their current closure."**

  <u>to</u>

  > **"Simulations VIIIa – b both have intense total energy flux and strong electric field strengths. Both of these qualities aid in high-altitude FAC closure. Both simulations, however, also have large FAC requirements and higher electron energy distribution peaks—qualities which, all else held equal, suggest the need for lower-altitude-reaching FAC flux tubes. Given the self-consistent nature of our auroral arc simulations, we can only hypothesize that a more moderate FAC top-boundary driver would result in less need for Hall closure, but it could also be true that this would result in a Cowling mechanism with reduced electric field strength."**

6. *On the 'operational' side, following the 3D closure, i.e., the current flux tubes, is rather complicated. It took me a while (and more readings) to combine (mind's eyes) the 3D plot with the overlay in the charge density projection (the eastern wall) and the current density in the topside projection (shown at the bottom). Obviously, the matter is not simple, so the tool cannot be simple either. On the other hand, for the sake of the broader audience, I can't help wondering if one cannot add also some sketchy insets, e.g., with streamlines (and their unions or bifurcations) which are easier to follow and assimilate. If feasible (by a talented drawer?), this would really help the reader.*
   - **We have tried many variations and permutations of these visualizations and what is shown is what has worked the best. Adding over- or under-layers tends to make the visualizations more cluttered. We would prefer to leave them as they are shown.**
   - **<u>Added</u> a rotating 3-D view of a simulation in the supplementary material which can also be found here: https://rcweb.dartmouth.edu/LynchK/pubdata/2025_vanirsel_jgr/data/supporting/**
7. *Characterizing the electron precipitation based on multi-spectral optical information makes a major contribution to the simulation input (Section 2.7, L995-996, L1065-1067). It would be interesting to cross-check the image inversion with satellite data, for conjugate events. In such cases, satellite data can provide independent estimates of the acceleration potential and of the source temperature (e.g., Marghitu et al., 2006, https://doi.org/10.1016/j.asr.2006.03.028; Imajo et al., 2024, https://doi.org/10.1029/2024JA032696), the more interesting to compare with given the rather sophisticated procedure based on optical data. If such cross-checks have already been done, please include a brief comment, if not, likewise.*

   - **The Swarm satellites on which this study is based do not have electron precipitation observations. We hope to make this comparison with the upcoming GNEISS rocket, which will launch this winter from PFRR and carries energetic electron measurements in conjunction with imagery. We have not yet had the opportunity to explore other camera/spacecraft conjunctions.**
   - **L386 – 392: <u>Added</u> "The methodology described in this section, at the time of writing, has not been validated experimentally because the measurement data available in our conjunctions exclude electron spectrometry. We do analyze the different spectral assumptions, and the effect they have on auroral system science, to great lengths in Section 4.2. That said, this methodology invites future studies applying these techniques with multi-spectral imagery data and data used in auroral acceleration region spectrometry (Marghitu et al., 2006; Imajo et al., 2024)."**
8. *The specificity of the electron distribution was circumvented by Robinson et al. (1987, https://doi.org/10.1029/JA092iA03p02565), who found proxies for the Pedersen and Hall conductance depending on the average energy, namely the ratio of the energy flux to the number flux. The proxies were shown to work reasonably well for average energies above ~1 keV, which is also the case for the six events here. Obviously, the accelerated and unaccelerated Maxwellians in the paper are constructed such that the average energy is the same. It would be instructive to compare the Pedersen and Hall proxies of Robinson et al. (1987) with the actual estimates, e.g., for Comparison VIII, already addressed in more detail, and to comment briefly (I guess the proxies of Robinson et al. (1987) should fit better with the accelerated Maxwellian).*
   - **The Robinson formulae, while useful, cannot fully capture how the impact ionization rate profiles depend on the specific energy distribution function of the electrons since they only use two parameters. I.e., any distribution with a high-energy tail is going to produce more low-altitude (Hall) conductivity even if the average energy is kept fixed. There is also the issue that the conductivity in our model depends on space and time due to transport (non-local) and chemical effects. The difference between two specific choices of distribution is captured in our model calculations and comparisons; neither of which will exactly mimic the Robinson formulae.**
   - **While we agree that all these comparisons would be informative, the particular point we are making in this manuscript is that, all else held equal, using an unaccelerated spectrum puts too much flux at too low altitudes, which can have a significant effect on lower-ionosphere current-closure interpretations.**
   - **Please do note that we do not in fact match the average energies between spectra, which was not conveyed properly in-text."**
   - **L329: <u>Added</u> "The energy spread, with Ua > Ts, is sqrt(<(E-Ua)^2>)=Ts*sqrt((6+2Ua/Ts)/(1+Ua/Ts))."**

Minor Comments

1. *L213, 223, 224: Please explain the 32 km (camera inverted precipitation, TII flow) and 16 km (FAC). The 1 Hz FAC data implies a spatial resolution of ~8 km, is this doubled because of Nyquist? I understand the reason to have the same resolution for E and \Sigma, but I do not fully get why the differential relation results in double size as compared to FAC (or perhaps the double size has a different motivation?). The qualitative comments at L228-235 can be made more quantitative, also by comparing to (typically thinner) arc scales. Along this line, Swarm provides also high resolution (50 Hz) magnetic field data, i.e., one can look also at smaller scales (also TII 16 Hz). Not sure I understand the sentence at L233-235.*
    - **The choice of resolution and smoothing is not straightforward and ultimately driven by a desire to have the resolutions between the values of the conductances and the electric field be similar but to still allow the FAC measurements to reflect their naturally higher structure. This is ultimately an ad hoc choice and future efforts may want to consider how much these types of choices affect the results or, more broadly, needs for making these different measurements at commensurate resolutions. This, however, is a very resource intensive exercise as it requires studying how input variations impact the simulation results, e.g. through a Monte Carlo exercise. The study in this manuscript is perforce limited by the available data.**
    - **L228 – 229: <u>Changed</u>**

      > **"to account for the differential relationship between the E and SigmaP,H maps, and j|| (see Equation 1)"**

      <u>to</u>

      > **"to account for their inherently finer structure"**

2. *Section 2.5: While the replication procedure is conceptually clear, it would be nice to see it also demonstrated for one event (like February 10), including 1-s/c vs 2-s/c replication. For arc geometry, I presume that moving the conductance iso-contour boundaries a little bit up or down does not make a big difference, but it would be good to see that on paper (the more so in view of L439-441). What proxy is used for the preliminary conductance estimates (L266-267)?*
    - **To keep the paper from getting too long, details of the replication technique are given in the referenced van Irsel et al. (2024, 10.1029/2024JA032722) which covers these details in full, including the double, or weighted, replication.**
    - **L286 – 290: <u>Added</u> "For example uses of the (weighted) replication method, see Sections 2.2 and 2.3 in van Irsel et al. (2024). For use of this method with FAC data, the electrostatic enforcement (Section 2.2.3) is omitted and the FAC data is treated as one of the components of the flow data."**

- **As far as a study of the dependence on this choice, for this manuscript we made a qualitative choice of a conductance contour that was representative of the shape of the arc; this, like the choices of data smoothing above, might be a topic for a future sensitivity study.**
- **L1130 – 1132: <u>Added</u> "the investigation of the sensitivity to other simulation choices made, such as data smoothing, conductance isocontours, etc. Also, "**
- **L273 – 273: <u>Added</u> " using Equations 3 and 4 in Robinson et al. (1987)"**

3. *L360-361: Can you elaborate a bit?*
   - **L369 – 377: <u>Changed</u>**

     > **"The percentiles used in filtering are chosen by simultaneously minimizing the 95% confidence range and maximizing the adjusted R-squared value of the fits. The different choices for these percentiles raise a rough precision of around +/-10 – 20% surrounding the Ts estimations."**

     <u>to</u>

     > **"The choice of top 40th and lower 30th percentiles for the energy flux and red emissions are determined by balancing low 95% confidence ranges and high adjusted R-squared values when fitting the filtered data in Figure 3d. The percentiles investigated for Qp range from the top 10th – 90th and for the red emissions ranged from the lower 10th – 40th. In this process, we find that the Ts estimates we report have around a +/-10 – 20% precision."**

4. *L392: Please explain modified apex longitudes.*
   - **They are described in https://link.springer.com/article/10.1007/s11214-016-0275-y Section 4.1.**
   - **L413: <u>Added</u> "(Laundal & Richmond, 2017)"**
5. *Section 2.8 and Figure 4: Besides the charge density, the Eastern wall includes also projections of the current flux tubes. This is an important piece in visualizing the current closure, which doesn't seem to be indicated, neither in the text, nor in the figure caption (see also point 3 above). To avoid confusion, it would help to also label the contours (in the 3D and top boundary) and indicate, e.g., by the same letter, contours associated with the same flux tube.*
   - **Thank you for catching this!**
   - **Figure 4: <u>Added</u> " along with flux tube projections" to caption.**
   - **L434 – 435: <u>Added</u> " For select flux tubes, a projection of the entire tube is also plotted on the eastern wall."**
   - **The authors prefer to not add more labeling to avoid clutter.**
6. *Section 3: As mentioned at L175-179, the campaign provided a variety of arc events. Please include a brief comment on the criteria that guided the selection of the six events in the paper (see also point 2).*

- **L186 – 190: <u>Added</u> "The six events are chosen based on them (a) occurring during February or March of 2023, (b) including at least one Swarm crossing with imagery, (c) having an unobstructed night sky, and (d) having one or more arcs that fit the quiet discrete arc description (Karlsson et al., 2020)."**

7. *L426-427: I thought just j_\parallel is based on s/c data. Moreover, E_0 is not shown in Figure 5.*
   - **L447 – 448: <u>Changed</u> "shows the top-boundary" <u>to</u> "shows selected top-boundary"**
   - **L449 – 450: <u>Changed</u>**

     "FAC maps, j||, replicated from the Swarm data."

     <u>to</u>

     "replicated FAC maps, j||."

8. *L454, 462, 481, 493: The Harang discontinuity / Harang region is associated with the overlap, in the same local time area, of the eastern and western electrojet (dusk and dawn cell), at lower and higher latitudes, respectively. To the extent of cells' visibility, Figure 6 does not seem to indicate overlaps. I think that two-cell split (L472) is a better term. (See also point 3)*
   - **L477: <u>Changed</u> "Harang discontinuity" <u>to</u> "two-cell split"**
   - **L485: <u>Changed</u> "Harang discontinuity" <u>to</u> "two-cell split"**
   - **L504 – 505: <u>Changed</u> "Harang region sits" <u>to</u> "two-cell split sitting"**
   - **L517: <u>Changed</u> "Harang discontinuity" <u>to</u> "two-cell split"**
9. *Figure 6: Would be good to show also the Swarm footpoint(s).*
   - **Unfortunately, aside from the purple box, these plots are generated online (https://superdarn.ca/pydarn) and then cropped. Plotting the exact Swarm ephemeris would be nice, but we prefer not to change these SuperDARN approved plot formats any further.**
10. *Table I: Ap is planetary and daily, not very relevant in the context. Replace with ap (3-hour)? And add AE? (see also point 2) What is the meaning of (a), after F10.7, and of the respective numbers in brackets?*
    - **The values f107a, f107, and Ap are directly input into the gemini simulation configurations to be passed through to MSIS (see https://github.com/gemini3d/gemini3d/blob/main/docs/Readme_input.md and https://ccmc.gsfc.nasa.gov/models/NRLMSIS~00/#inputs). They might be less descriptive of the events, but they are most descriptive of the simulations themselves.**
    - **The f107a is the 81-day f10.7 average centered around the event dates.**
    - **Table 1: <u>Added</u> "[d]F10.7a is the 81-day F10.7 average centered around the event dates."**
11. *L477: In view of L362-363, the 60 eV is within the error margin.*

- **L500 – 501: <u>Added</u> "(this change is within the +/-10 – 20% precision of estimated Ts values)"**

12. *L495-496: Unalignment looks limited. The along-arc structure is there, but just by eyeballing Figure 5, it doesn't seem to be more prominent than for the other five events.*
    - **The span of the events are not constant (see Table 1, "Region"). From tip to tip of the primary boundaries, the slopes are 11.3, 7.2, 4.3, 4.2, 2.7, and 21.8% respectively for the rows of Figure 5.**
13. *L556: 'relatively weak' => This looks like very weak / extremely weak, I guess essentially zero within the error margin.*
    - **L582: <u>Removed</u> "relatively"**
    - **L583: <u>Changed</u> "infective" <u>to</u> "ineffective"**
14. *Joule heating panels of Figures 8,In 9, 11, 12, 13, 15, 16: It would be nice to indicate also the total power, integrated over the surface. The same for the Figure S1-S4 under Supporting info.*
    - **The areas of the different simulations range from 27,720 km^2 to 125,712 km^2, which is why we prefer to show the Joule heating per unit area.**
15. *Figure 9c: The northern, upward leg of the red flux tube is not visible, apparently hidden behind the orange tube.*
    - **This red tube is more visible in Figure S14 in the Supporting Information.**
    - **L569 – 571: <u>Added</u> "For a more complete 3-D visualization of current closure, the Supporting Information also contains isometric views, along with the side and top views, for all simulations."**
16. *L684-686: Figure 9a-b confirms the non-involvement in the FAC closure. On the other hand, the orange flux tube follows the convection lines and consists of eastward Hall current just for a while, then it turns north-eastward and changes to mainly Pedersen current, at the same time with an increase in altitude, visible also in Figure 10. This mix looks interesting too. (I hope my reading of Figures 9a-b and 10 is correct – see also points 4 and 5).*
    - **This is a great thing to note and we thank the reviewer for the suggestion.**
    - **L713 – 714: <u>Changed</u>**

      "is much less involved"

      <u>to</u>

      "has negligible involvement"

    - **L714 – 715: <u>Added</u> " This electrojet current does, however, connect with Pedersen currents as shown in Figures 9a – b and 10."**
17. *L752: Please expand a bit on the hidden assumptions. Is this about (implicit) prevalence of polarization?*
    - **All that is meant by "hidden assumptions" is what's shown by Equations 2 and 3; Ebar = 0 implies j|| = delta j||**
    - **L790: <u>Added</u> "(see Equations 2 - 3)"**
18. *L858: I think 'despite' is not the right word, perhaps 'besides'?*

- **"despite" is what is meant here, but the sentence is long and confusing.**
- **L893: <u>Changed</u> ", hence, " <u>to</u> ". This is why,"**

19. *L896-898: This sentence is a bit difficult. I guess what you mean is that, even if $j_{||}$ has some artefacts, this will not damage the relative weight of the polarization, Pedersen, and Hall terms. I also guess that the sentence provides also a bit of an a priori conclusion of the forthcoming simulations.*
    - **What was meant by this sentence is that Equation 1 does not directly include a gradient term, hence the source of error is entirely encapsulated by the assumptions of the replication technique alone.**
    - **L942 – 945: <u>Changed</u>**

      > **"such gradients have less physical implication on the system as a whole"**

      <u>to</u>

      > **"these gradients do not directly enter into Equation 1. I.e. the source of error these gradients introduce are the same as those introduced by the replication technique"**

20. *L960-961: I am a bit skeptical about this sentence too, feels somewhat tautologic.*
    - **The last part of that sentence was indeed redundant.**
    - **L1007: <u>Removed</u> ", up to the differences in auroral arc simulations seen here"**
21. *Discussions & Conclusions: Some adjustments might be needed, depending on the response to points 1–5.*
    - **Here is a summary of our changes to Section 5:**
    - **L1022 – 1025: <u>Changed</u>**

      > **"(1) the along-arc structure in FAC and the arc-boundary replication technique, (2) the constant background flow, and (3) the specifics of electron precipitation.**

      <u>to</u>

      > **"(1) the constant background flow, (2) the specifics of electron precipitation, and (3) the along-arc structure in FAC and the arc-boundary replication technique."**

    - **L1042 – 1044: <u>Added</u> " Along-arc variations below this scale size may well exist, but these are beyond the scope of this work given that we are limited by the 50 km Swarm spacecraft separation."**
    - **L1076 – 1080: <u>Added</u> "The availability of multi-spectral, rather than white-light, all-sky imagery allows the community to move away from the assumption of unaccelerated Maxwellian precipitation spectra, and toward**

energy distributions which decouple the energy spread from the peak energy, allowing for more flexibility in modeling electron precipitation."

- **L1092 – 1093: Changed**

    "flow data"

  to

    "data such as those from the Electrojet Zeeman Imaging Explorer mission "

- **L1105 – 1106: Added " (except for perhaps Simulation IIIb)"**
- **L1119: Added ", though still there,"**
- **L1131 – 1132: Added "the investigation of the sensitivity to other simulation choices made, such as data smoothing, conductance isocontours, etc. Also, "**

22. *L976: Move (1) to the end, aligned with Sections 4.1, 4.2, 4.3 (?)*
    - **Done.**
23. *L995: The distance of 50 km is related to the Swarm separation and therefore arbitrary.*
    - **It is arbitrary, yes, but it's the only number we have information about to comment on.**
    - **L1042 – 1044: Added " Along-arc variations below this scale size may well exist, but these are beyond the scope of this work given that we are limited by the 50 km Swarm spacecraft separation."**
24. *L1049-1050: To some extent I agree that polarization is mostly a minor player for the events selected, as pointed out under point 3. However, Event 3 looks like an exception, see point 5.*
    - **L1105 – 1106: Added " (except for perhaps Simulation IIIb)"**
25. *L1063: Once again, Event 3 seems to show that the masking is there (in the Pedersen closure of primary FAC, Figure 9 a-b), but not complete (the strong ionospheric loop of secondary Pedersen and Hall current, Figure 14 i-k).*
    - **L1119: Added ", though still there,"**
26. *L1076: Like ~100 m, i.e., thin arcs (Maggs and Davis, 1968, https://doi.org/10.1016/0032-0633(68)90069-X) ?*
    - **If the imagery resolution allows for such scales, yes.**
27. *L1134: I could not open the link https://rcweb.dartmouth.edu/lynchk.*
    - **Fixed.**

Typos, Grammar, and Spelling

1. *L32, 51, 1042: 17 simulations or 18, as in the Supporting info?*
    - **There are 17 simulations. Figures S5 and S8 are the same simulation with 2 different tube sets.**
2. *L69: surroundING (?)*
    - **Done.**

3. *L87: In THE case (?)*
    - **Done.**
4. *L137: from => on*
    - **Done.**
5. *L137: studied (?)*
    - **Done.**
6. *L140: define DASC*
    - **Done.**
7. *L149: ON different*
    - **Done.**
8. *L172: this paper => the main body of the paper (?)*
    - **Done.**
9. *L199, 200, 203: Grubs II, Michell, Samara,… => Grubs II et al., 2018a, b*
    - **This is a “agujournal2019.cls” error. It should be fixed in the published version.**
10. *L1225: 2018a*
    - **See item 9.**
11. *L1228: 2018b*
    - **See item 9.**
12. *L210, 247, 256, 385, 521: Move the hyperlinks to the References*
    - **Done.**
13. *L258: was => were*
    - **Done.**
14. *L304: Delete M. D.*
    - **This is also a “agujournal2019.cls” error. It should be fixed in the published version.**
15. *L318: Appendix Appendix*
    - **Done.**
16. *Caption of Figure 4: an example February 10 => a February 10*
    - **Done.**
17. *L439-440: determines => controls (?)*
    - **Done.**
18. *L515: are simulated for => a duration of*
    - **Done.**
19. *L554: >0.1 kA => <0.1 kA (?)*
    - **Done.**
20. *L554: exists => exits*
    - **Done.**
21. *L641: >0.1 kA => <0.1 kA*
    - **Done.**
22. *L805: Comparison (singular)*
    - **Done.**
23. *L846: peakS*
    - **<u>Changed</u> “band” <u>to</u> “bands”**

Reviewer #2

Evaluations

Recommendation (Required): Return to author for major revisions
Significant: Yes, the paper is a significant contribution and worthy of prompt publication.
Supported: Yes
Referencing: Yes
Quality: Yes, it is well-written, logically organized, and the figures and tables are appropriate.
Data: Yes
Accurate Key Points: Yes

Summary

This manuscript investigates the current closure path and Joule heating effect in a discrete auroral arc system through 3D data-driven simulation, with a focus on the influence of background on the convective electric field, electron settling energy spectrum, and current structure along the arc field (FAC). This study systematically quantifies the independent effects of background electric field and electronic energy spectrum on the closure of auroral currents, filling the gap in 2D models that ignore the height dimension. The data-driven approach (Swarm+DASC+radar) and the rigorous design of 17 control experiments provide a new tool for MIT coupling research.

We thank the reviewer for their helpful questions. We have addressed them with careful consideration, hopefully to the satisfaction of the reviewer.

This manuscript is suitable for publication in this journal. However, the reviewer has the following questions that they would like to discuss with the author:

Major Comments

1. *Ts estimation: Why choose to filter out the "top 40% Qp+and bottom 30% red green ratio" for determining the characteristic energy (Ts) of the electron source region? What is its physical explanation? Will this threshold cause system bias? Are the filtering criteria universal (applicable to other events)?*
    - **We looked at 10 – 90% for Qp and 10 – 40% for the red light. These values provided reasonable goodness-of-fit.**
    - **L369 – 377: <u>Changed</u>**

        > **“The percentiles used in filtering are chosen by simultaneously minimizing the 95% confidence range and maximizing the adjusted R-squared value of the fits. The different choices for these**

percentiles raise a rough precision of around +/-10 – 20% surrounding the Ts estimations."

<u>to</u>

"The choice of top 40th and lower 30th percentiles for the energy flux and red emissions are determined by balancing low 95% confidence ranges and high adjusted R-squared values when fitting the filtered data in Figure 3d. The percentiles investigated for Qp range from the top 10th – 90th and for the red emissions ranged from the lower 10th – 40th. In this process, we find that the Ts estimates we report have around a +/-10 – 20% precision."

2. *In section 2.2, it was mentioned that a smooth window (32 km) may suppress small-scale structures. Have sensitivity tests been conducted on parameters of different smooth scales?*
    - **Such sensitivity studies have not yet been conducted.**
    - **The choice of resolution and smoothing is not straightforward and ultimately driven by a desire to have the resolutions between the values of the conductances and the electric field be similar but to still allow the FAC measurements to reflect their naturally higher structure. This is ultimately an ad hoc choice and future efforts may want to consider how much these types of choices affect the results or, more broadly, needs for making these different measurements at commensurate resolutions. This, however, is a very resource intensive exercise as it requires studying how input variations impact the simulation results, e.g. through a Monte Carlo exercise. The study in this manuscript is perforce limited by the available data.**
    - **L228 – 229: <u>Changed</u>**

"to account for the differential relationship between the E and SigmaP,H maps, and j|| (see Equation 1)"

<u>to</u>

"to account for their inherently finer structure"

3. *Uncertainty of background electric field: In event V, there is a significant difference in flow velocity between PFISR and SuperDARN. How to determine a reasonable and effective background electric field?*
    - **We do not address which of these two options is more correct. The point of this work is to illustrate the effects of choosing different data drivers, such as different observations of the background electric field, on the resulting simulations of current closure in auroral arc systems.**