Current Continuity in Auroral System Science: Data-Driven Auroral GEMINI Simulations

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Background

- Local auroral coupling of the ionosphere and magnetosphere (MI) is the subject of an ongoing sequence of system science studies (Wolf, 1975; Cowley, 2000; Khazanov et al., 2018; Lynch et al., 2022).
- MI coupling studies demand self-consistent, topside maps of field-aligned current (FAC) and $\mathbf{E}\times\mathbf{B}$ plasma flow that agree with ionospheric conductivity patterns created by charged particle, auroral precipitation.
- Discrete auroral precipitation provided by the auroral acceleration region creates arc-scale morphology in the ionospheric conductivity volume to which the MI coupling is highly sensitive.
- Quasi-static ionospheric plasma flow, FAC, and conductivity have a 2D topside relation given by Eq. 6.12 in Kelley (2009):

$$j_\parallel(x,y) = \Sigma_P \nabla\cdot\mathbf{E} + \mathbf{E}\cdot\nabla\Sigma_P + (\mathbf{E}\times\mathbf{b})\cdot\nabla\Sigma_H \quad (1)$$

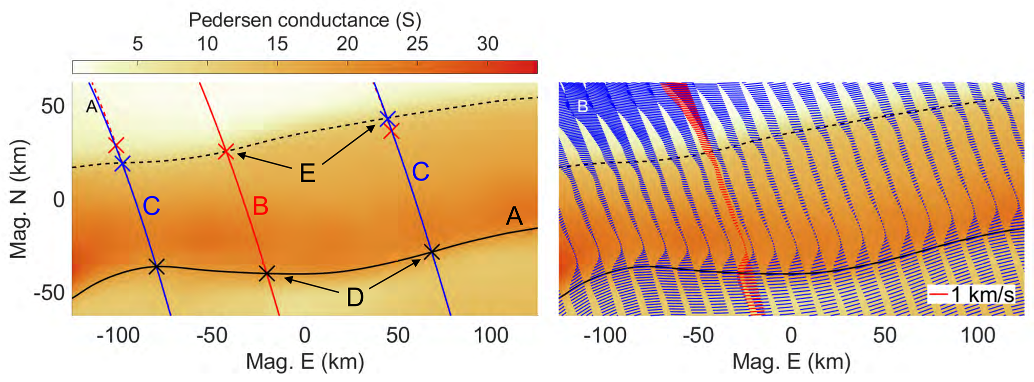
  where $j_\parallel$ is a horizontal map of FAC at the topside ionosphere, Σ_P and Σ_H being the height-integrated Pedersen and Hall conductivities, and $\mathbf{E}$ is the perpendicular ionospheric electric field.
- For sheet-like arcs (arcs that are latitudinally narrow, longitudinally aligned, with no along-arc gradients) finding self-consistent solutions to this is relatively well-posed (Marghitu, 2012).
- This 2D picture can hide the 3D nature of auroral current closure.
- Due to limitations of auroral system experiments in 3D, or even 2D, 3D data driven auroral simulations are rare.

Problem Statement

- How can we find **physical**, **self-consistent** solutions to the ionospheric **current continuity** equation using 3D modelling for less idealized discrete auroral arc systems?
- How can 3D simulations be properly driven using 2D electrostatic, **continuous topside boundary conditions** from **distributed data** provided by all-sky, multi-spectral imagery and in situ data from spacecraft?
- What can we learn from 3D, electrostatic, auroral ionospheric simulations?

Plasma Flow Data Replication Technique

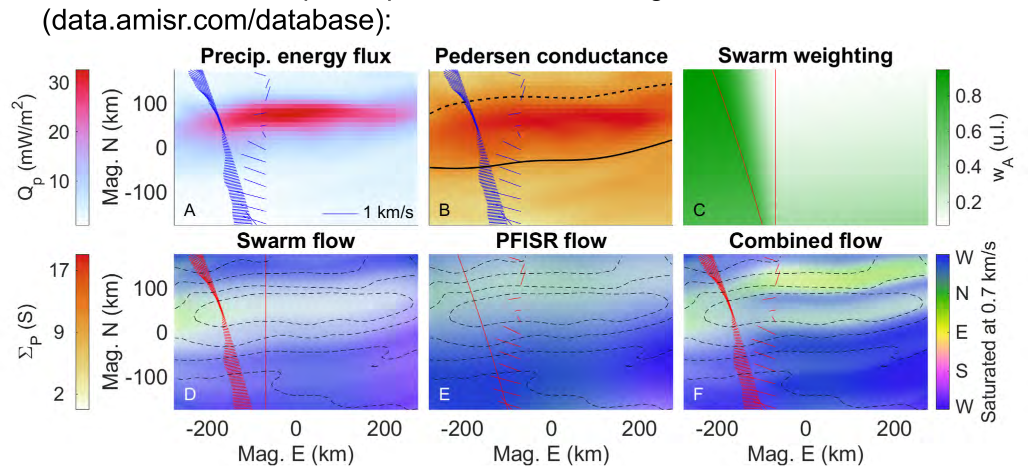
- We present auroral arc case studies using ion flow data from ESA's Swarm spacecraft's TII (Knudsen et al., 2017) in conjunction with multi-spectral, all-sky imagery from the UAF GI's Poker Flat DASC (Conde et al., 2001).
- These data are molded into topside plasma flow maps used to drive 3D auroral simulations provided by GEMINI.
- To create spatially continuous 2D flow driver maps we use the *replication* method based on Clayton et al. (2019, 2021), and outlined by van Irsel et al. (in prep., see github.com/317Lab/aurora_gemini), summarized below:



1. The flow data are translated in the east-north plane following the primary arc boundary (A) such that the original (B) and replicated (C) flow data are equal at the primary boundary-trajectory intersections (D).
2. The data then are along-track scaled such that the original and replicated flow data are equal at the secondary boundary-track intersections (E).
3. The flow data of the replicated track is rotated by a constant angle per data track such that it remains to be tangent to the primary arc boundary.
4. This replication is repeated for multiple translations along the arc until the top-boundary is filled with a sufficient replication rate.

Plasma Flow Replication Example

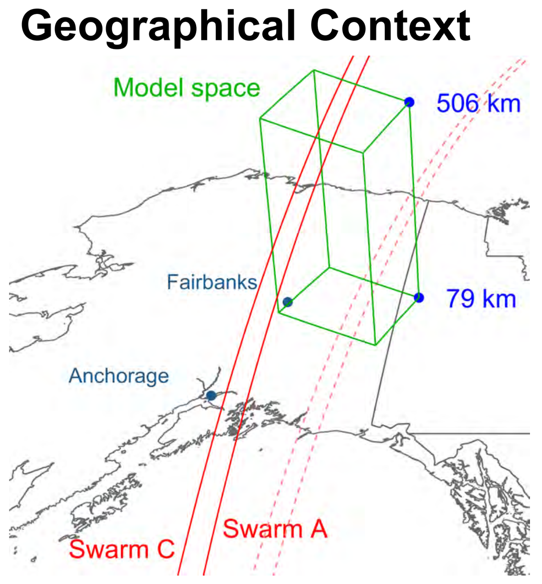
- Below is an example replication done using Swarm and PFISR data (data.amisr.com/database):



The GEMINI Model

- We use multi-fluid model runs provided by GEMINI (Zettergren & Semeter, 2012; Zettergren & Snively, 2019). For details see github.com/gemini3d.
- This model is state-of-the-art and can simulate the ionosphere at auroral arc scales (see Figure 1 for context).
- GEMINI solves for static current continuity to account for changes in model parameters impacting conductivities as it steps forward in time.
- It is driven with top-boundary precipitation maps of energy flux and characteristic energy covering impact ionization (Fang et al., 2008).
- Additionally, the model is forced at the top-boundary with either a map of FAC or plasma flow. The simulations done in this work are all flow driven.

Geographical Context



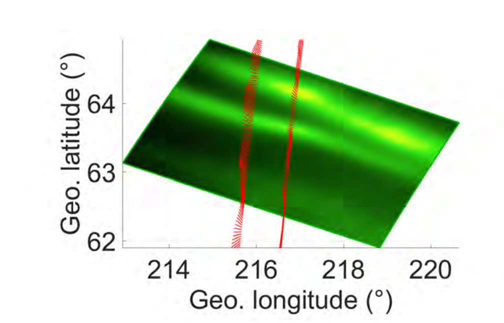
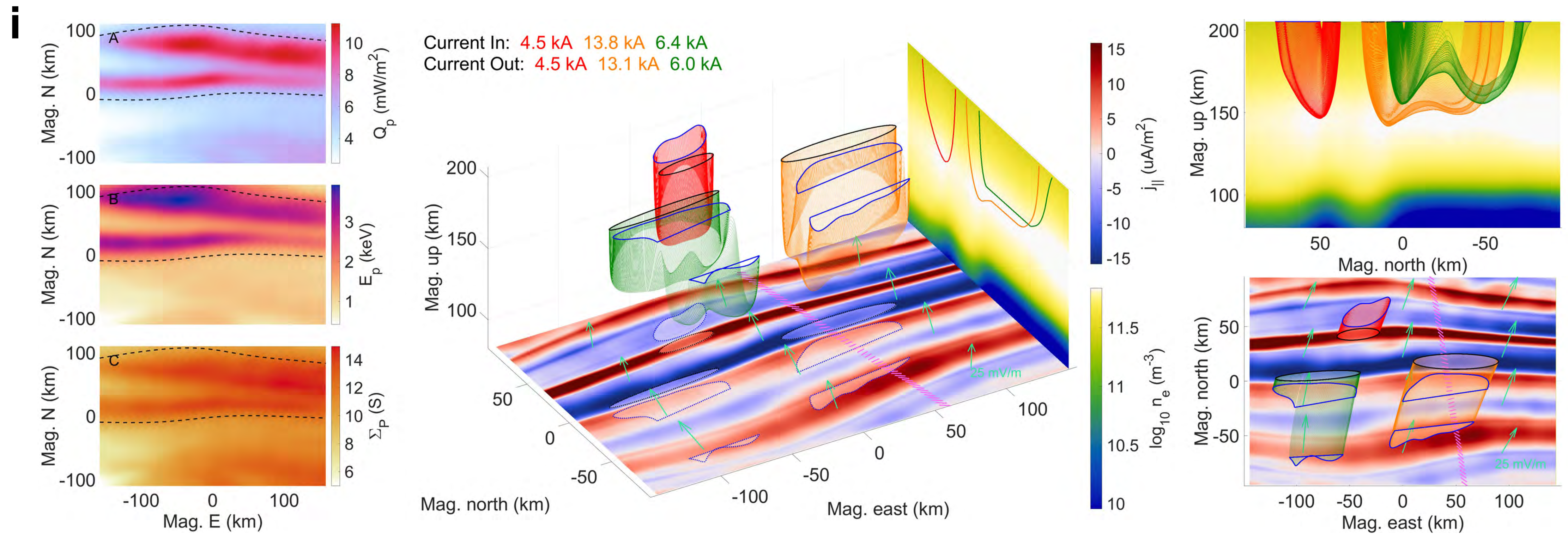


***Figure 1**: Geographical context for the Feb. 10, 2023 event. **Left**: The GEMINI model space in reference to Alaska and Swarm spacecraft. Dashed red lines are ground projected trajectories. **Above**: The total precipitating electron energy flux in reference to the TII plasma flow data.*

i



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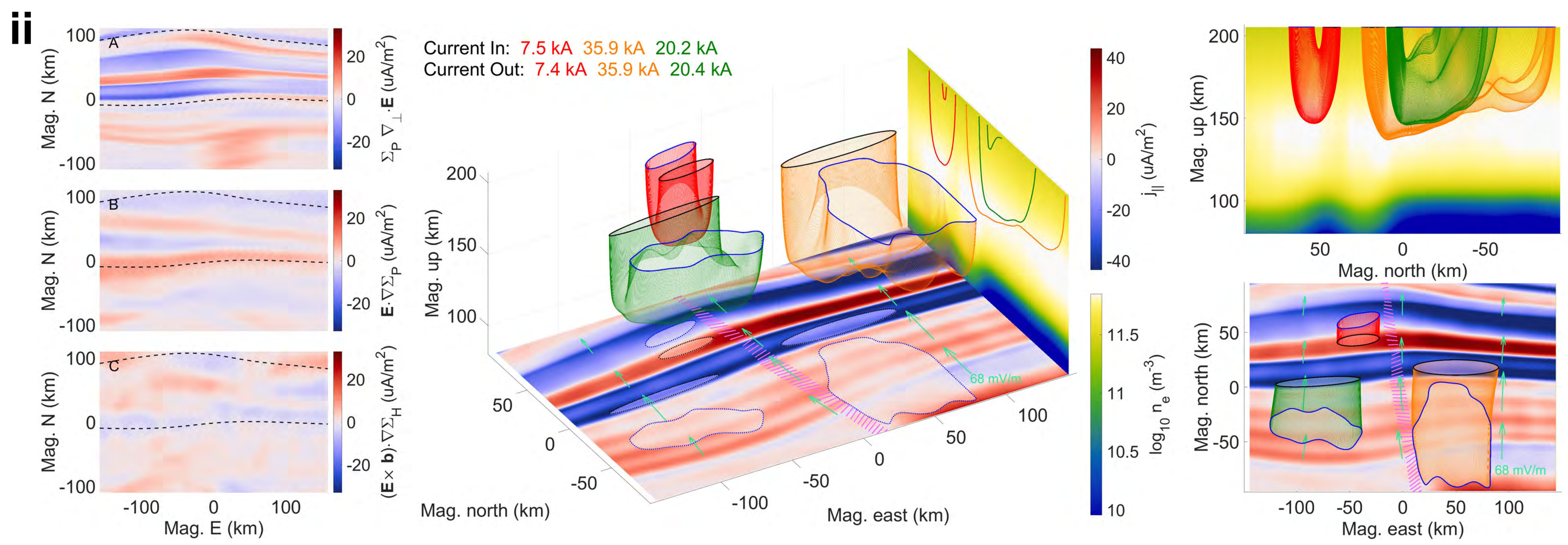

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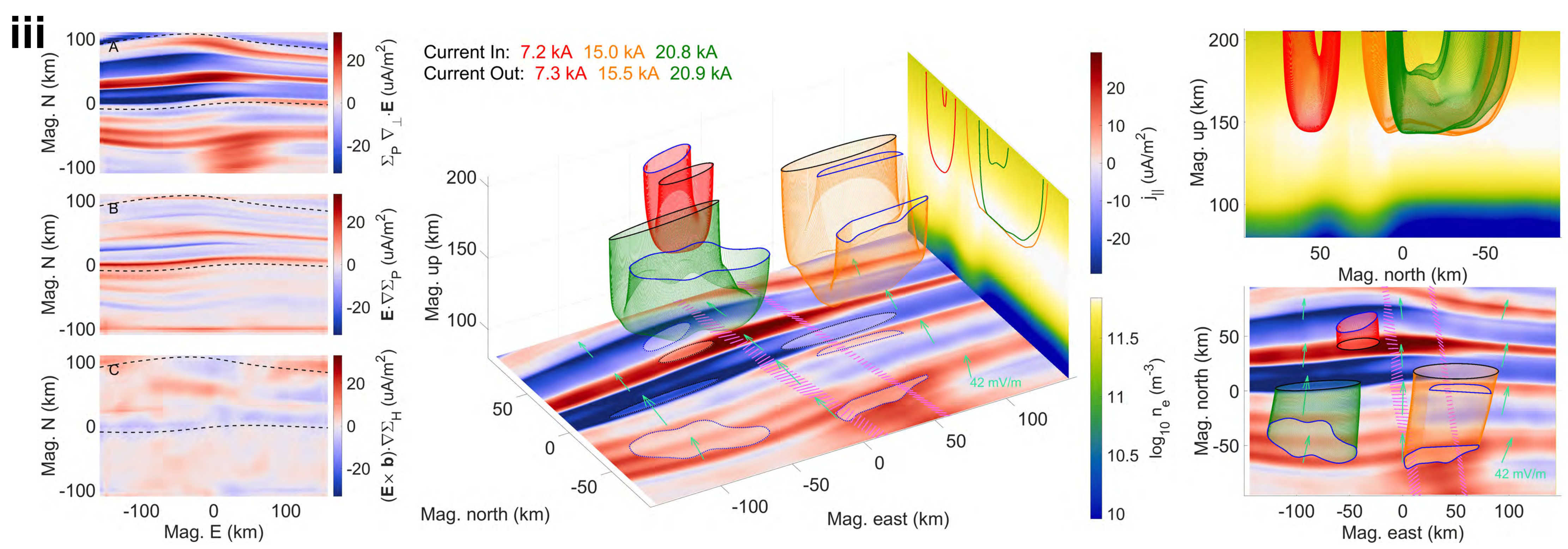

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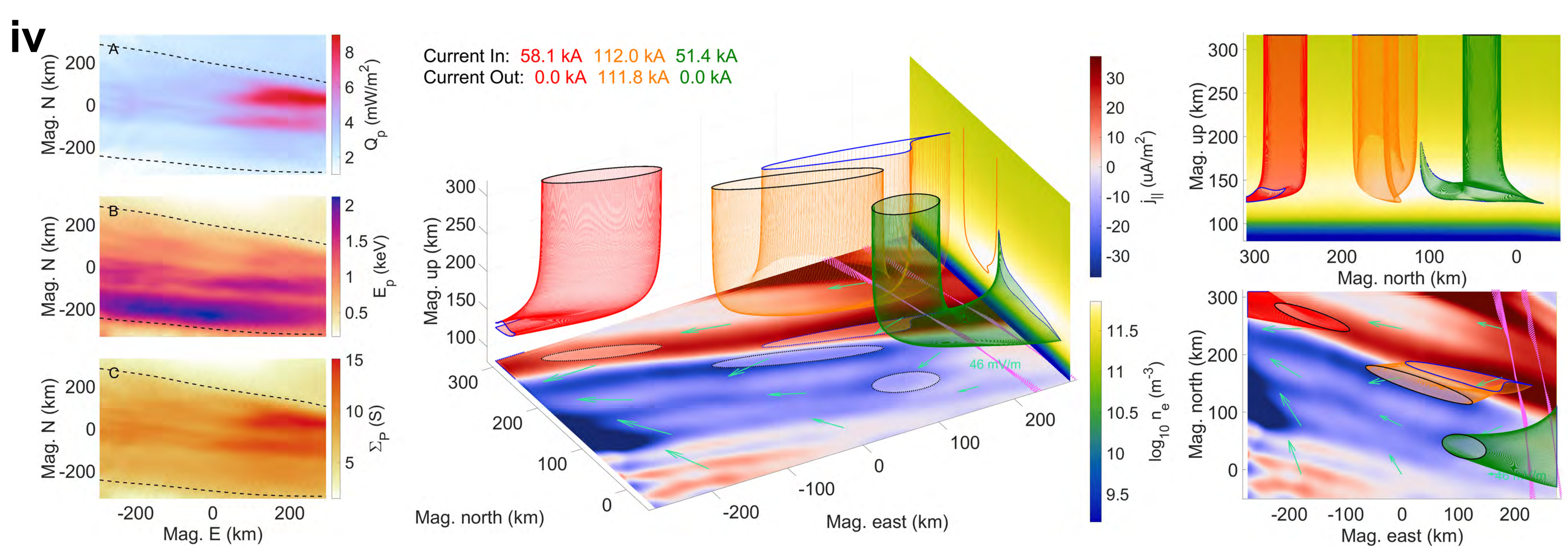
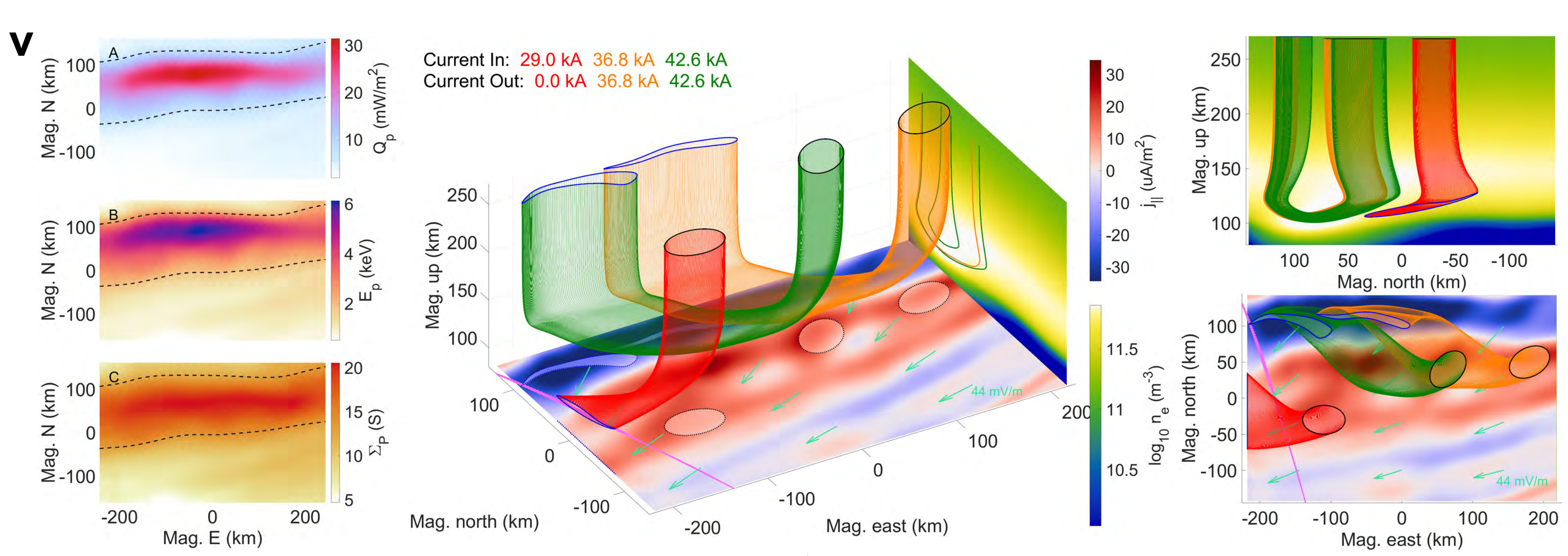


v



3D Simulation Results

- The center column presents five simulations:
  - i. **Feb. 10, 2023**: Conjunction with Swarm A only.
  - ii. **Feb. 10, 2023**: Conjunction with Swarm C only.
  - iii. **Feb. 10, 2023**: Conjunction with Swarm A and C.
  - iv. **Mar. 14, 2023**: Conjunction with Swarm B.
  - v. **Mar. 19, 2023**: Conjunction with Swarm A and C.
- The left of rows **i**, **iv**, and **v** show their respective precipitation drivers along with the arc boundaries superimposed on the Pedersen conductance.
- The left of row **ii** shows the FAC terms from Eq. (1) for simulation **iii** derived from the input electric field and the imagery inverted conductances.
- The left of row **iii** shows the same as the left of row **ii** but with GEMINI calculated conductances used instead.
- The center and right of all rows show the isometric, side, and top views of the 3D simulation result.
- To visualize 3D current closure, we use current flux tubes made possible by the condition of static current continuity, ∇·**j**=0, enforced by GEMINI.
- The bottom and east wall of the model space plot the topside FAC and the central electron density cuts, respectively.
- The magenta arrows shows the Swarm ion flow data projected to 80 km.
- The aquamarine arrows provide a sparse array of electric field vectors.
- For more information of the all-sky imagery inversions, see Poster MITC-9 by A. Mule.

Discussions & Conclusions

- Deriving FAC using all-sky imagery inverted conductance maps is insufficient when determining both magnitude and morphology of auroral currents.
- Even for the most basic auroral systems, a 2D description hides the 3D nature of current closure.
- Two plasma flow data tracks crossing seemingly sheet-like auroral arcs can unveil significant along-arc structure.
- Current flux tubes close to inflection lines of up-down FAC sheet pairs can close through Pedersen current at altitudes well above where Pedersen conductivity maximizes.
- Current flux tubes surrounding auroral arcs can split; a region of FAC inside one downward current sheet can close in two upward current sheets.
- Strong along-arc electric fields extend FAC Pedersen closure along this same direction resulting in closure at lower altitudes altogether.

Scan for videos of current flux tubes and more!

Hiring?

I am graduating in the coming year and I am starting to look for future career opportunities. If you, or someone you know, is hiring please let me know! For my online resume please visit www.julesvanirsel.com.

Unionization

The work presented here does not exist without the graduate student population at Dartmouth College. The graduate workers of Dartmouth, under GOLD-UE, are currently on strike fighting for protections for our community. We fight for the college to remove systematic barriers preventing people from pursuing graduate school, as well as hindering the work done by current graduate students. We have fought for retaliation policy,ded care, childcare, short term disability, a living wage, and more. I am happy to discuss the graduate student union further!

Please, donate to our strike fund! (I didn't get paid this month...)

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