Analysis and modeling of ion-neutral coupling in small-scale auroral structures within the ionosphere

Hayley Clevenger[1], Matthew Zettergren[1], Leslie Lamarche[2], Marilia Samara[3], Kristina Lynch[4]

Embry Riddle Aeronautical University[1], AMISR[2], NASA Heliophysics[3], Dartmouth University[4]

ABSTRACT:

Local-scale models of the auroral ionosphere rely on input specifications for electromagnetic, energetic charged particles and neutral-dynamical quantities in order to accurately represent plasma behavior. In this study we use the GEMINI ionospheric modeling suite to investigate ion-neutral coupling in small-scale auroral structures, focusing on a two-month period with the SWARM satellite conjunctions near the Poker Flat Incoherent Scatter Radar system (PFISR) and co-located optical measurements with the all-sky camera (DASC) and scanning doppler imager (SDI). The study leverages a nightly conjunction of the Swarm A and C satellites (and occasionally B as well) coordinated with ground-based data, of which there are a handful of distinct auroral events (mid-February to late March 2023). Data sets such as these are near-ideal for constructing inputs for the model to simulate the measured active aurora from each respective night. These inputs include the electric field, ion temperature, neutral particle temperature, flux, intensity, electron density, and drift velocity. New scripts within the GEMINI suite are developed to allow for processing of conjunction data inputs (or data from similar experiments) to enable data interpolation, data smoothing, model grid definition, file configuration and processing, and data output for user analysis. Alongside these tools, we run a number of GEMINI auroral simulations to look at momentum and energy transfer into the neutral atmosphere. Analyzing a data set of this nature will help us to further understand the dynamics of the small-scale aurora with the ion-neutral winds and how they can be better incorporated into modeling for inclusivity of variability in factors such as ionospheric density and temperature structure, instabilities of the ionospheric plasma, and the overall behavior of the ionosphere.

METHODS :

- Using the GEMINI suite alongside a set of processing scripts, IDL save-sets are taken from .sav form, sent through a process of data smoothing, interpolations, and mapping to use as simulation inputs.
- Plasma parameters such as density, temperature, and velocity are derived from processed, filtered all-sky camera data in addition to incoherent scatter radar data, which will (in the future) be used as validation for electric field mapping within the simulation.
- The Nicholls and Cosgrove [1] method of monostatic, multibeam ISR measurements is used the estimate the vector electric field in conjunction with assumptions and analysis provided by [2].
- Analysis of the ISINGLASS sounding rocket mission is used to pave the way for modeling and analysis of the SWARM-Over-Poker campaign and associated data.

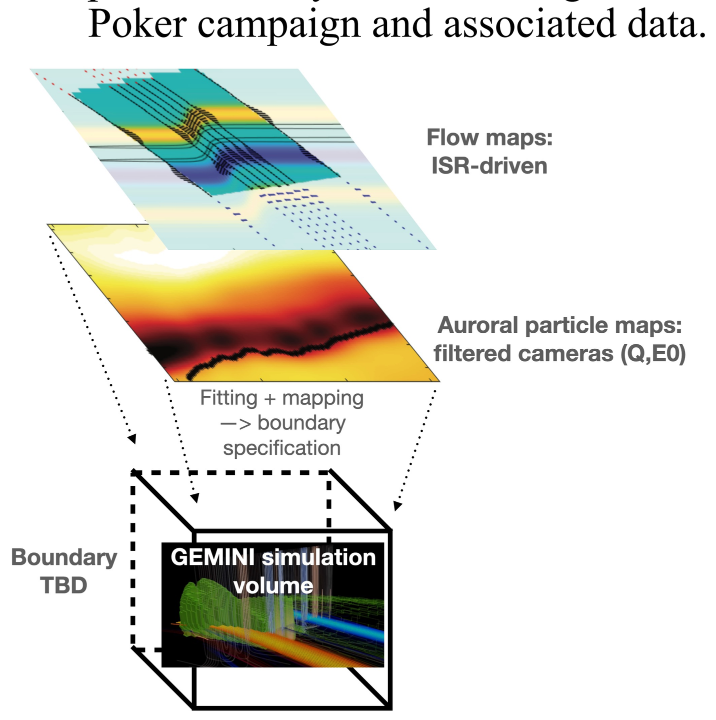

Figure 1. The GEMINI simulation volume contains solutions to the set of ionospheric equations for 3D electrodynamics of the ionosphere. Inputs to the GEMINI simulation for the purposes of this data analysis include flow maps that are to be driven by ISR data (plasma parameters, etc…), auroral particle maps from filtered all-sky cameras (which allow for us to find Q and E_0 to feed into the simulation volume after a series of fitting, mapping, and boundary specifications), and additional boundary conditions that are defined in reference to the specific data set being used as input to the simulation space.

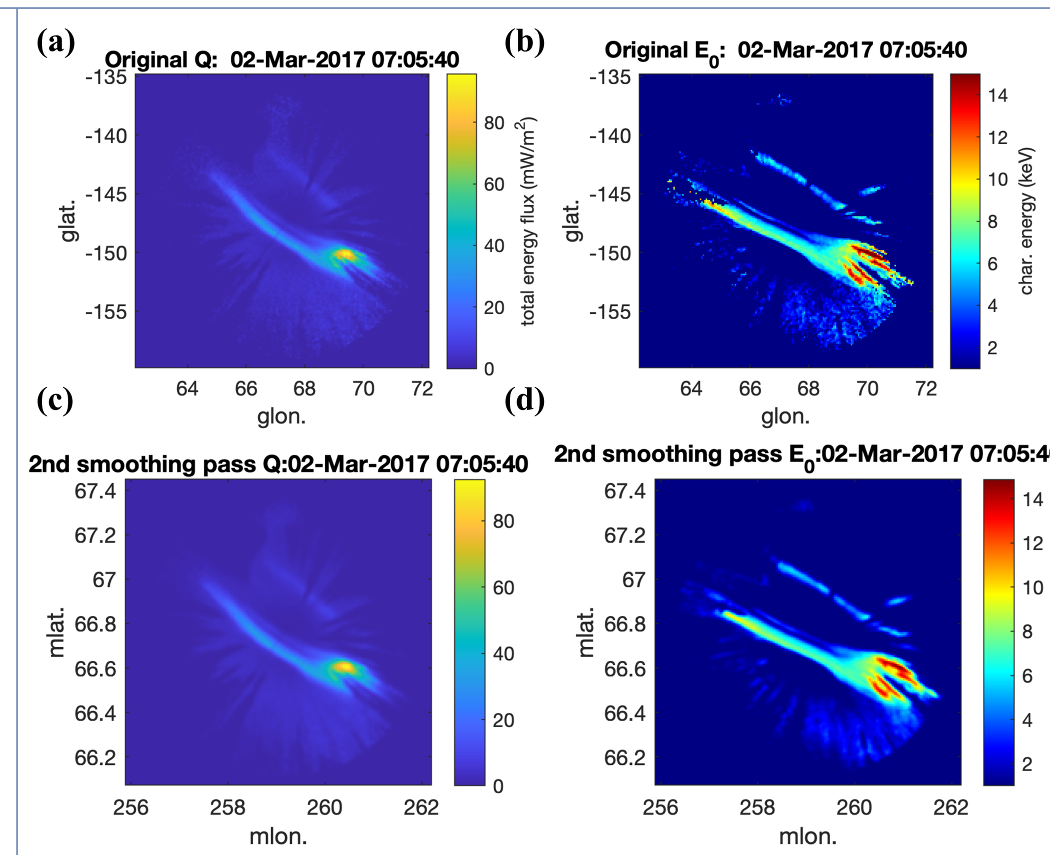

Figure 2. To the left, (a) and (b) show the original/raw data form of Q and E_0 respectively, and (c) and (d) show the versions of Q and E_0 which are used as inputs to the simulation. To translate from (a) to (c) and (b) to (d), the raw input data from the ISINGLASS mission undergoes a series of smoothing, plotting, data resampling, and mapping functions to take data in the form of IDL .sav to .h5 files that are used as inputs to the simulation.

ANALYSIS & DISCUSSION :

ISINGLASS MISSION :

- As seen in the chosen point associated with Figs 7 and 8, it can be noted that there is an eastward flow of lower to higher electron density. Here, we have an example of the dynamics of momentum and energy transfer within a single second slice of auroral data. The interactions between the higher-density plasma and the neutrals lead to this momentum/energy transfer. This correlates to the enhancements indicated in Fig 5 (a) in both E- and F-regions for the later data point, as well as with F- for the earlier data point.
- At both chosen data points, the scalar velocity component tends to increase in magnitude as altitude increases, which correlates with Fig 5 (d).

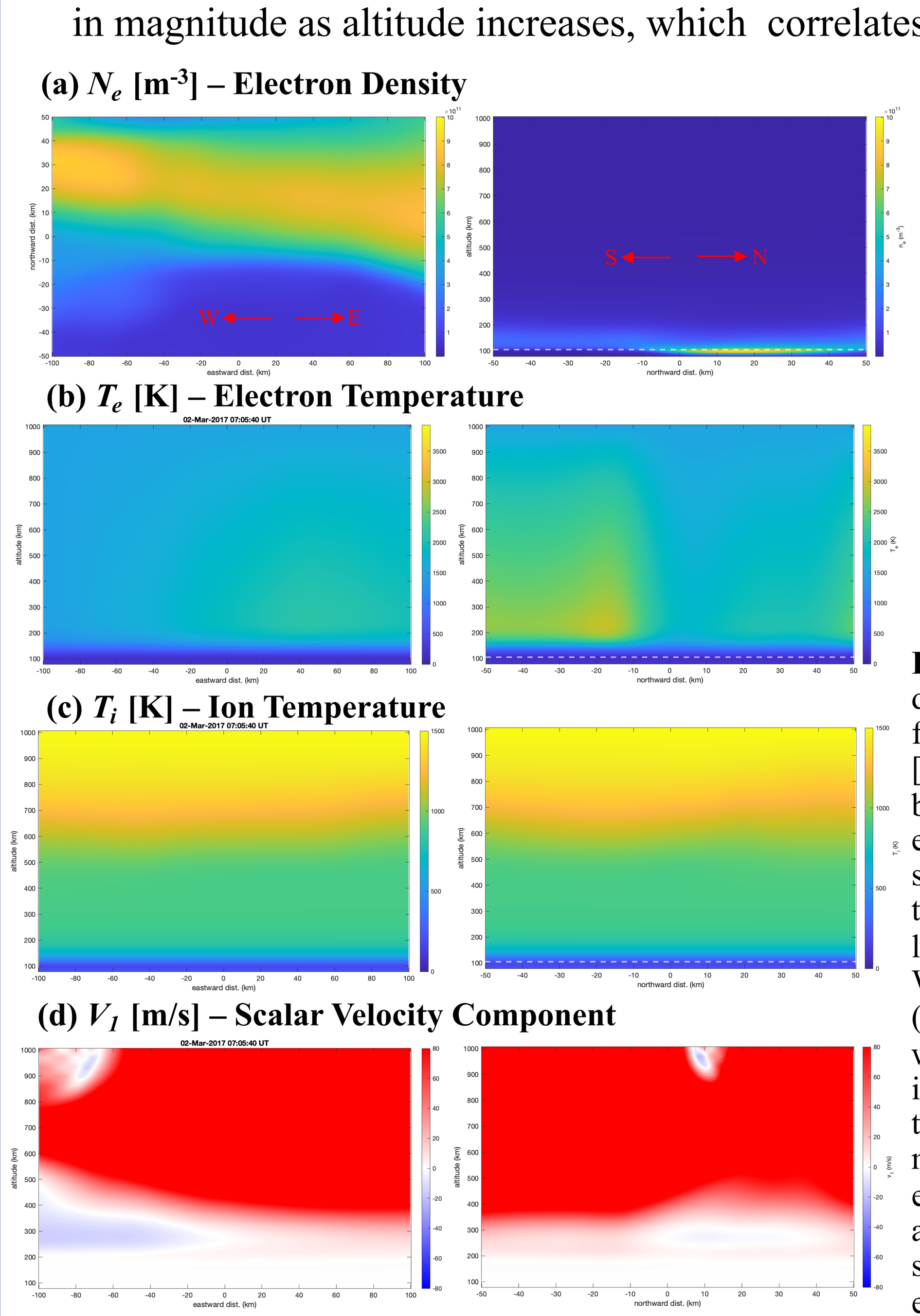

Figure 3. The above figure shows the simulation outputs for the electron density, electron and ion temperatures, and velocities of the measured auroral structure by the ISINGLASS rocket on March 2nd, 2017 at 07:05:40 UT. The auroral shape is revealed by (a), the electron density.

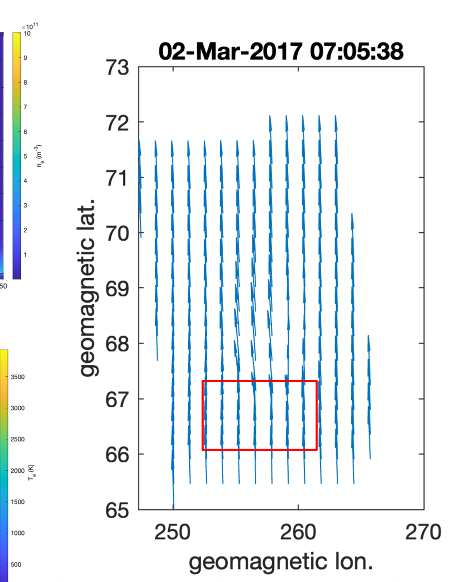

Figure 4. The above figure depicts the vector electric field, as solved for in [1] and [2]. The quivers within the red box correspond to the vector electric field in the same spatial domain represented by the geomagnetic latitudes and longitudes spanned in Fig 2. While the scalar parameters (a), (b), (c), and (d) of Fig 2 will later be used as model inputs, this figure represents the roughly estimated and model-simplified vector electric field obtained through assumptions made within the scripts used to generate this estimation.

SWARM-OVER-POKER CAMPAIGN :

- The method used in [1] is a valuable technique for estimating the vector electric field – however, this method does not easily translate to data sets that do not follow the same assumptions and simplifications that are specific to [1]. Differences in setup, instrument characteristics, and analysis/modeling techniques make it so that other methods need to be explored, especially for data sets like the ISINGLASS mission and from the data collected from the SWARM-over-Poker campaign.
- This campaign will require the utilization of ISR data measurements injected into the model as inputs to achieve accurate and reliable estimates of the vector electric field.
- With six weeks of data collection across the campaign, the model will host a variety of auroral simulations from several nights, including less-predictable events once validated with several predictable events.

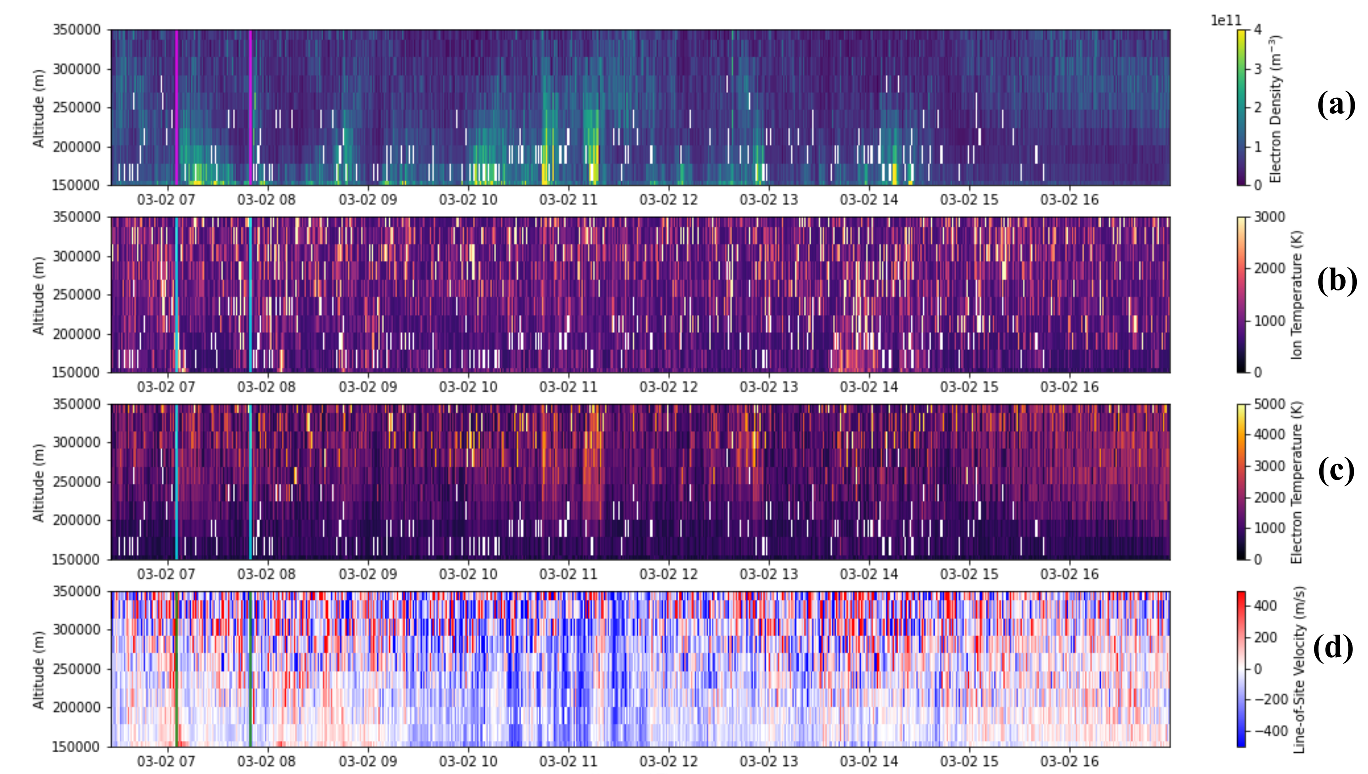

Figure 5. The above figure shows, from top to bottom, the electron density (a), ion (b) and electron (c) temperatures, and line-of-site velocity (d) as measured by the Poker Flat Incoherent Scatter Radar system (in ISINGLASS mode), on the same night as the ISINGLASS mission. The colored bars indicate (left) the Fig 2 and 3 measurements and the (right) Fig 7 and 8 measurements.

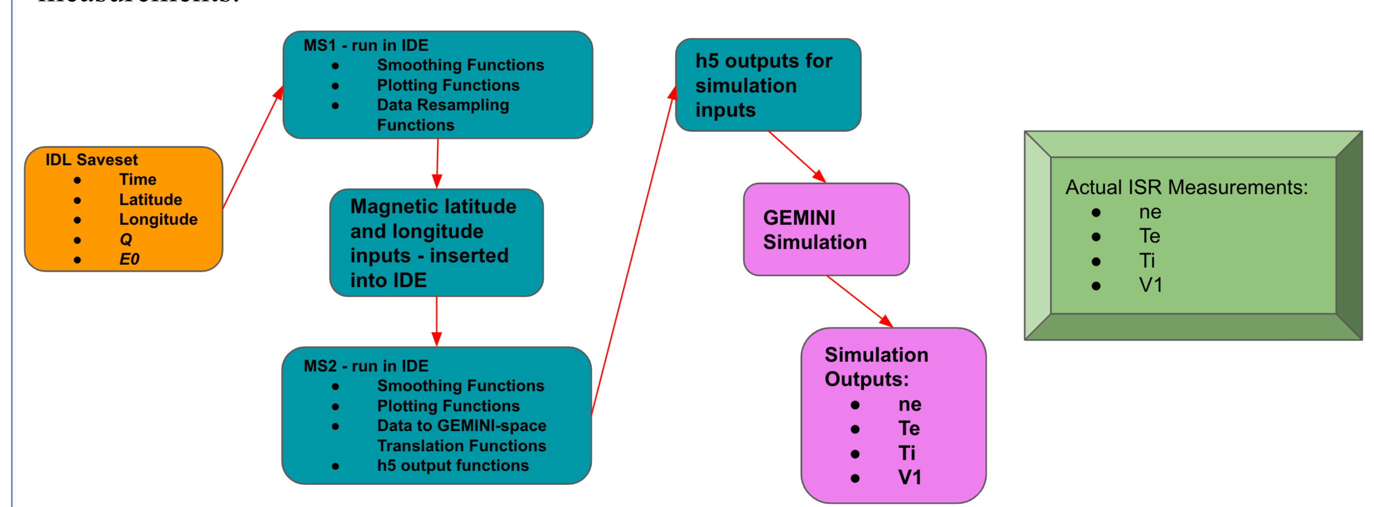

Figure 6. The above diagram shows the flow of the process of expressing the simulation data from initial IDL format to simulation outputs that can be compared to that of the actual observed and measured quantities of electron density, electron/ion temperature, and velocity taken with incoherent scatter radar. Orange artifacts indicate raw data inputs, blue artifacts indicate scripting (using newly developed scripts and functions alongside the GEMINI suite) components that all stay within the same IDE (inputs, script runs, and script outputs), pink artifacts represent simulation components that are run from the command line using the GEMINI suite, and green artifacts represent the physical measurements taken using ISR. Further development in expressing the vector electric field was used from [1] and [2].

REFERENCES:

[1] Nicolls, Michael. Cosgrove, Russel. *Estimating the vector electric field using monostatic, multibeam incoherent scatter radar measurements*

[2] Clayton, Robert. *Examining the Auroral Ionosphere in Three Dimensions Using Reconstructed 2D Maps of Auroral Data to Drive the 3D GEMINI Model*

[3] Burleigh, Meghan. Lynch, Kristina. Zettergren, Matthew. *Spatiotemporal Limitations of Data-Driven Modeling: An ISINGLASS Case Study*

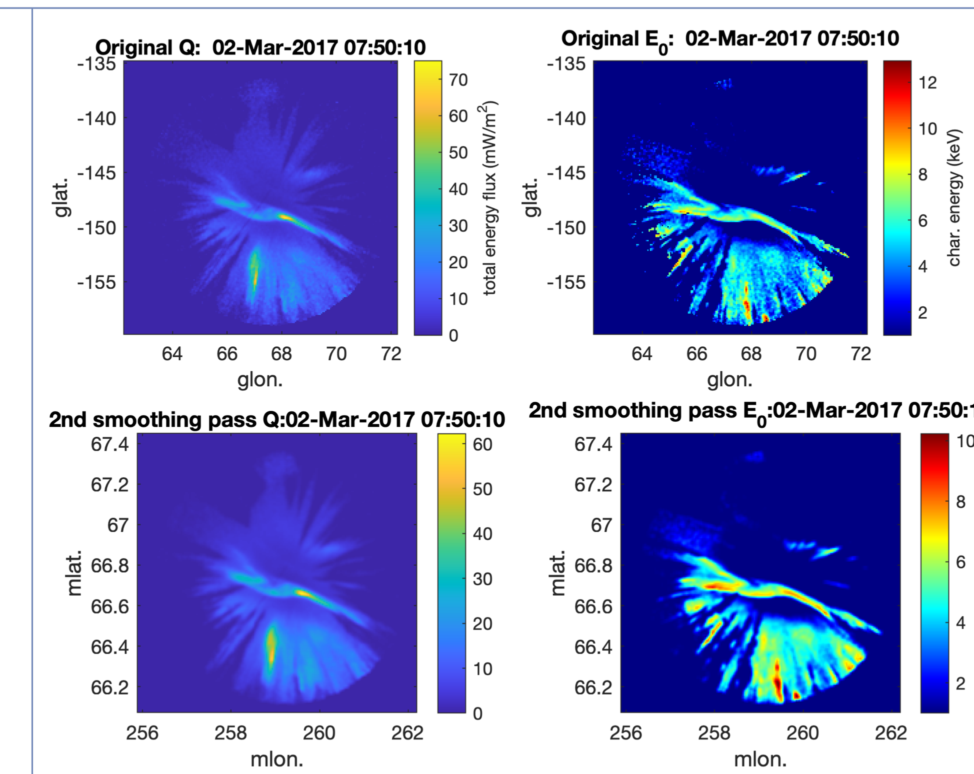

Figure 7. Similar to Fig 2, (a) and (b) show the original/raw data form of Q and E_0 respectively, and (c) and (d) show the versions of Q and E_0. While Fig 2 shows a more comparatively "stable" aurora, this set of plots displays more substorm-like activity. With nearly the entire field-of-view filled with measurable Q and E_0, removing artifacts and obscurities through smoothing such as trees, light sources, etc…from the data becomes increasingly important with higher activity storms and sub-storms.

RESULTS & CONCLUSION:

- Overall, this analysis shows the challenges of translating pre-existing methods to determine vector electric fields, and that future integration of ISR measurements as model inputs will enable us to overcome the limitations that currently exist within the model and will enhance the accuracy of the simulations as outlined in [3]. Combining this effort with the added validity of combined ground- and satellite-based data collection from the SWARM-over-Poker campaign will provide a more comprehensive and validated framework for modeling and analysis of ion-neutral coupling in small-scale auroral structures within the ionosphere.

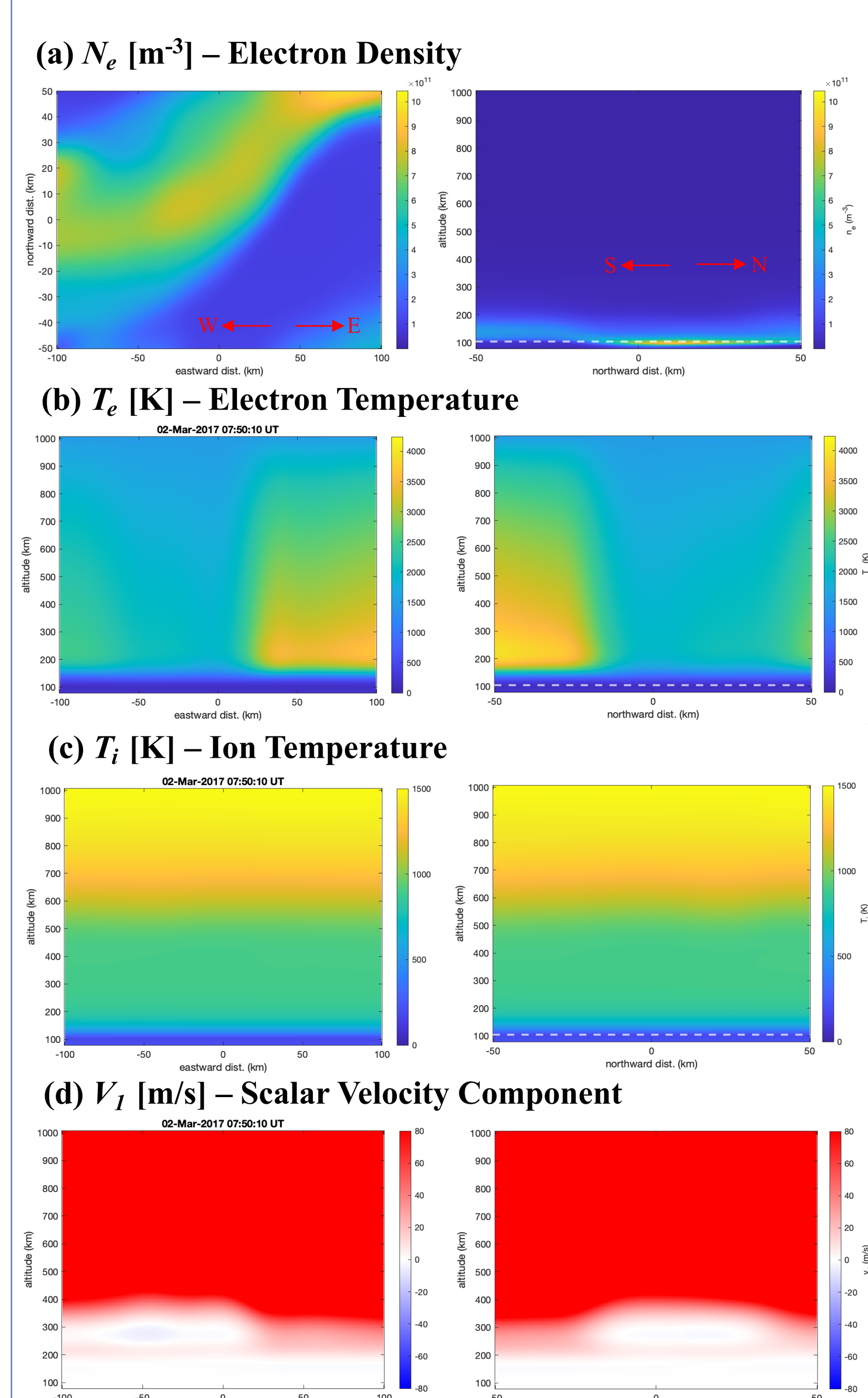

Figure 8. The above figure shows the simulation outputs for the electron density, electron and ion temperatures, and velocities of the measured auroral structure by the ISINGLASS rocket on March 2nd, 2017 at 07:50:10 UT. The auroral shape is revealed by (a), the electron density.

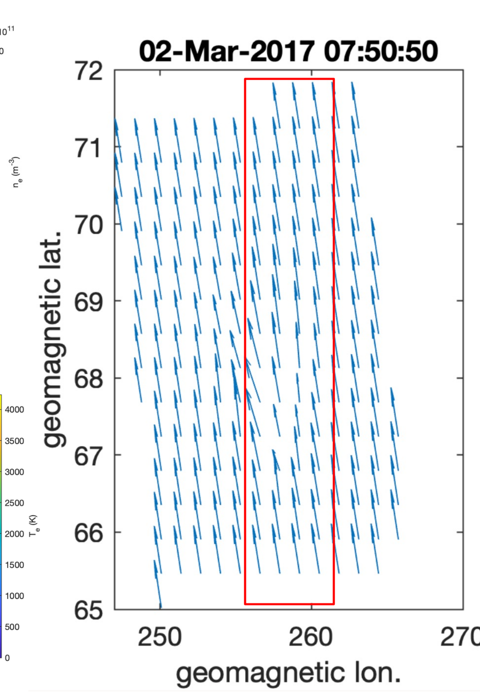

Figure 9. The above figure depicts the vector electric field, as solved for in [1] and [2]. The quivers within the red box correspond to the vector electric field in the same spatial domain represented by the geomagnetic latitudes and longitudes spanned in Fig 2. While the scalar parameters (a), (b), (c), and (d) of Fig 2 will later be used as model inputs, this figure represents the roughly estimated and model-simplified vector electric field obtained through assumptions made within the scripts used to generate this estimation.