Small Scale dB/dt Fluctuations: Resolving and Exploring Spikes in Global Models

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November 26, 2022

Abstract

One of the prominent effects of space weather is the variation of electric currents in the magnetosphere and ionosphere, which give rise to rapid geomagnetic field variations on the surface of the Earth. These Geomagnetic Disturbances (GMDs) can be highly localized and large amplitude. Because the causes of localized GMDs are unresolved, we seek to identify the physical drivers of these localized dB/dt spikes measured by ground magnetometers. We use the Space Weather Modeling Framework (SWMF) models to simulate the magnetosphere and reproduce these small-scale spikes. We use the operational Geospace configuration, which couples a global magnetohydrodynamic model to a height-integrated ionospheric electrodynamics solver and a kinetic ring current model. We run a series of simulations with increasingly higher spatial resolution to resolve small scale dB/dt dynamics. We quantify the success of the model against observation using Regional Station Difference (RSD), a metric calculated using dB/dt or geoelectric field to pinpoint when a single magnetometer station records a significantly different value than others within a given radius. We discuss future work to improve the model's accuracy and our understanding of these small-scale structures.

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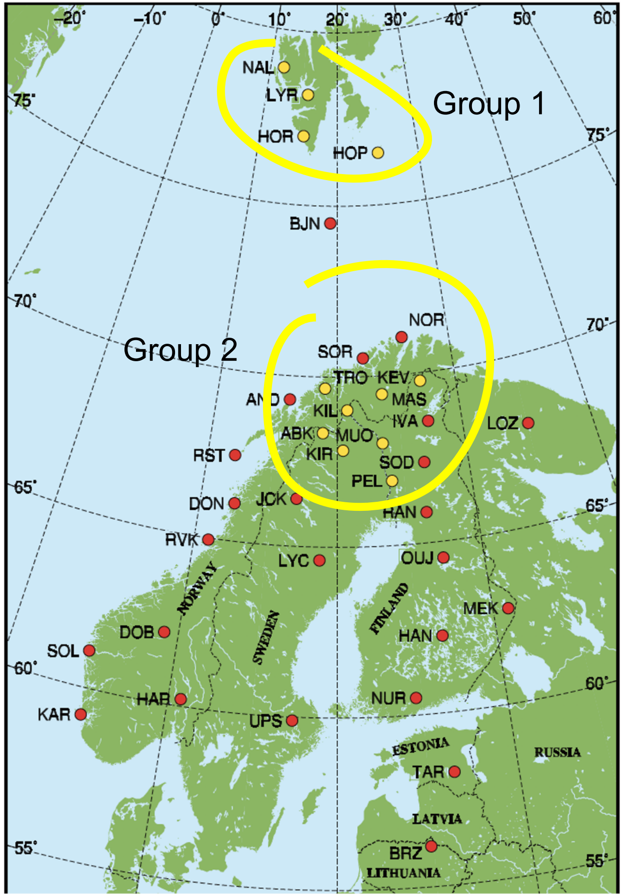
What is a Localized dB/dt Fluctuation?

- We examine magnetic field data from two subsets of the IMAGE magnetometer network, following *Dimmock, et al.* 2020
- During storms, often a single station will record a different value for the change in magnetic field (dB/dt) than the other stations in the group
- Strong localized dB/dt fluctuations can affect ground conducting systems, which motivates a need for modeling and predicting these fluctuations
- We define Regional Station Difference (RSD) as $RSD = \max\left(\frac{dB_H}{dt} - \overline{\frac{dB_H}{dt}}\right)$

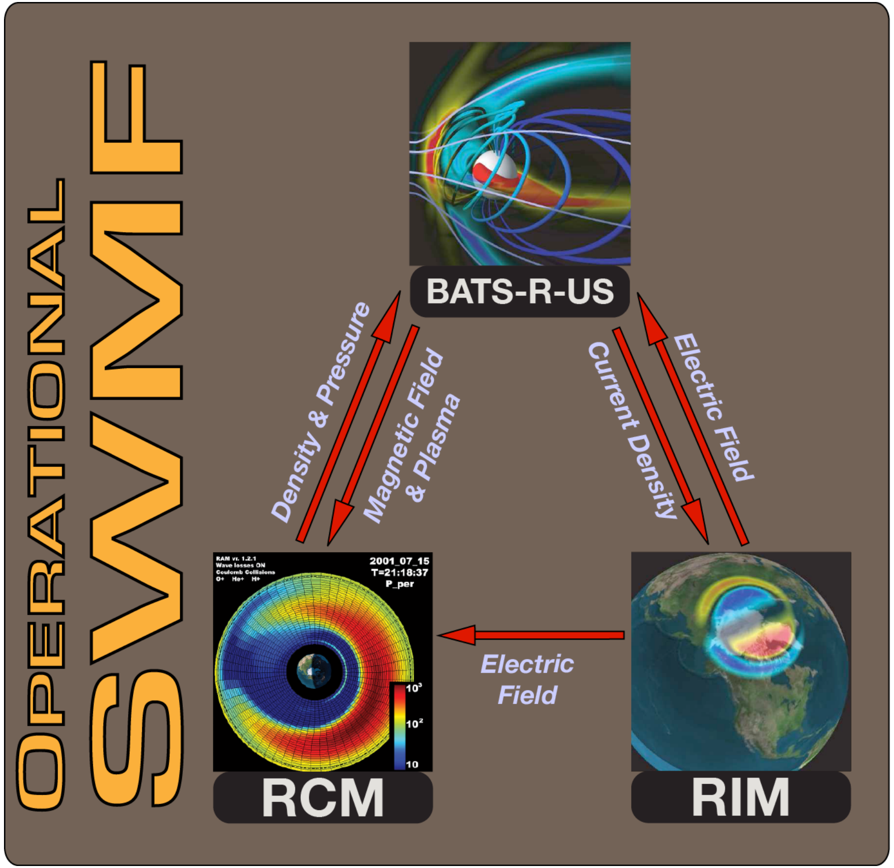


Key Questions

- How well does a global-level numerical model reproduce these small-scale spikes?
- What are the possible drivers of these spikes?
- How can we improve our model to more accurately predict the spikes?

What Does Our Model Look Like?

- Only inputs are upstream solar wind and F10.7 flux
- Three MHD grid configurations used.
- IE grid defaults to 2º X 2º, can be refined as needed.
- Dense output:
  >200 real virtual mags
  1º X 1º gridded output
  10s output frequency



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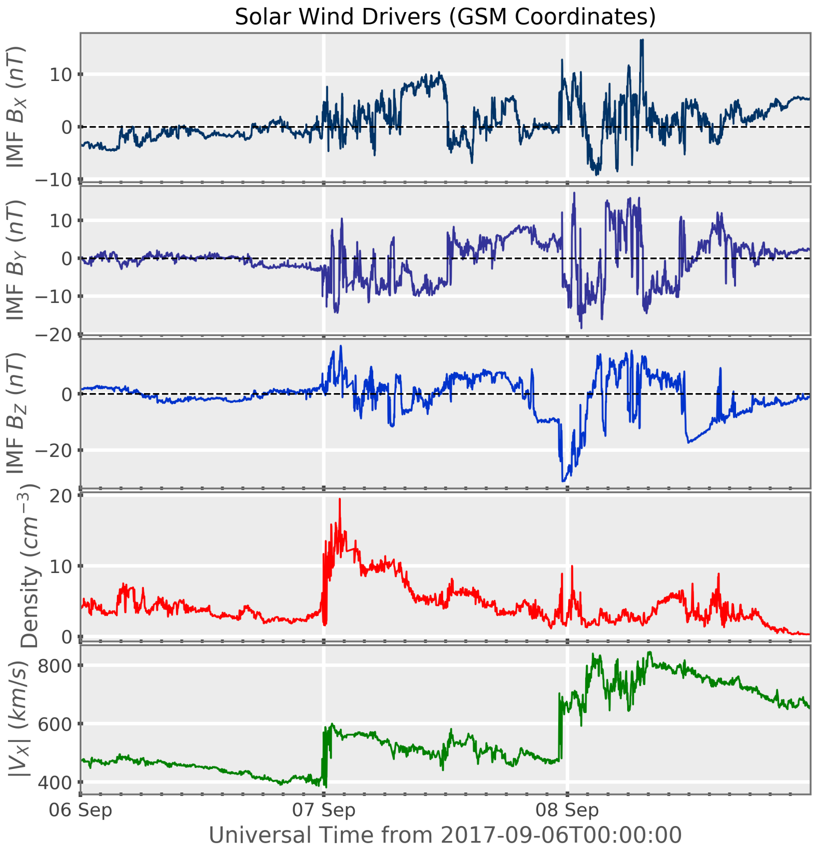
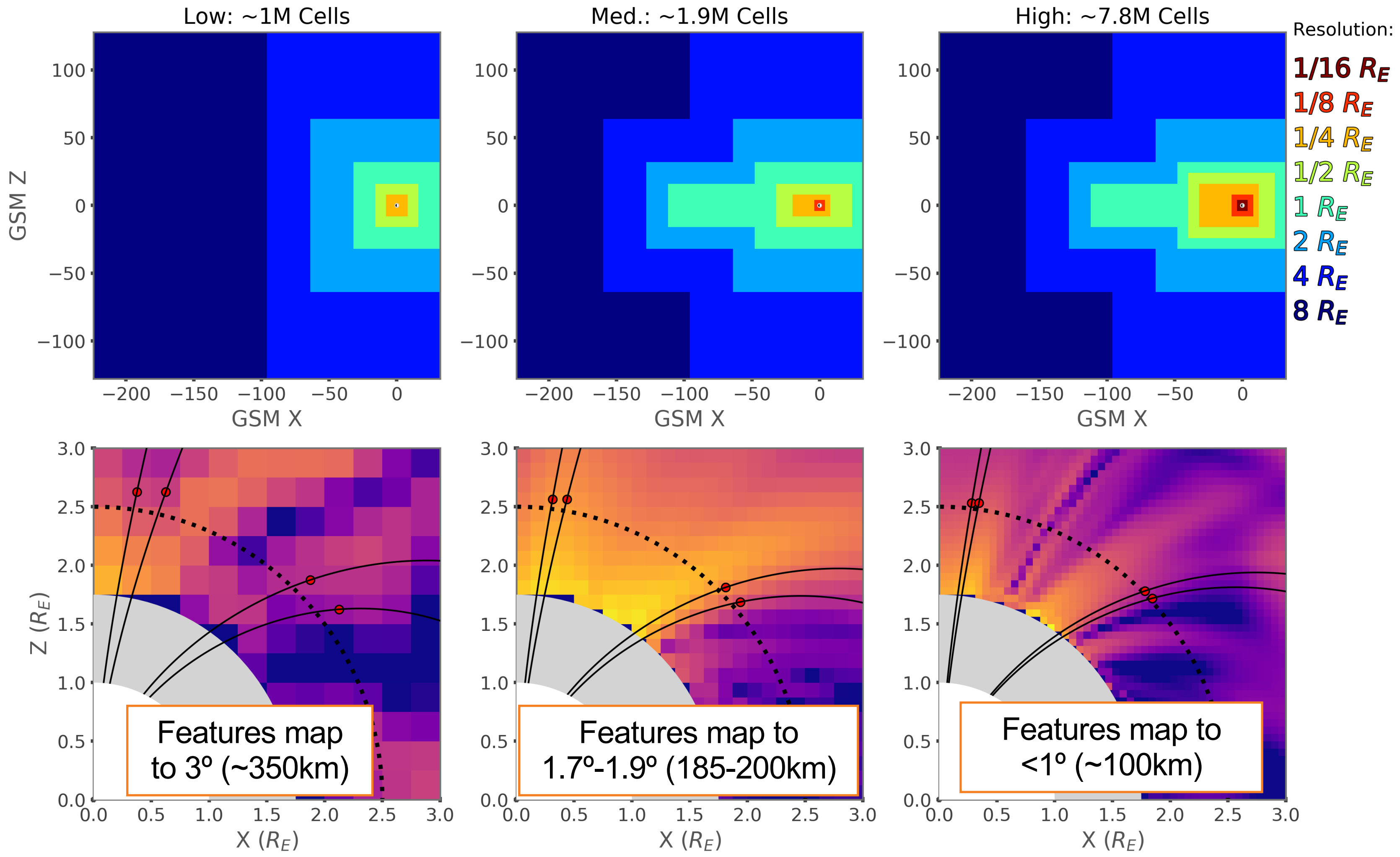


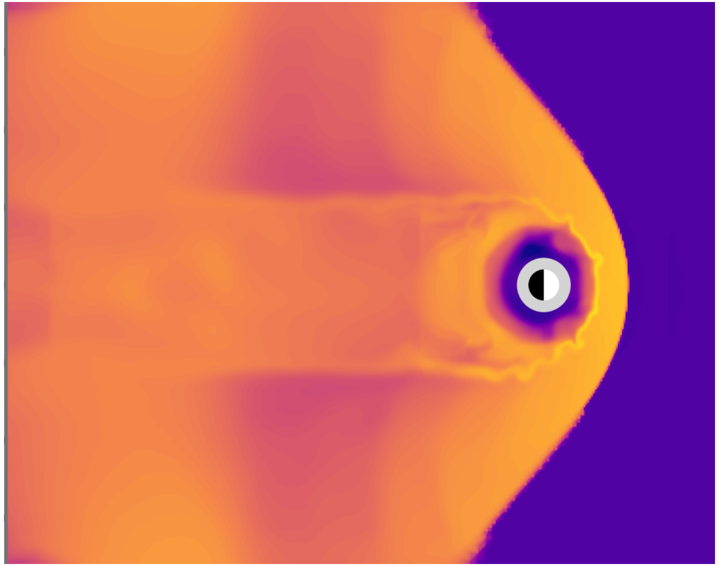
Refining the Numerical Grid

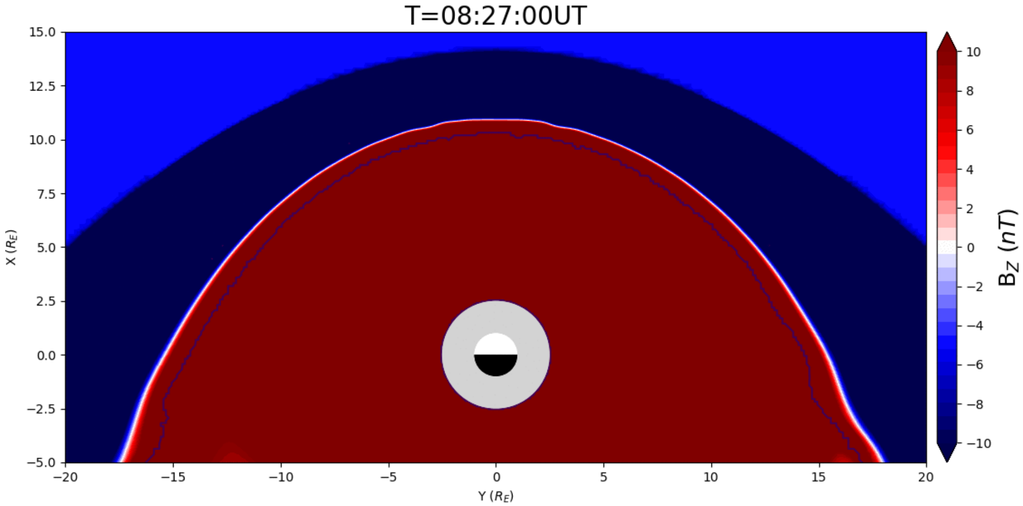


Refining Grids to Refine dB/dt

Global models produce fine structures if properly resolved.

Ground observations show structure at small (<200km) scales.

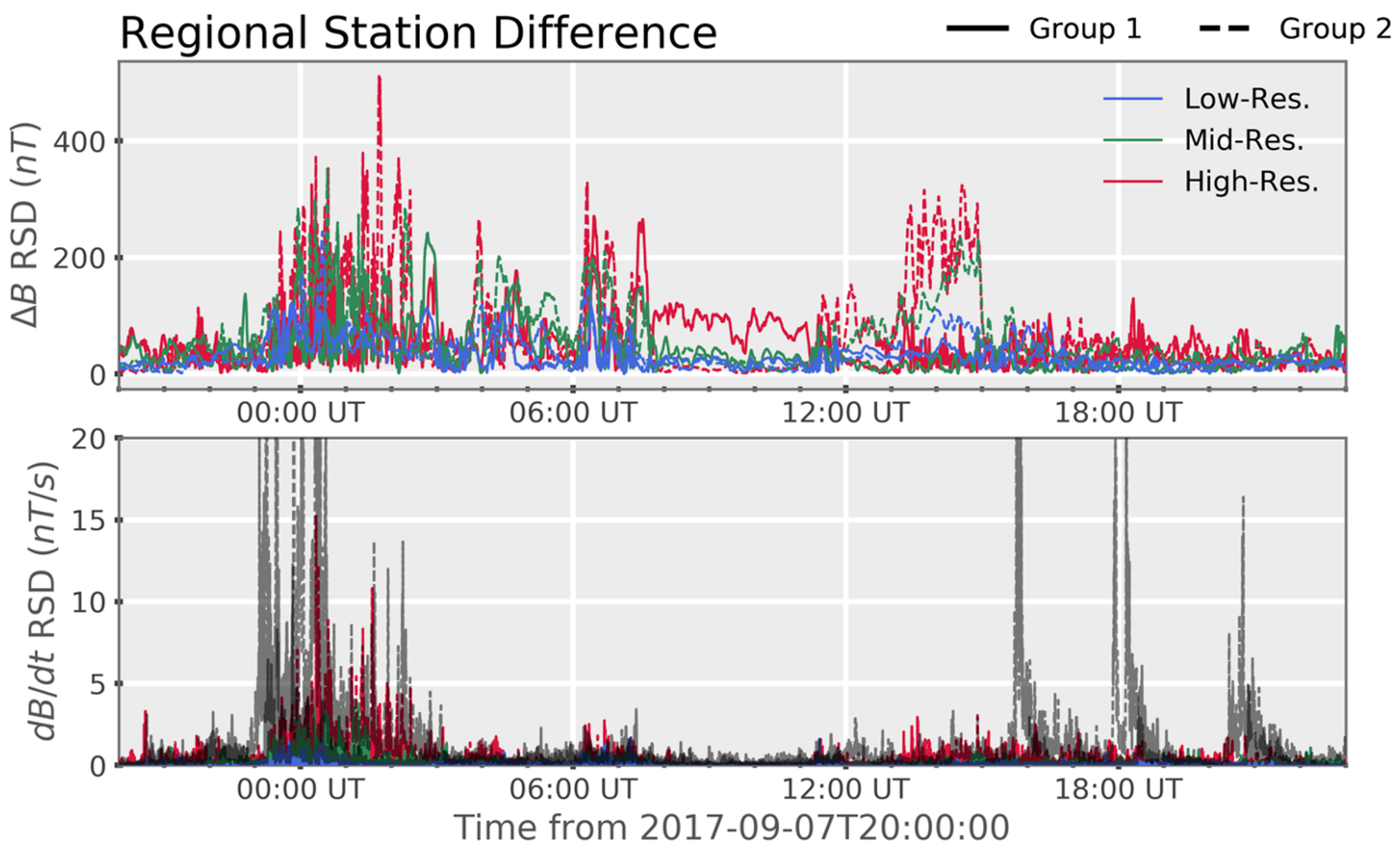




Can we capture small spatial scale dB/dts?

…with skill?

Defining RSD to Identify Spikes



How Accurate is Our Model?

- To quantify how well our model matches the values of RSD calculated from observation, we construct a binary event table
- We specify a threshold and ask two questions at each timestep
  - Did the observed RSD surpass the threshold?
  - Did our model RSD surpass the threshold?
- From these questions, we can define a "hit" as a point at which RSD falls above the threshold in both observation and model, and a "miss" as a point at which observational RSD falls above the threshold, but model RSD does not.

6 Group 2 - High Res dB/dt Threshold = 5 nT/s, Window = 300 sec

Event Forecasted?	Event Observed? Yes	No
Yes	10	2
No	42	595
Total	649	

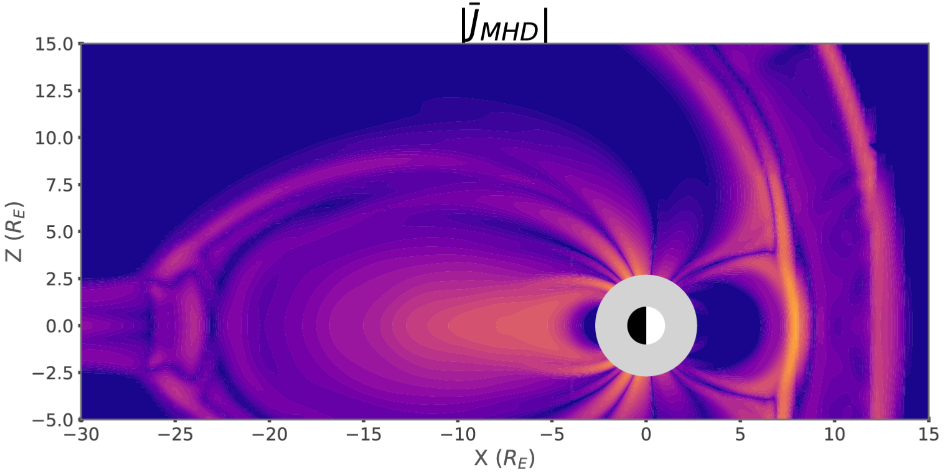
Table 6: Binary event table for predicted values using a threshold of 5. Under these conditions, the model yielded a Hit Rate of 0.192, a False Alarm Rate of 0.003, and a Heidke Skill Score of 0.291.

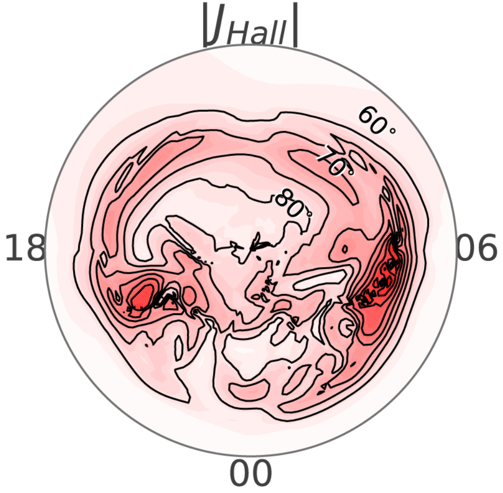
7 Group 2 - High Res dB/dt Threshold = 5 nT/s, Window = 1200 sec

Event Forecasted?	Event Observed? Yes	No
Yes	6	0
No	12	145
Total	163	

Table 7: Binary event table for predicted values using a threshold of 5. Under these conditions, the model yielded a Hit Rate of 0.333, a False Alarm Rate of 0.000, and a Heidke Skill Score of 0.471.

Virtual Magnetometers

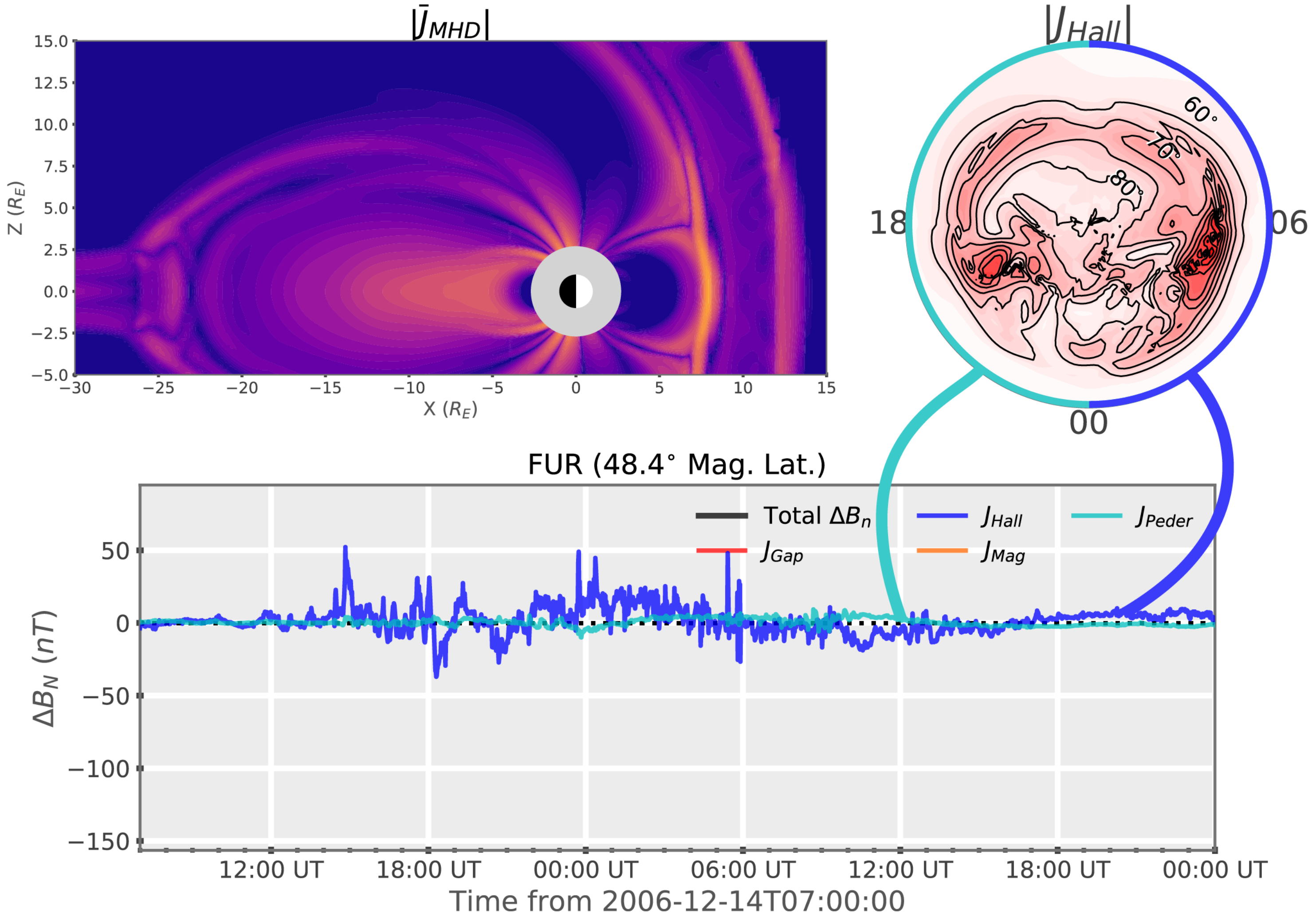




SWMF virtual magnetometers convert currents into magnetic perturbations via *Biot-Savart* Integrals:

$$\Delta\bar{B}(\bar{r}) = \frac{\mu_0}{4\pi}\int\frac{\bar{J}\times(\bar{r}-\bar{r'})}{|\bar{r}-\bar{r'}|^3}\,d\bar{r'}^3$$

Virtual Magnetometers



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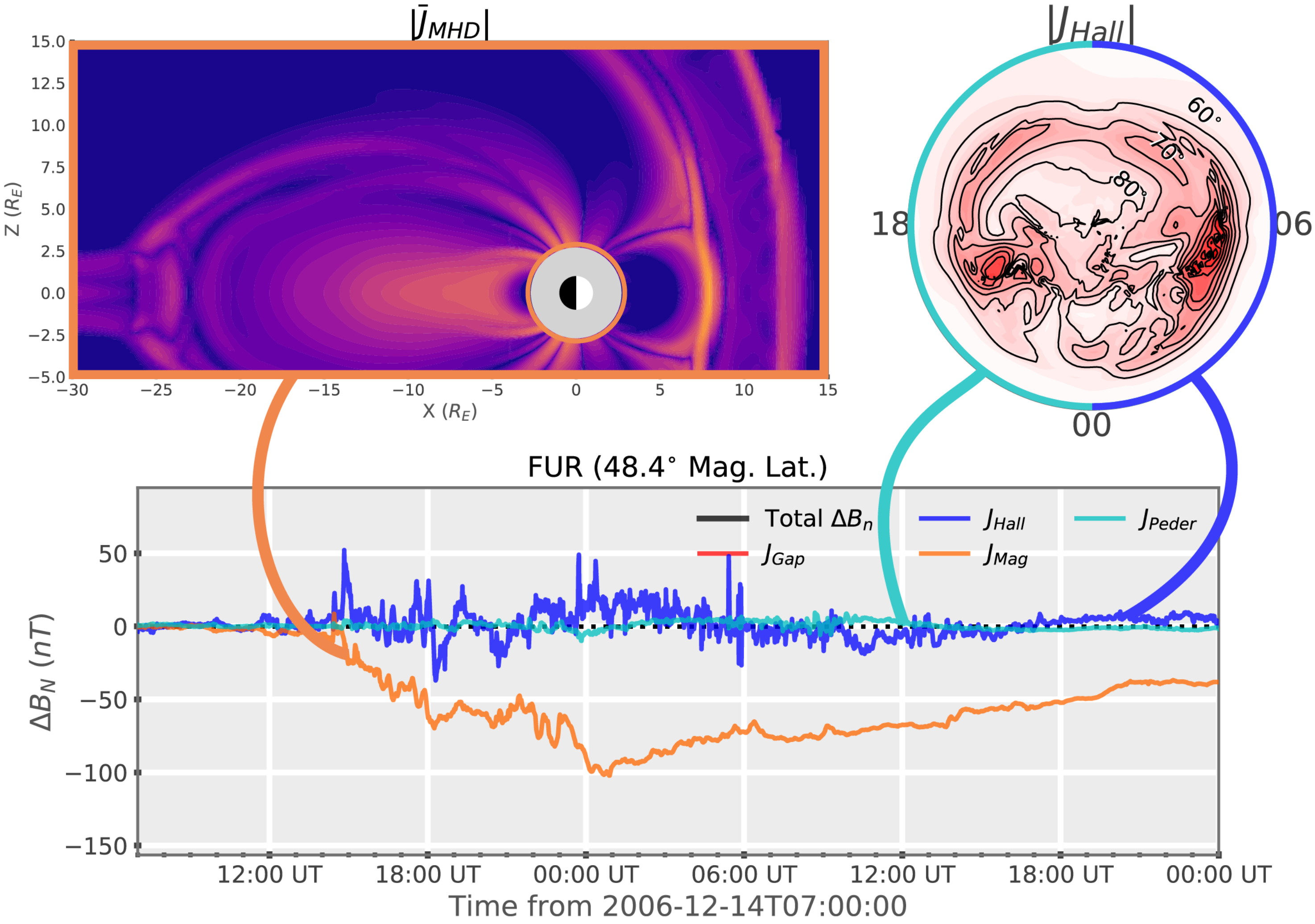

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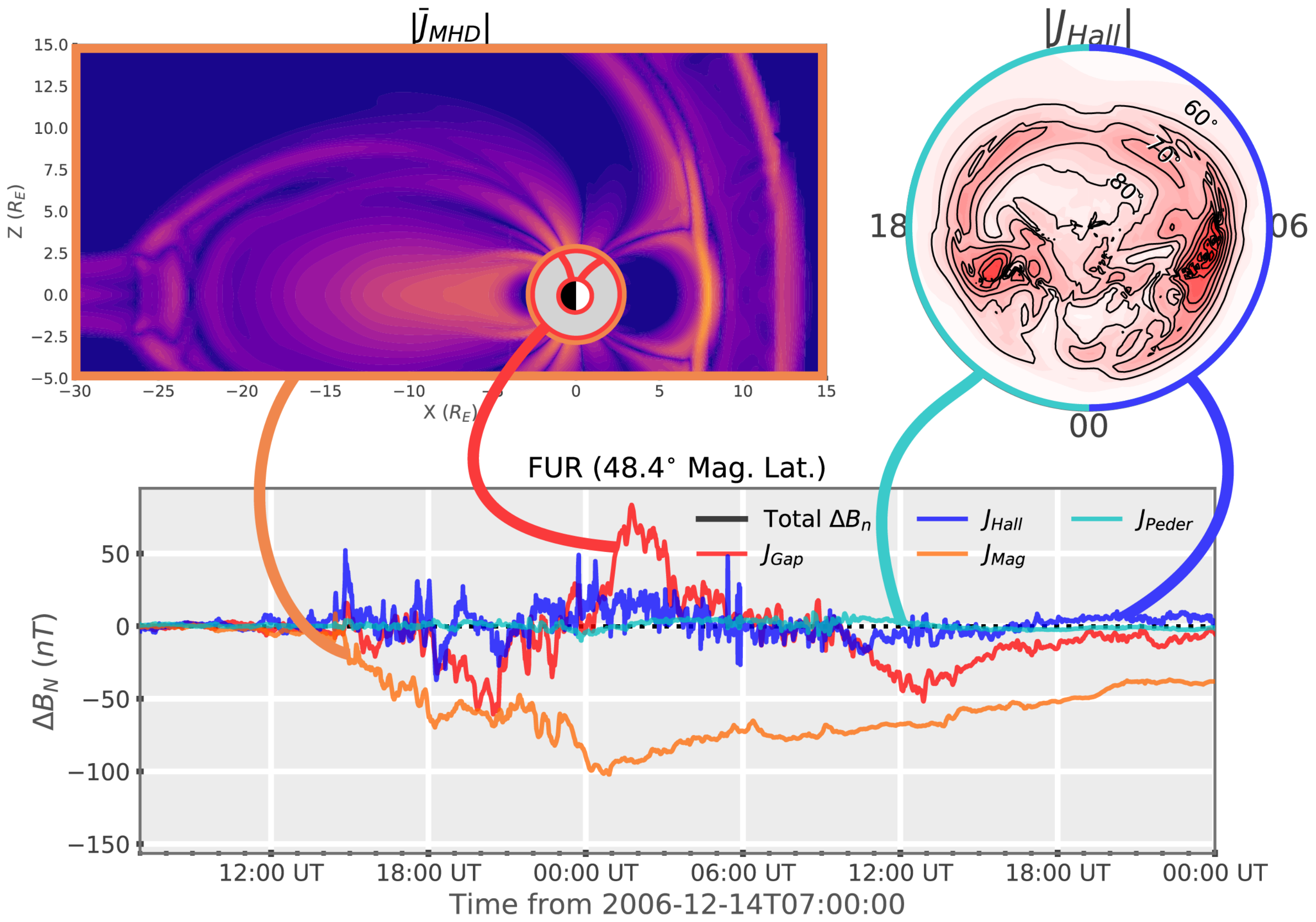

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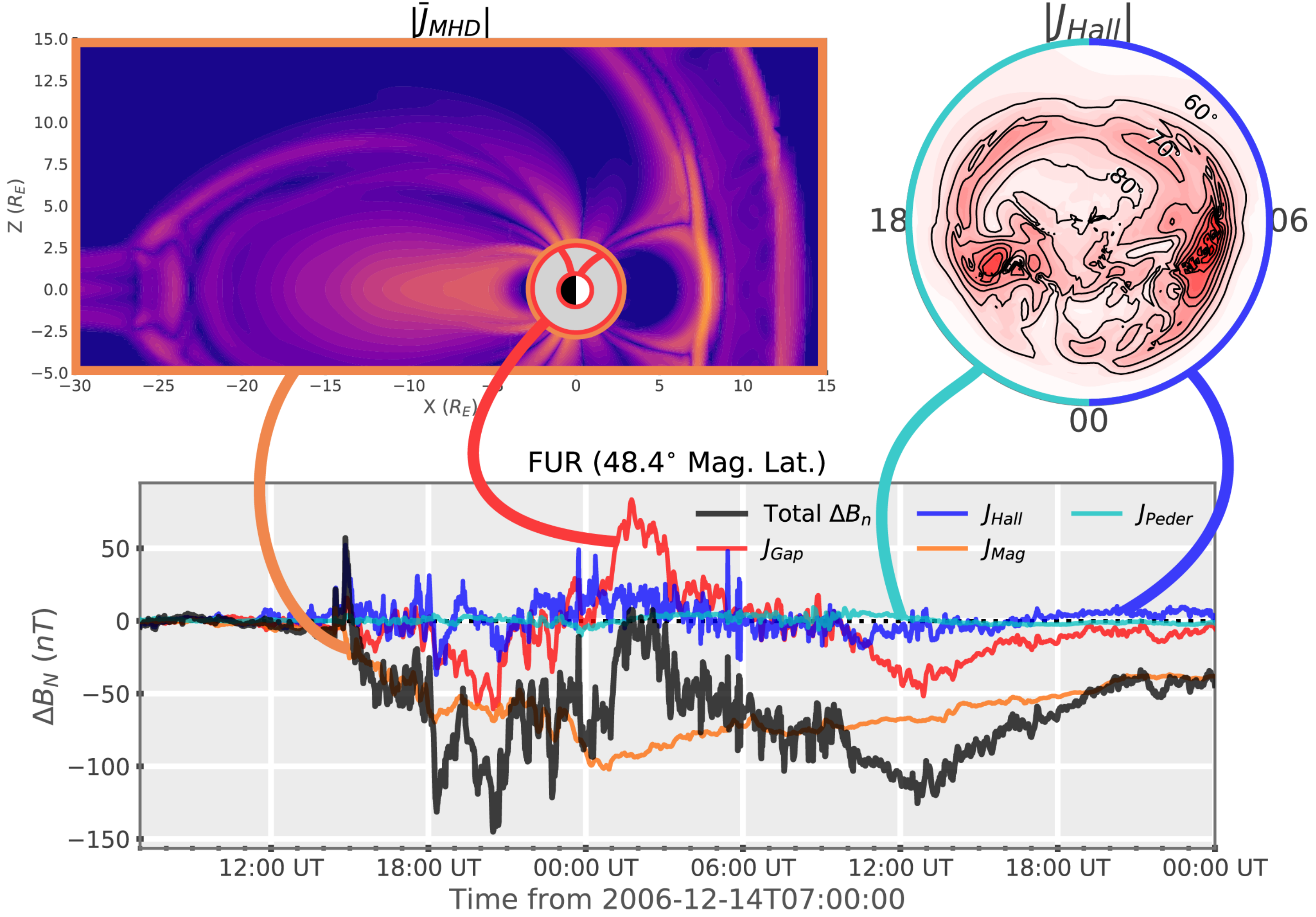
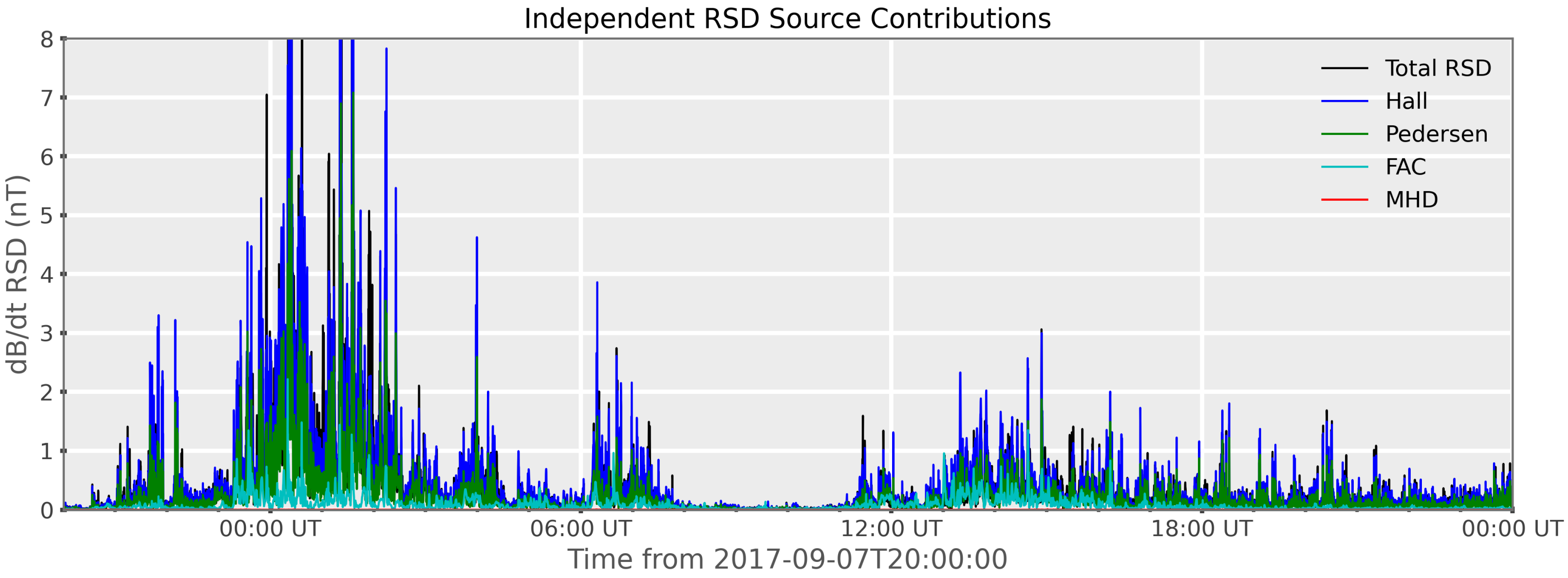


Individual RSD Contributions

- We can examine the individual sources of RSD for the 2017 event to determine which current sources contribute most heavily to total RSD



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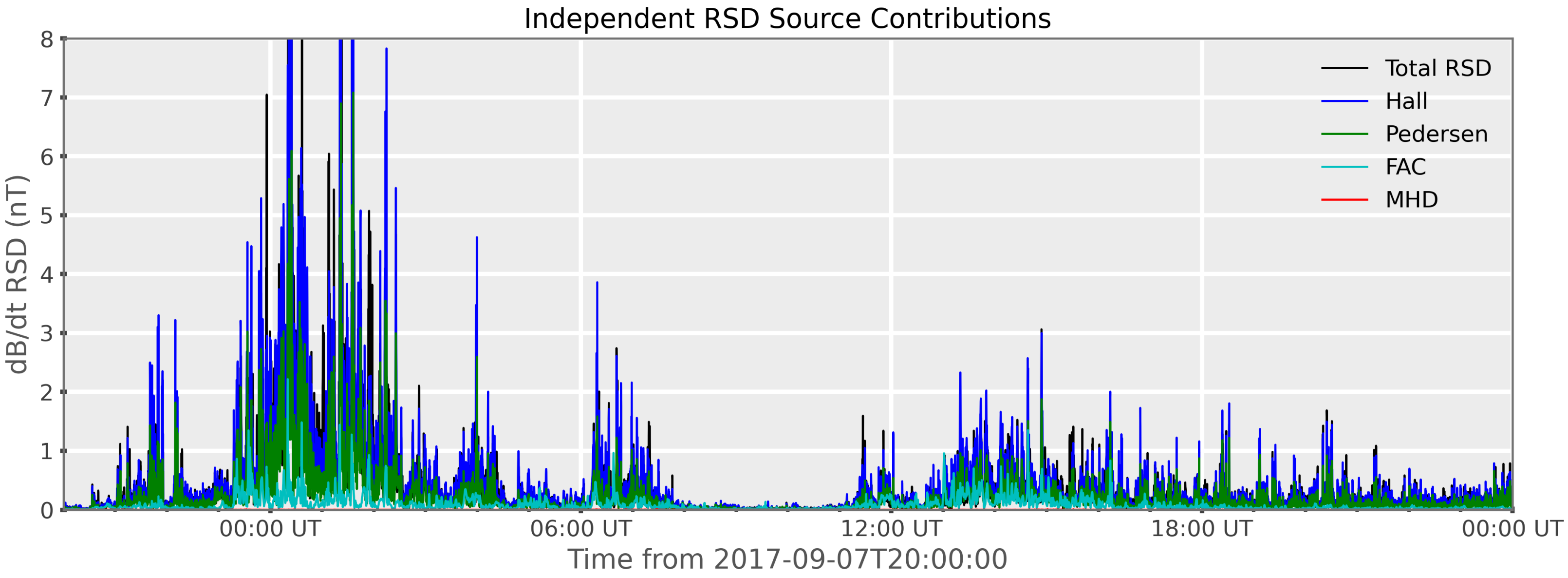

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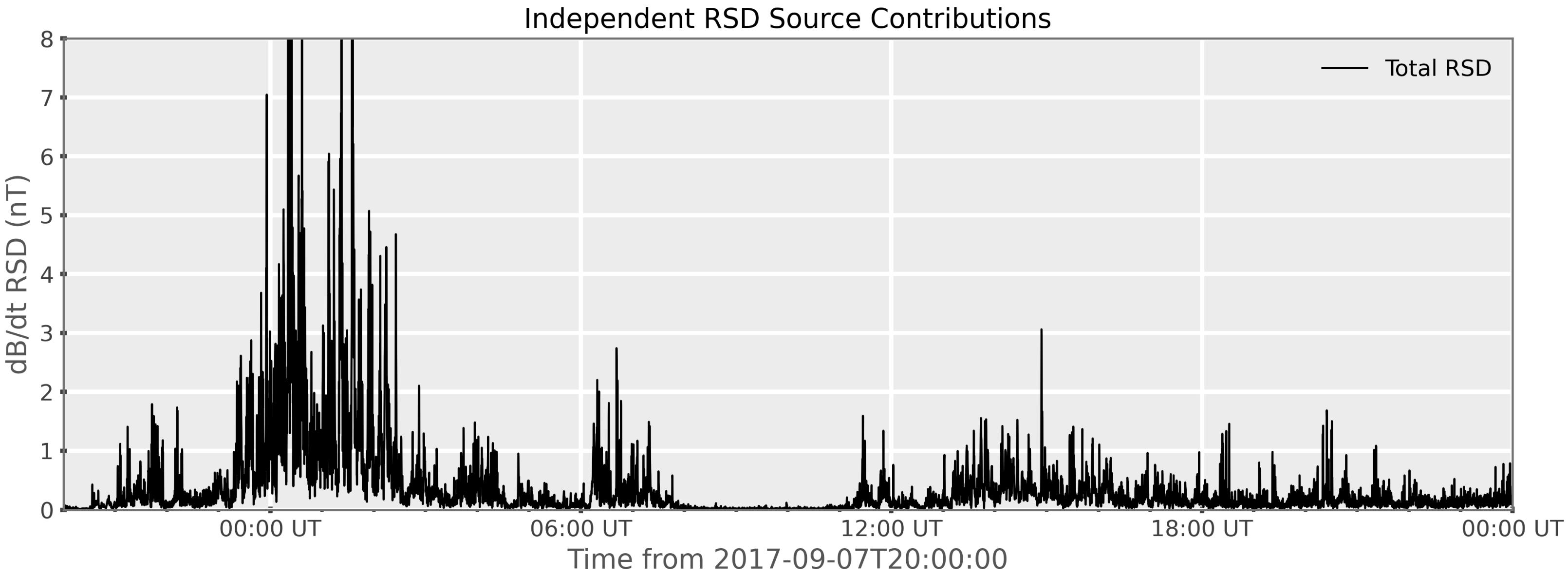

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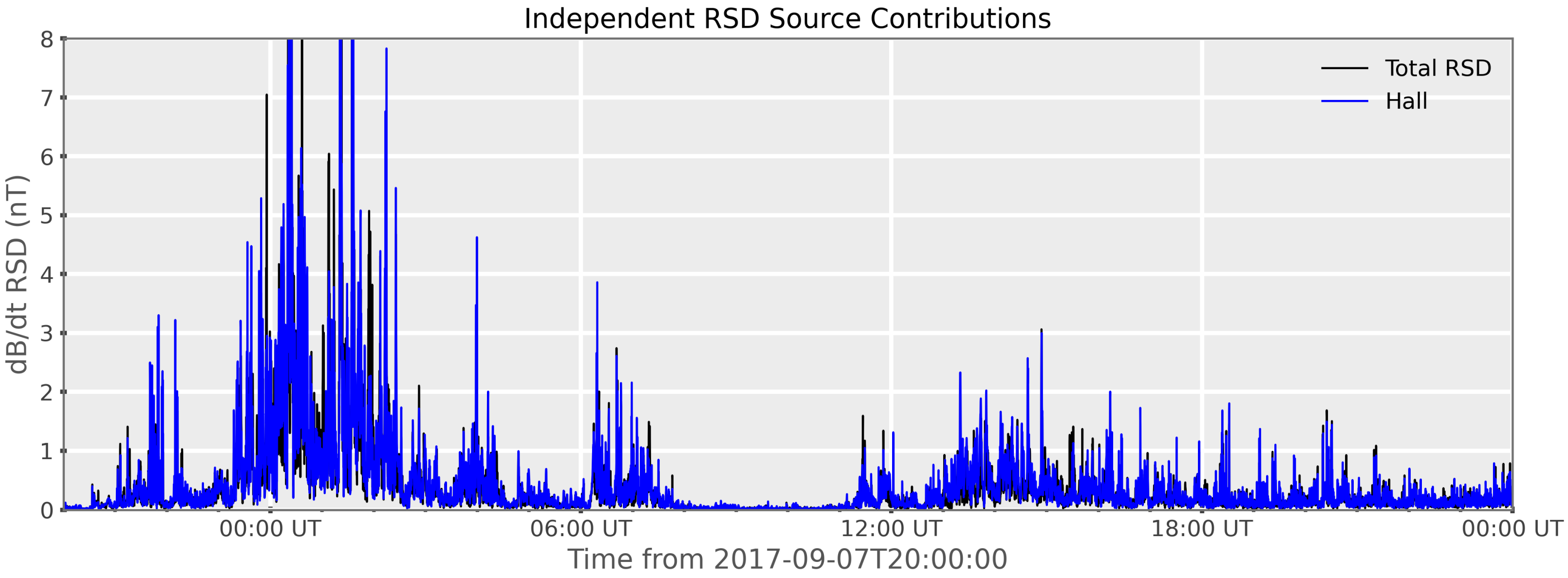

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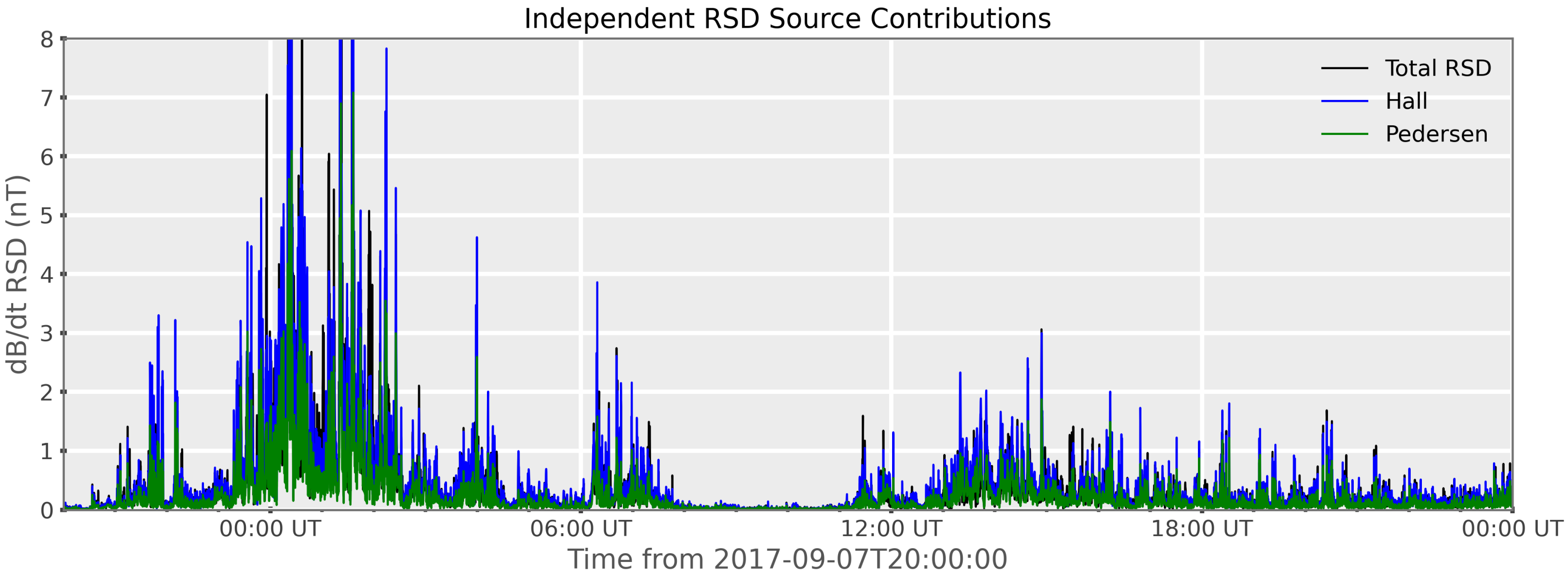

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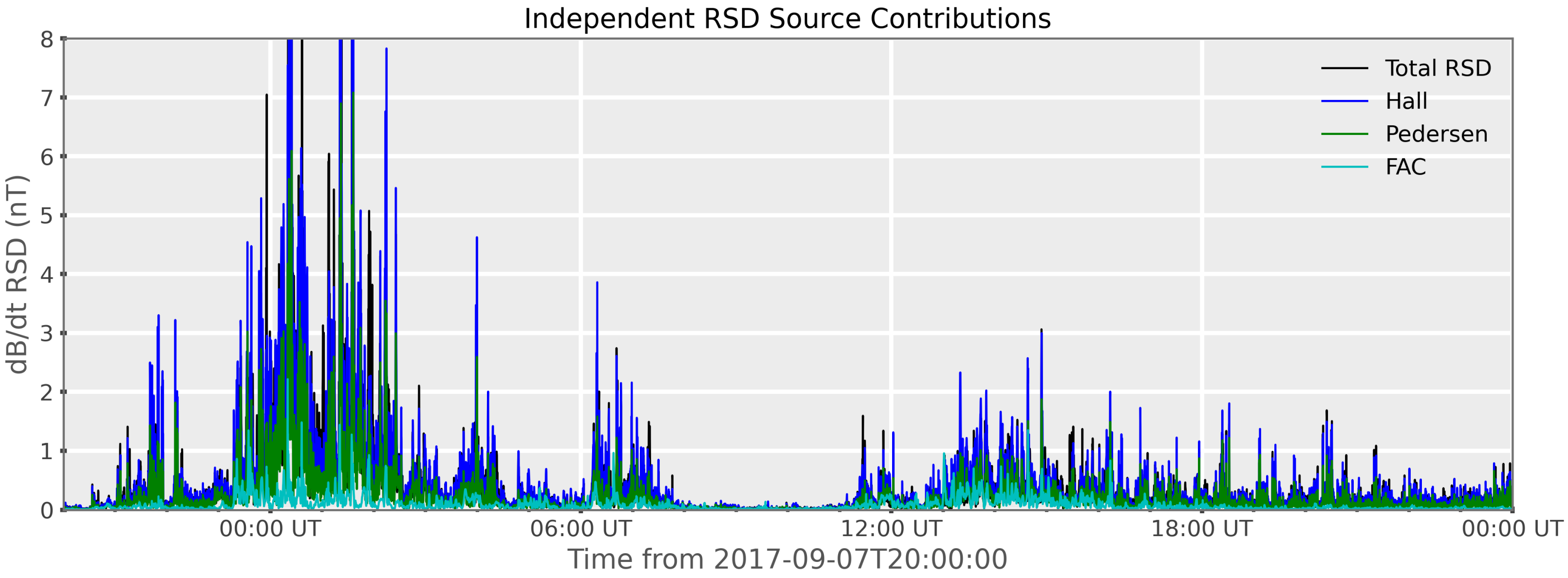

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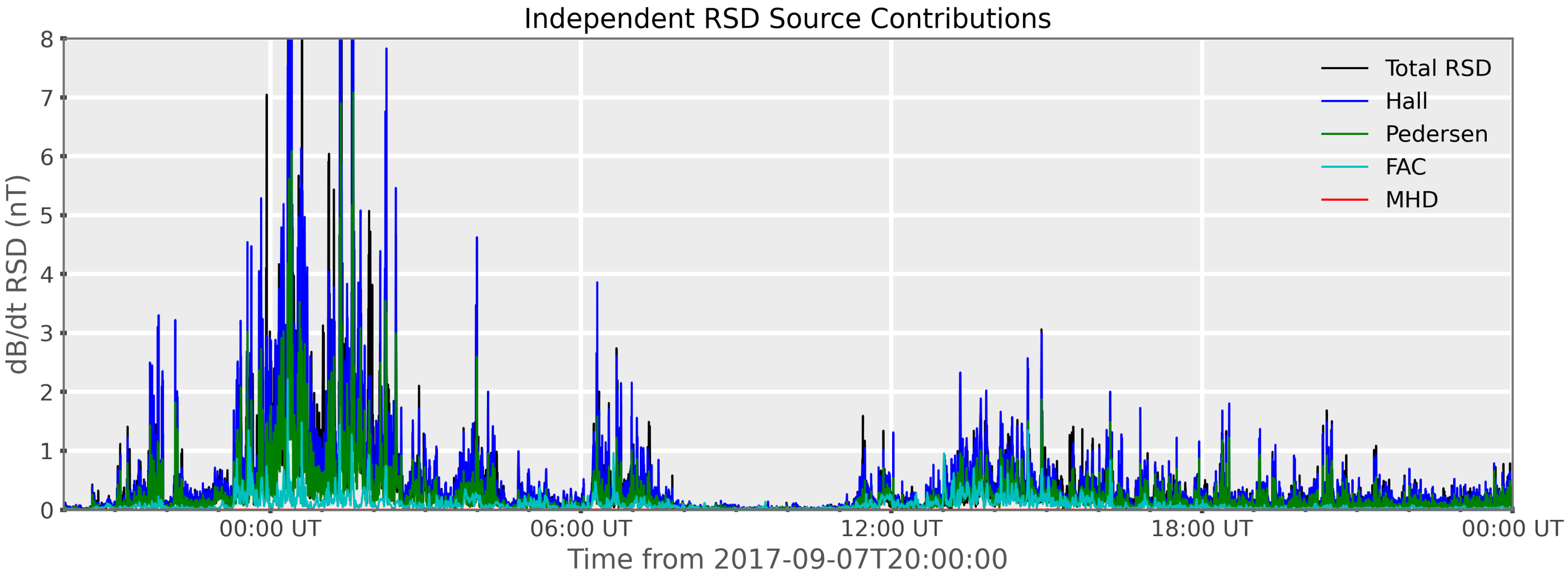

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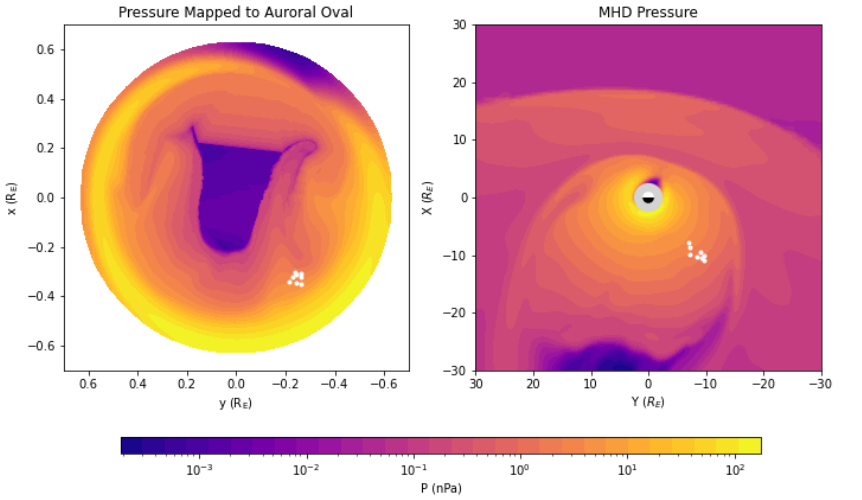
Mapping Field Lines to Plasma Sheet

- To improve our model's accuracy, we need to understand the physics behind these fluctuations. We examine tail dynamics of our existing model to identify possible drivers.
- We trace field lines from ionosphere to plasma sheet to determine the point in the magnetosphere that corresponds to each magnetometer location.
- Small-scale ionosphere effects will originate from localized structure in the tail, which pressure does not seem to have.

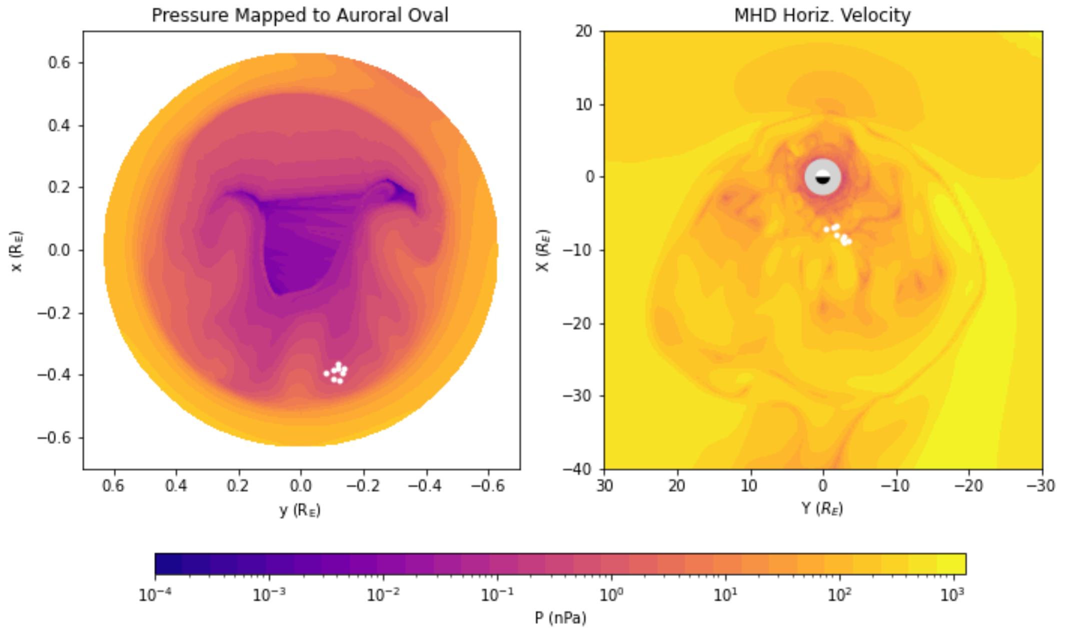


Examining Small-Scale Tail Structure

- We now examine horizontal velocity

$$v_{horiz} = \sqrt{v_x^2 + v_y^2}$$

- As before, we show the locations in the tail that map along field lines to the station locations in the ionosphere.



- We see high speed flow bursts in the tail and near the boundary of the ring current. Localized structure of these bursts could be the driver of the small-scale dB/dt fluctuations.

Conclusions

- We explored different model resolutions and utilized RSD and Binary Event Tables to quantify how well our model reproduces small-scale dB/dt fluctuations as seen by ground magnetometers – can reproduce some but miss most.
- We examined pressure and horizontal velocity in the tail to determine possible physical drivers of spikes
- We suggest a soft association between small-scale dB/dt effects and Bursty Bulk Flows (BBFs) or fast flows in the tail

What’s Next?

Future Work

1. To increase the detail of structure in the tail, we can run simulations using the Bats-R-US fifth-order solver.

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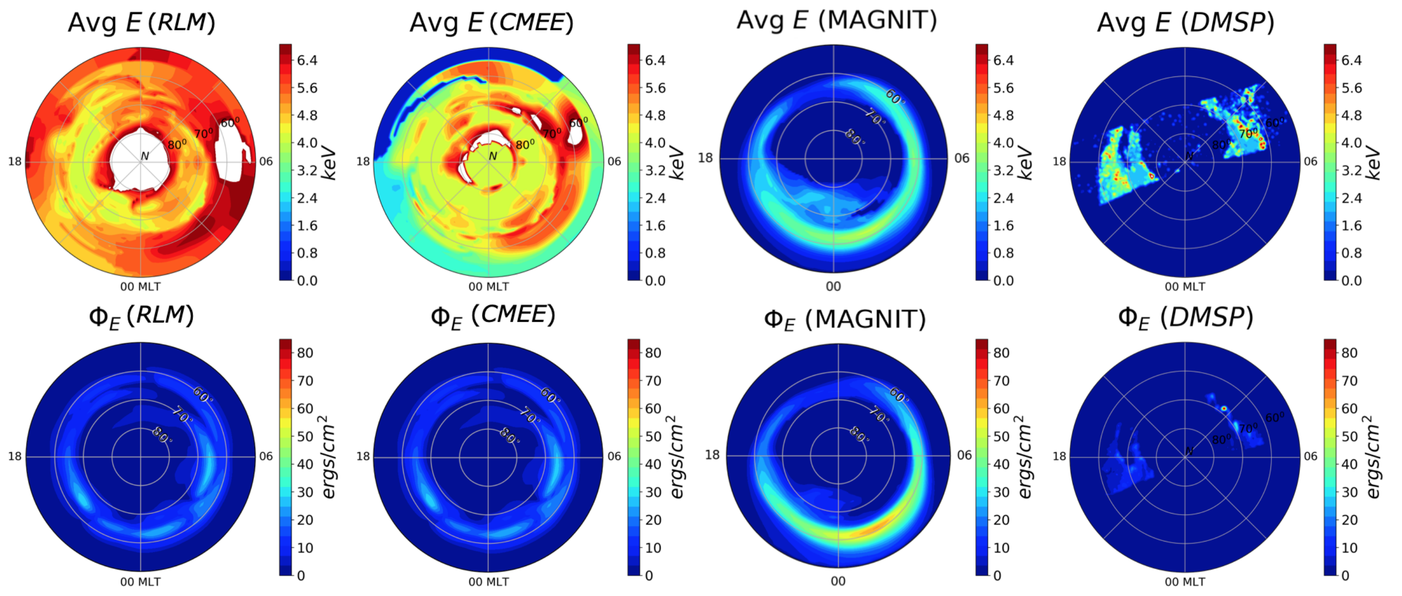

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3. Superimpose epochs to determine what hits and misses have in common or how they are different.
4. Extract a timeseries for relevant variables to explore how they correspond to RSD
5. Define a new metric – Regional Tail Difference (RTD) to examine what magnetospheric values along each stations' respective field line exhibit localized variability that tightly correlates with the surface RSD

Collaborator Acknowledgements

- Thanks to collaborators at the Swedish Institute of Space Physics, Los Alamos National Laboratory, and the Swedish Defense Research Agency:
  - A. Dimmock
  - S. Morley
  - L. Rosenqvist
  - E. Yordanova