Forecasting of Localized Geomagnetic Disturbances in Global Models: Physics and Numerics

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November 22, 2022

Abstract

One of the prominent effects of space weather is the variation of electric currents in the magnetosphere and ionosphere, which can cause localized, high amplitude Geomagnetic Disturbances (GMDs) that disrupt ground conducting systems. Because the source of localized GMDs is unresolved, we are prompted to model these effects, identify the physical drivers through examination of the model we use, and improve our prediction of these phenomena. We run a high-resolution configuration of the Space Weather Modeling Framework (SWMF) to model the September 7, 2017 event, combining three physical models: Block Adaptive Tree Solar wind Roe Upwind Scheme (BATS-R-US), an ideal magnetohydrodynamic model of the magnetosphere; the Ridley Ionosphere Model (RIM), a shell ionosphere calculated by solving 2-D Ohm's Law; and the Rice Convection Model (RCM), a kinetic drift model of the inner magnetosphere. The configuration mirrors that which is used in Space Weather Prediction Center (SWPC) operations; however, the higher grid resolution can reproduce mesoscale structure in the tail and ionosphere. We use two metrics to quantify the success of the model against observation. Regional Station Difference (RSD) is a metric that uses dB/dt or geoelectric field to pinpoint when a single magnetometer station records a significantly different value than others within a given radius, indicating a localized GMD. Regional Tail Difference (RTD) performs the same calculation using relevant variables in the magnetosphere at points that map down along field lines to the magnetometer station locations on the ground. We theorize two distinct causes of RSD, the first being small-scale structure in the tail and the second being station field lines mapping to spatially separated locations in the tail. We examine the differences between RSD spikes that we can reproduce in the model and those that we cannot. We categorize spikes by cause of localized GMDs to examine model capability for each theorized cause. We investigate the improvements in our model when we switch from empirical specification of ionosphere conductance to a physics-based one, MAGNetosphere-Ionosphere-Thermosphere (MAGNIT) Auroral Conductance Model. For small-scale effects we cannot reproduce, we explore the deficiencies in our model.

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What is a Localized GMD?

- A group of ground magnetometers may record different values for the change in magnetic field (dB/dt) during a magnetic storm, despite being located within ~200km of each other.

- In some cases, a station may record a vastly higher dB/dt than the surrounding stations. We call these localized Geomagnetic Disturbances (localized GMDs).

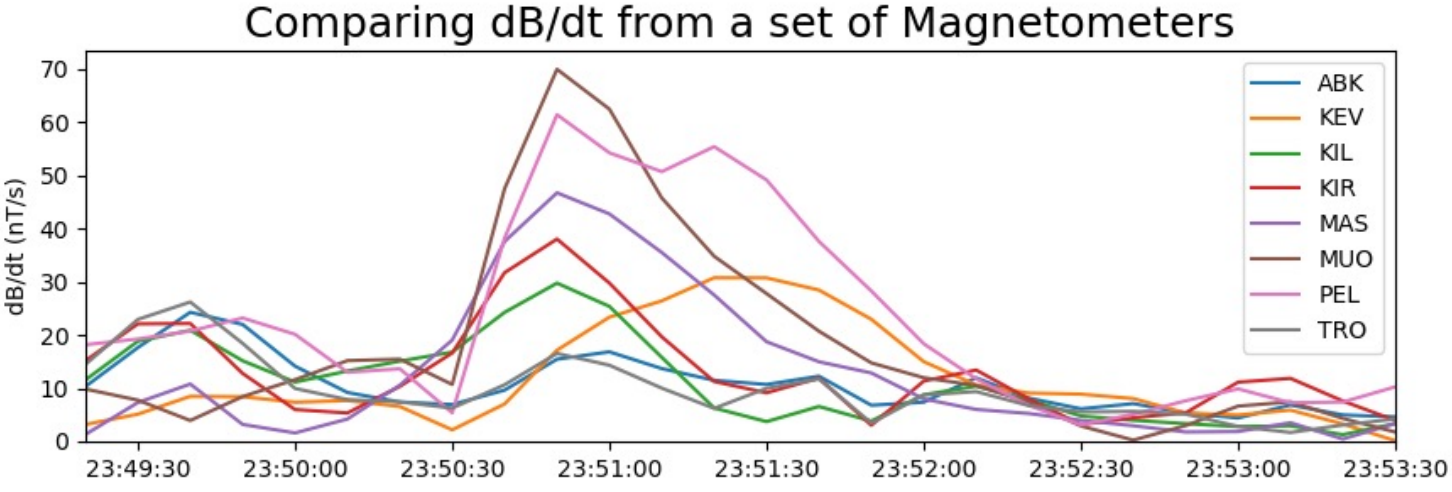
- We have a limited understanding of why localized GMDs occur, what is the physics that causes them, and how to reproduce them in our models.

- In this study we compare observed magnetometer data to a global magnetohydrodynamic (MHD) model of the Sept 2017 event, **theorize distinct drivers of GMDs** using metrics and analysis of the model, and explore ways to **improve the reproduction of observed GMDs in our model.**

Why do we care?

- Localized GMDs can cause strong currents along ground conducting systems, which motivates a need for modeling and predicting these effects.

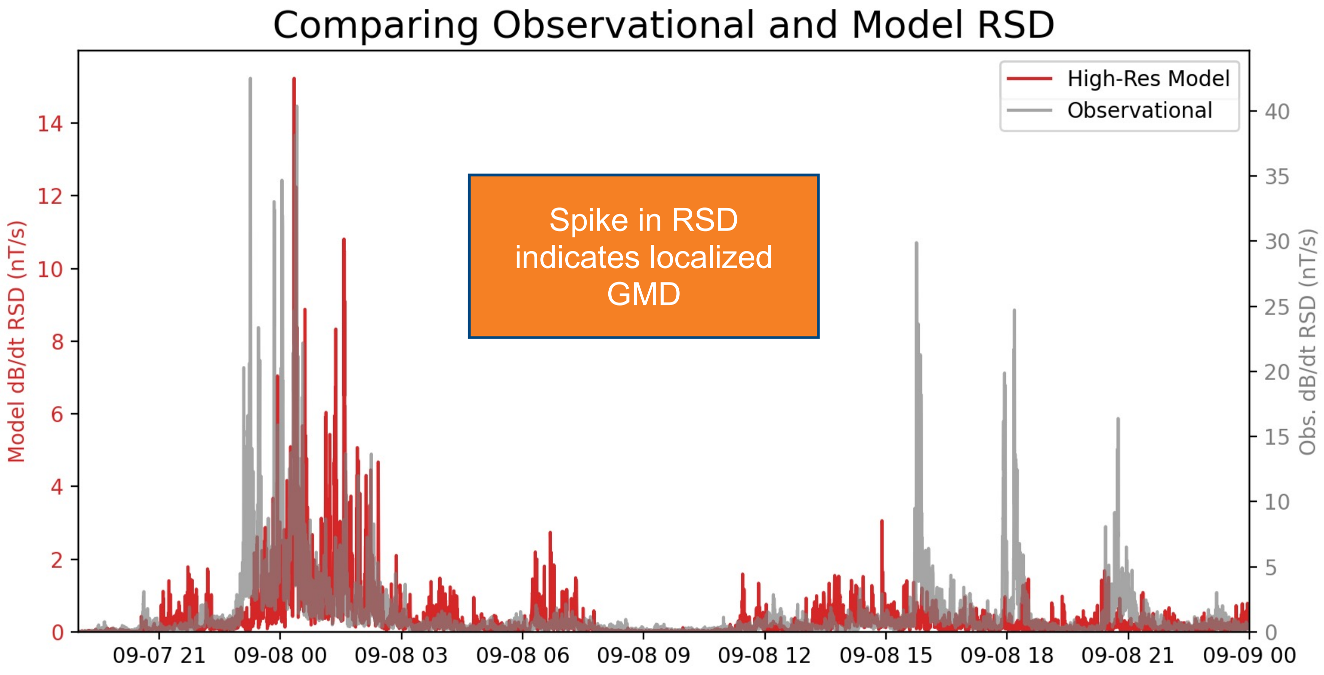
- Learning about the drivers of these fluctuations will allow us to improve our models of the magnetosphere, help us better understand the physics of space weather processes, and uncover new physics.



September 7, 2017

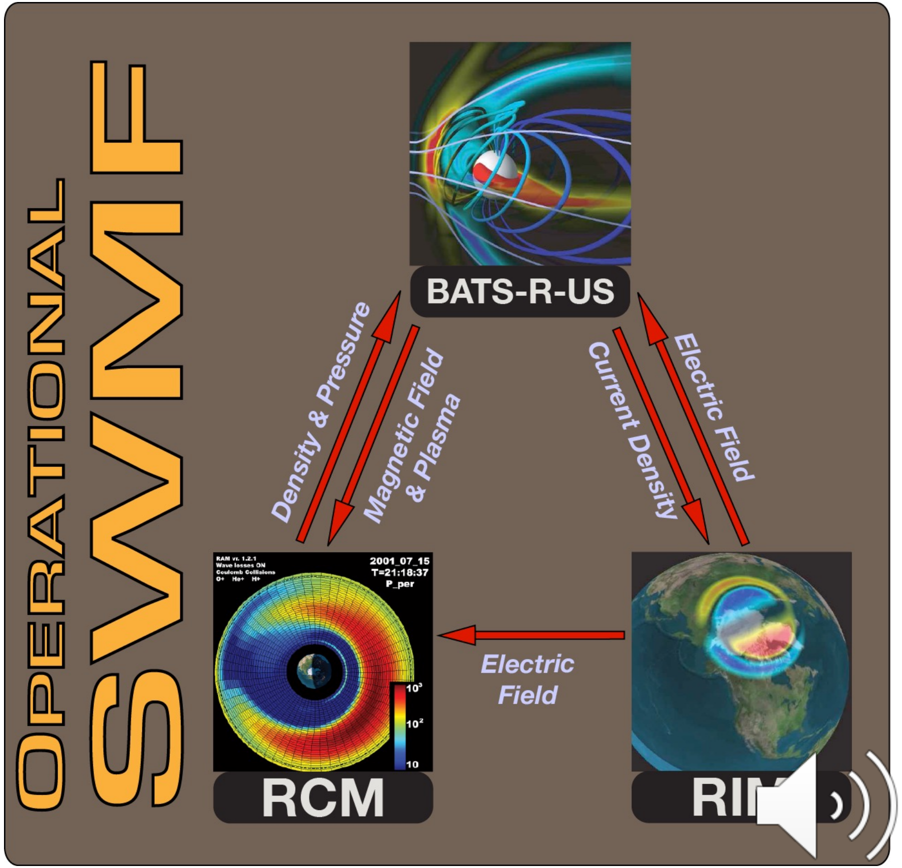
How do we Identify GMDs?

- To identify times that a localized GMD occurs, we define the metric Regional Station Difference (RSD) as $RSD = \max\left(\frac{dB_H}{dt} - \overline{\frac{dB_H}{dt}}\right)$



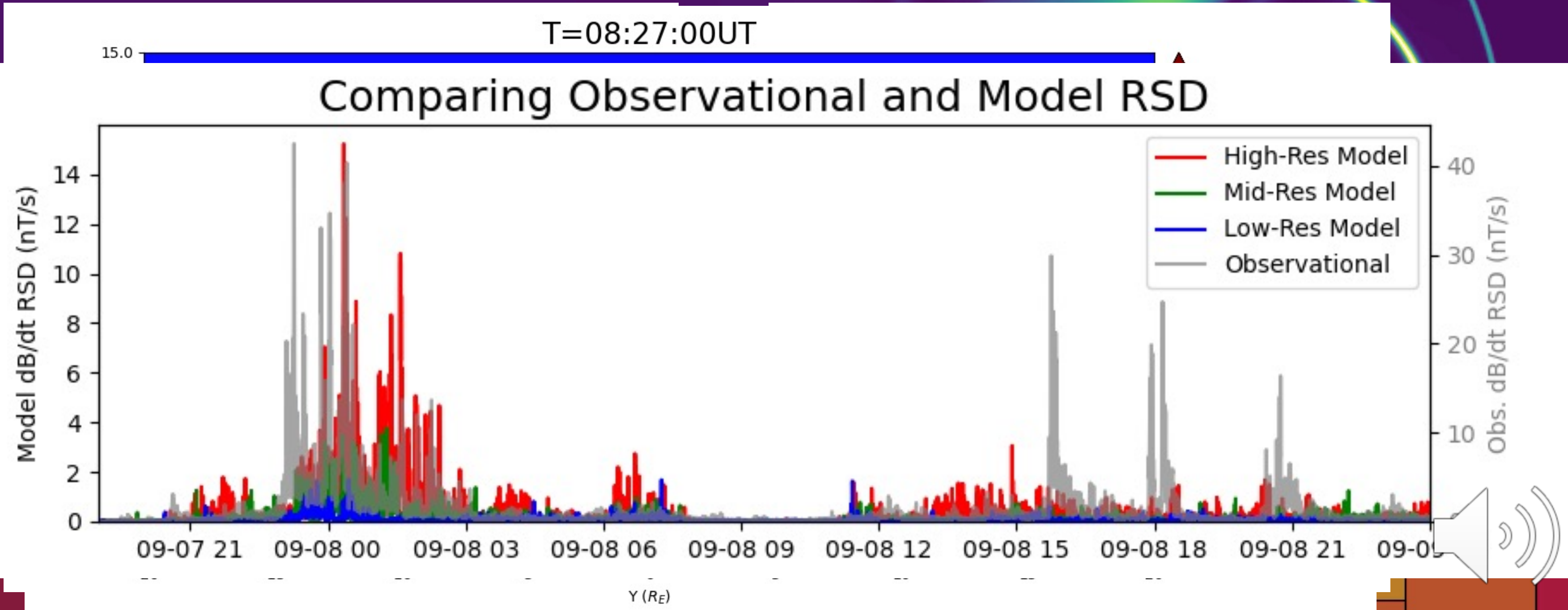
What Does Our Model Look Like?

- Three coupled models:
  - BATS-R-US, Global MHD
  - RCM, ring current
  - RIM, Height-integrated ionospheric electrodynamics
- Configuration follows SWPC operational version:
  - Input is F10.7 flux & solar wind/IMF
- Changes for this study:
  - High density magnetometer output
  - Higher resolution configuration



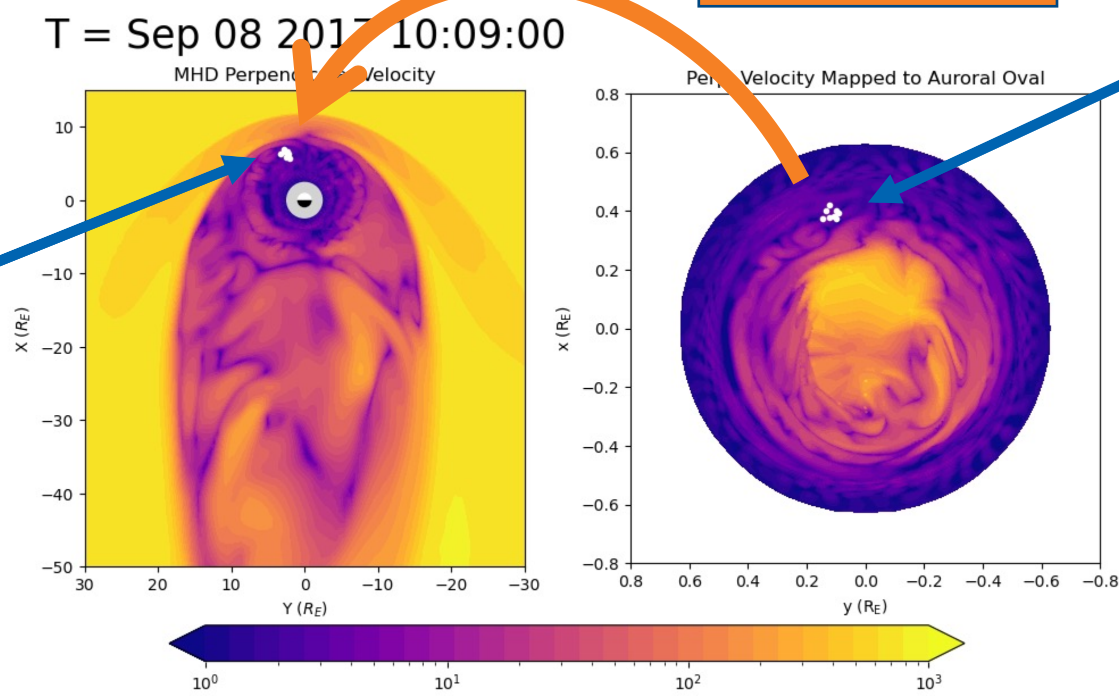
What can the model tell us?

- High resolution model runs are needed to reproduce small-scale fluctuations



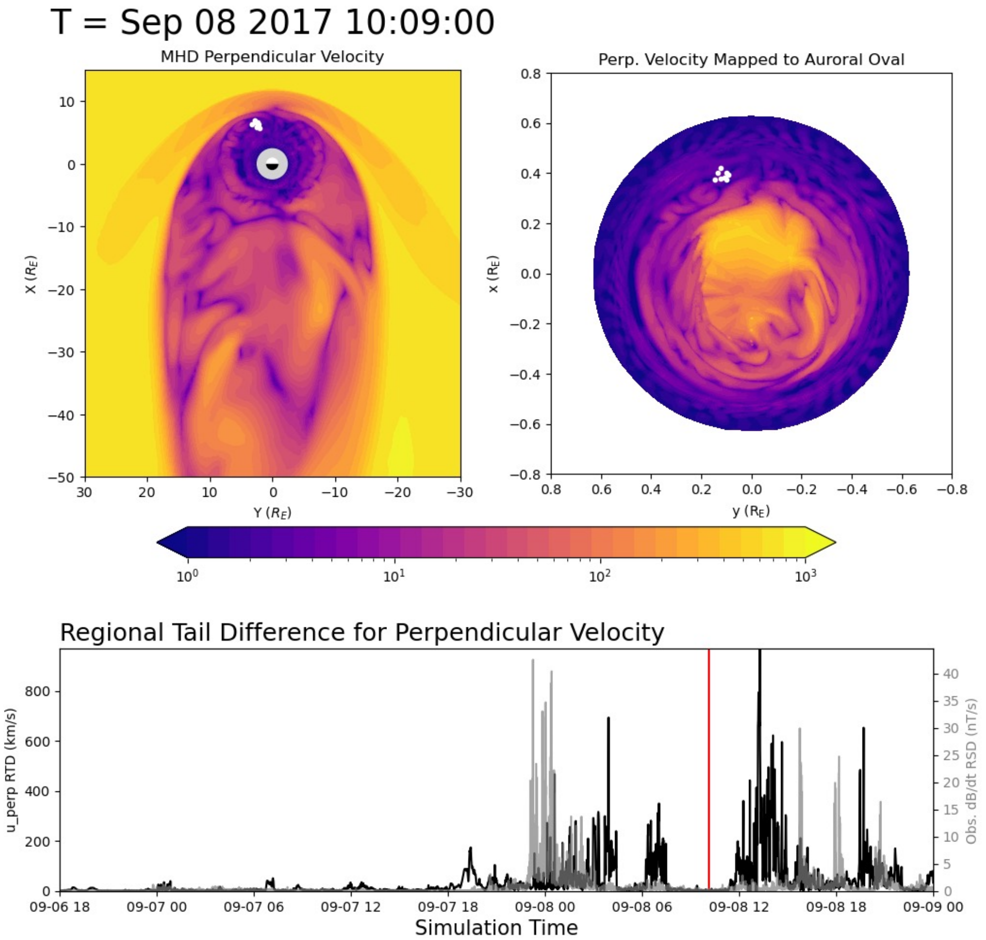
What can the model tell us?

- We are looking for drivers of localiz[...] we must examine magnetospheric conditions [...] affect magnetometer readings.
- Our mode[...] magnetota[...]

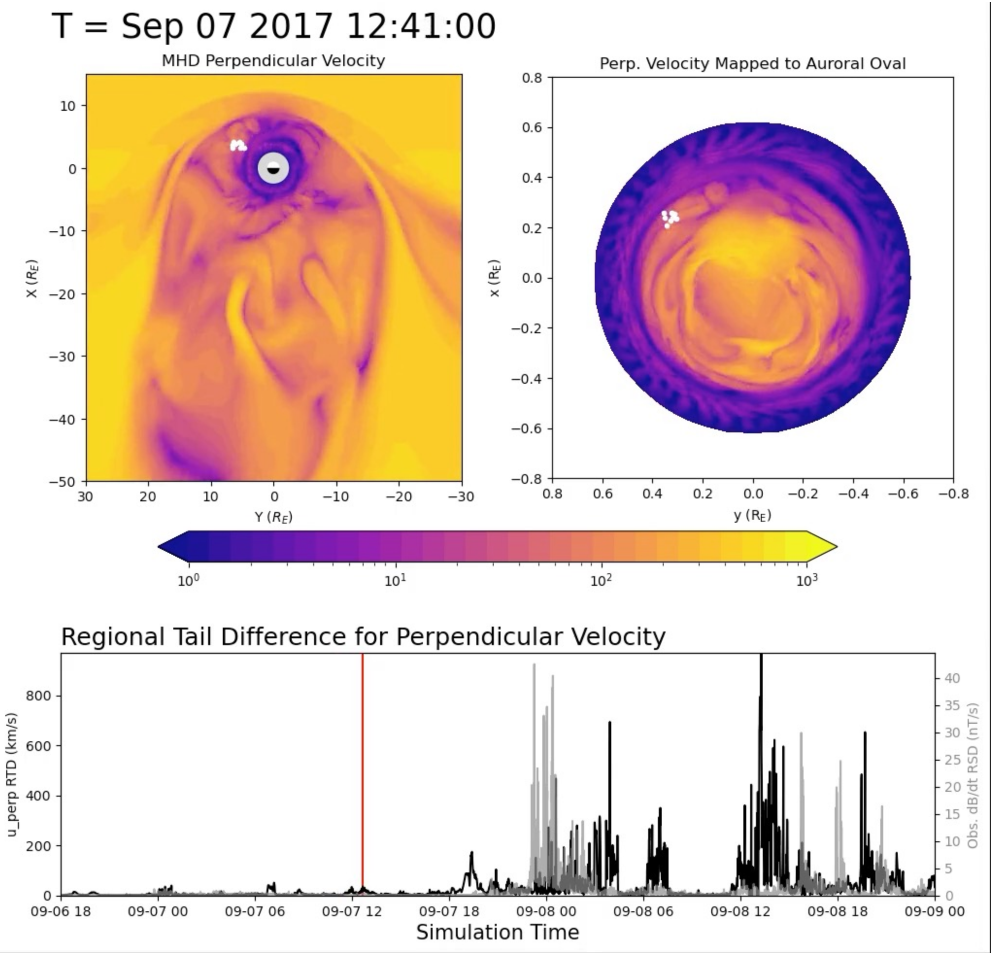


Regional Tail Difference

- To quantify th… …pped to the tail, we define a n… (RTD).
- We calculate … the tail by taking the ma… …apped magnetomete… …the variable.
- A variable's R… …ped tail location records a diff…



Regional Tail Difference

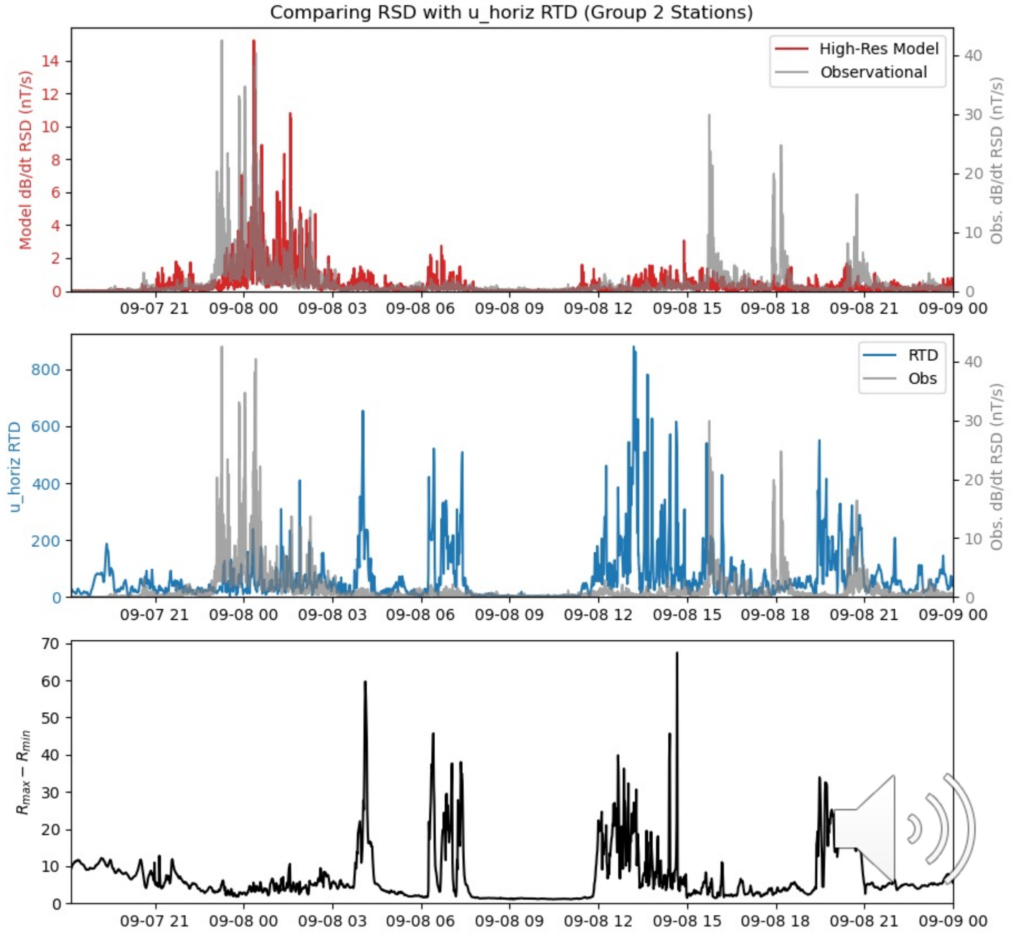


- Two distinct causes of these small-scale effects appear in the model:
- True small-scale structure
- Spread in field line mapping

Spread in Field Line Mapping

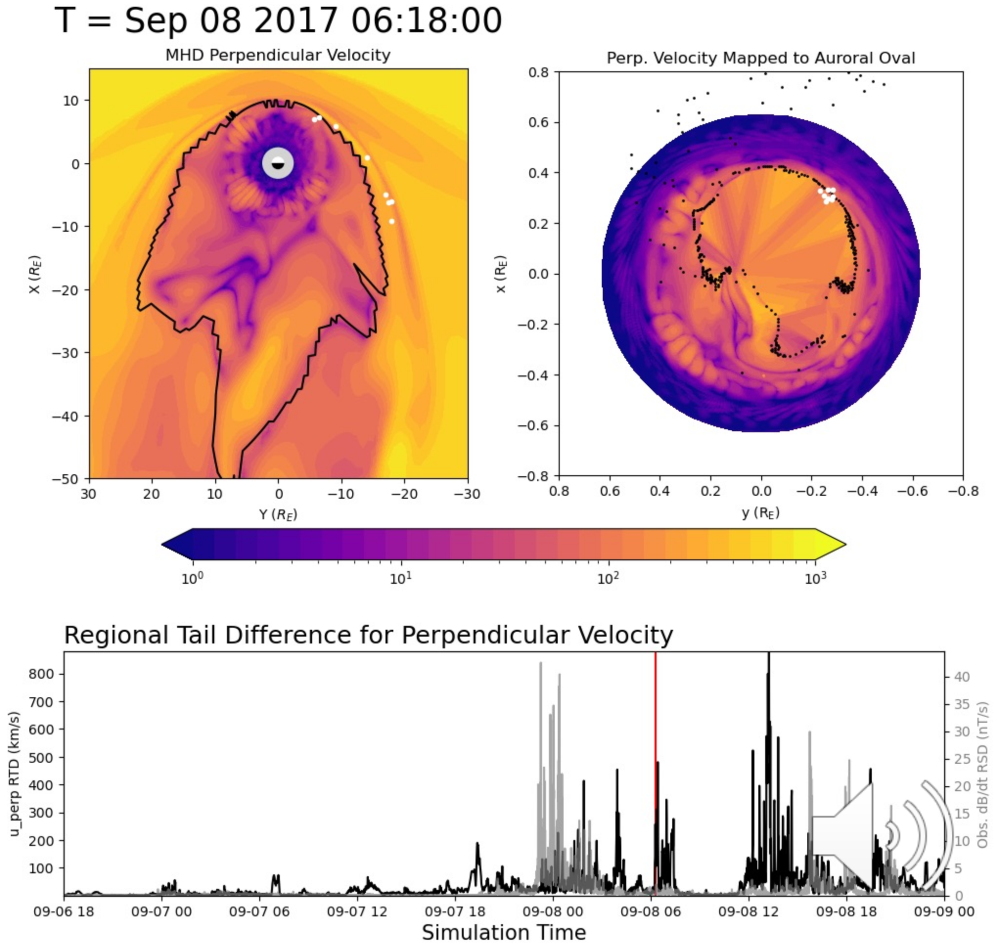
- We examine spread in field line mapping by comparing RSD and RTD for perpendicular velocity to a plot of station spread,
$$R_{max} - R_{min}$$

- Clearly spread in field line mapping is important – what is causing it?



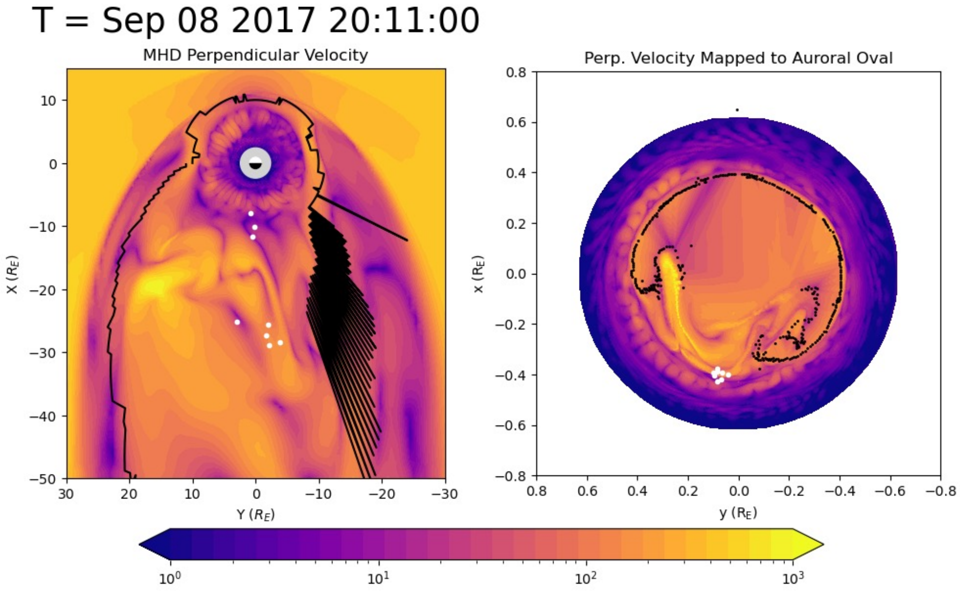
Open-Closed Field Line Boundary

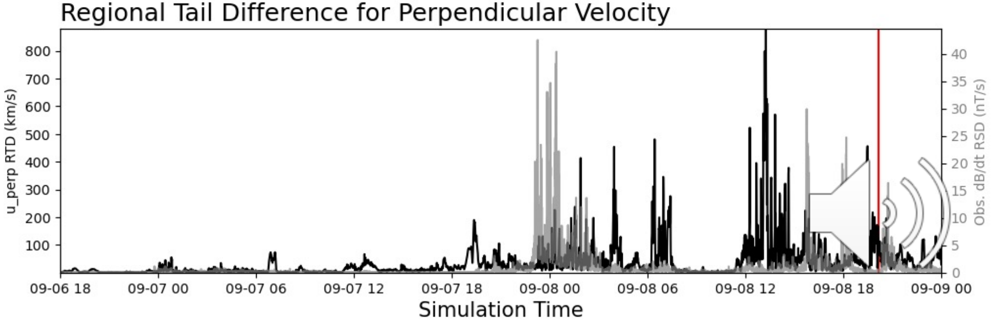
- To look for causes of spread in field line mapping, we examine the boundary between open and closed magnetic field lines in our model.
- We see that proximity to the open/closed field line boundary can affect spread in field line mapping



Fast Flows in the Tail

- Spread of field line mapping does not exclusively occur near the open/closed field line boundary
- Fast flow shears can also cause spread in station field line mapping
- Is there another MHD state variable that will show this effect more explicitly?





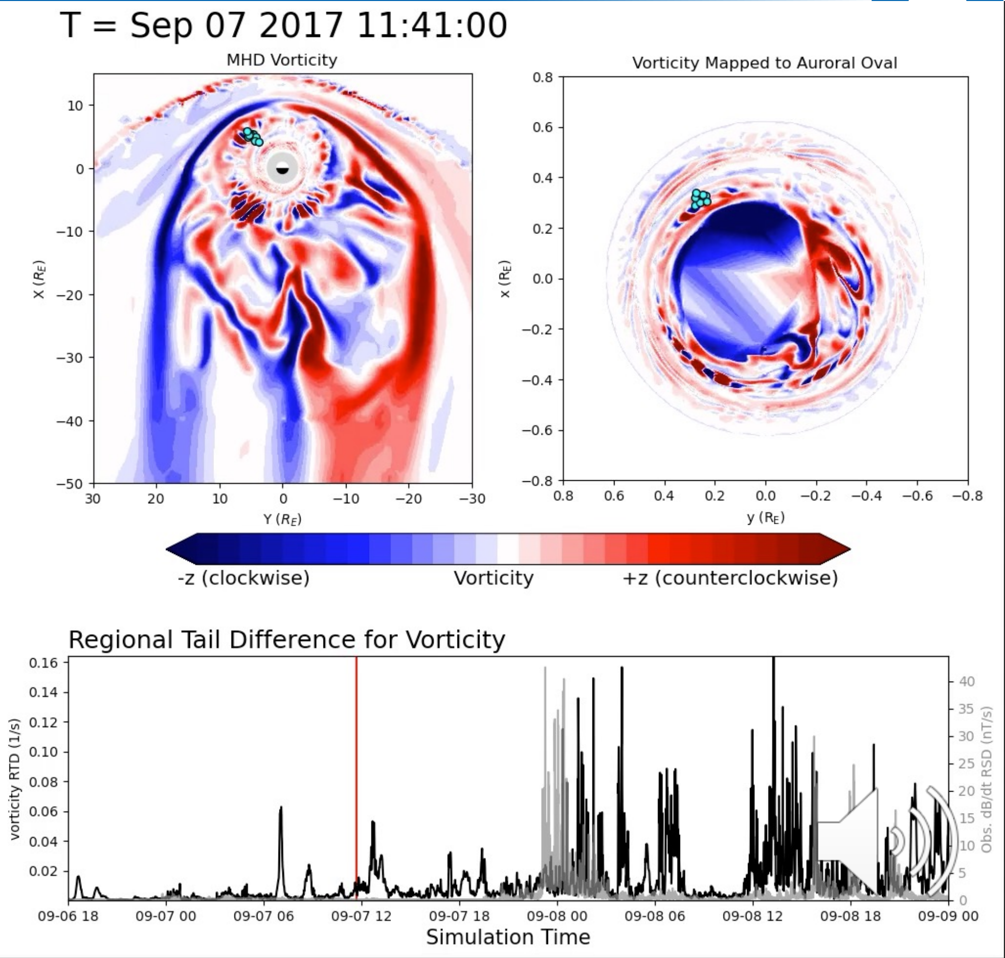
Vorticity

- Vorticity also correlates to station spread
- Under the limit of the frozen-in flux theorem, Ampere's law becomes

$$\nabla \times B = \mu_0 J$$

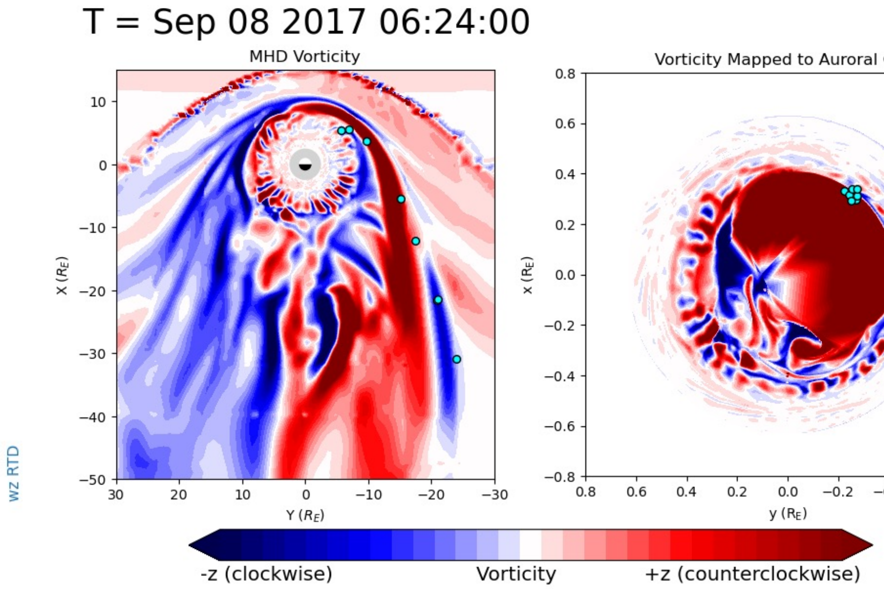
- Because magnetic field moves with plasma, we can see how the field-aligned currents (FACs) move by examining the vorticity

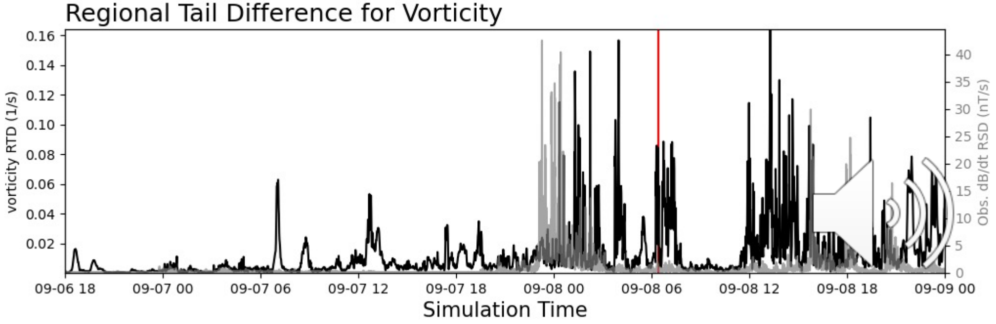
$$\nabla \times u$$



Vorticity

- Of all the state variables from the MHD output, the RTDs for vorticity and perpendicular velocity correlate most closely with $R_{max} - R_{min}$
- As with perpendicular velocity, we identify times that vorticity causes spread of field line mapping



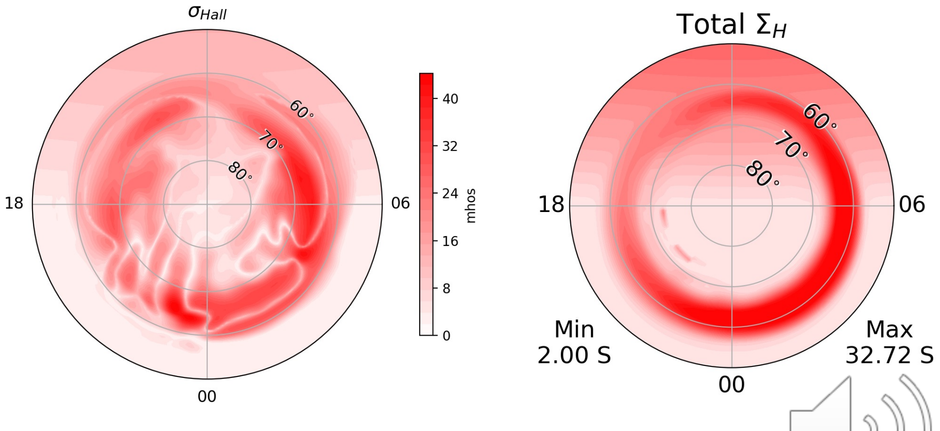


Conclusions

- Two classes of localized GMDs hypothesized:
  - localized magnetospheric/ionospheric activity
  - spread in magnetic field line mapping of stations
- Analysis of MHD state variables shows various hypothesized causes for spread in field line mapping:
  - Proximity to the open/closed field line boundary in the model
  - Fast flow shears in the tail
- We still have unanswered questions:
  - How do we quantify causes of spread in field line mapping?
  - What are causes of localized GMDs not associated with spread of field line mapping?
  - Can we make model improvements to help answer these questions?

Model Improvements - MAGNIT

- **MAGN**etosphere **I**onosphere **T**hermosphere Conductance Model
- Physics-based model replacing empirical ionosphere model
- Provides Global-MHD derived auroral conductance
- Particle precipitation contributions weighted by four sources
  - Electron Diffuse Precipitation
  - Ion Diffuse Precipitation
  - Monoenergetic Precipitation
  - Broadband Precipitation
- MAGNIT clarifies the structure in the ionosphere and improves the smearing of conductance present in the empirical model



Without MAGNIT

With MAGNIT

Next Steps

- Development and incorporation of MAGNIT is ongoing and full use will allow us to answer more questions about GMDs
- We are testing use of a fifth-order solver in our model to increase structure in the tail and examine small-scale structure more effectively
- Questions? Please contact me:
  - elizabeth.vandegriff@mavs.uta.edu