

# Exploring Localized Geomagnetic Disturbances in Global MHD: Physics and Numerics

Erik M. Vandegriff<sup>1,2,3</sup>, Daniel T. Welling<sup>4</sup>, Agnit Mukhopadhyay<sup>5</sup>, Andrew P.  
Dimmock<sup>6</sup>, Steven K. Morley<sup>7</sup>, Ramon E. Lopez<sup>3</sup>

<sup>1</sup>American University

<sup>2</sup>NASA Goddard Space Flight Center

<sup>3</sup>University of Texas at Arlington

<sup>4</sup>University of Michigan

<sup>5</sup>Center for Space Environment Modeling, University of Michigan

<sup>6</sup>Swedish Institute of Space Physics (IRF)

<sup>7</sup>Los Alamos National Laboratory

## Key Points:

- High resolution Space Weather Modeling Framework can reproduce Localized Geomagnetic Disturbances (LGMDs) driven by ionospheric sources.
- Magnetospheric disturbances associated with substorms appear in model, but effects do not translate to LGMDs on the ground.
- Improvements to calculation of ionospheric conductance and capture of substorm dynamics in model needed to better predict LGMDs.

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Corresponding author: Erik M. Vandegriff, [vandegri@american.edu](mailto:vandegri@american.edu)

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## Abstract

One of the prominent effects of space weather is the formation of rapid geomagnetic field variations on Earth's surface driven by the magnetosphere-ionosphere system. These Geomagnetic Disturbances (GMDs) cause Geomagnetically Induced Currents (GICs) to run through ground conducting systems. In particular, localized GMDs (LGMDs) can be high amplitude and can have an effect on scale sizes less than 100 kilometers, making them hazardous to power grids and difficult to predict. In this study, we examine the ability of the Space Weather Modeling Framework (SWMF) to reproduce LGMDs in the September 7, 2017 event using both existing and new metrics to quantify the success of the model against observation. We show that the high-resolution SWMF can reproduce LGMDs driven by ionospheric sources, but struggles to reproduce LGMDs driven by substorm effects. We calculate the global maxima of the magnetic fluctuations to show instances when the SWMF captures LGMDs at the correct times but not the correct locations. To remedy these shortcomings we suggest model developments that will directly impact the ability of the SWMF to reproduce LGMDs, most importantly updating the ionospheric conductance calculation from empirical to physics-based.

## Plain Language Summary

Studying the negative effects of space weather on Earth is a crucial part of protecting ourselves and our technology from solar phenomena. Fluctuations in Earth's magnetic field cause high-amplitude currents to run through ground conducting systems such as underwater cables and power lines, causing damage to the hardware. Being able to predict these magnetic field fluctuations is essential to protecting ourselves and our technology; however these effects can be highly localized, making them more difficult to predict. This study presents an analysis of a high-resolution model run of Earth's magnetic field that captures localized magnetic fluctuations on the ground. We use the model results to explore the causes of these fluctuations in the model and compare the results with observation. We show that the model can reproduce magnetic fluctuations associated with some dynamics in Earth's ionosphere, but misses some of the fluctuations caused by complex dynamics farther out in Earth's magnetic field. We also show that in some cases the model captures fluctuations at the correct times but not the correct locations. Finally we suggest model improvements that will directly improve our model's ability to reproduce and predict localized magnetic fluctuations.

## 1 Introduction

As the solar wind interacts with Earth's magnetic field, it transfers mass and energy into the magnetosphere (Dungey, 1961) and generates currents that flow through the magnetosphere and close through the ionosphere. One of the prominent effects of the solar wind-magnetic field interaction is the formation of rapid geomagnetic field variations on Earth's surface driven by the magnetosphere-ionosphere system. Induction of  $dB/dt$  and ground conductivity causes the geoelectric field, which in turn causes Geomagnetically Induced Currents (GICs) to run through ground conducting systems (Bedrosian & Love, 2015; Pulkkinen et al., 2017; Ngwira et al., 2018). Because currents in the magnetosphere can close through small regions in the ionosphere, GICs can be highly localized and of large amplitudes (Ngwira et al., 2015), which can have an intensely adverse effect on the power grid (Kappenman, 1996; Boteler et al., 1998; Molinski, 2002). GICs are manifestations of space weather that have been studied extensively to advance our understanding of magnetosphere-ionosphere interactions and to protect our ground conducting systems (Pulkkinen et al., 2013; Pulkkinen, 2015; Ngwira & Pulkkinen, 2019; Mate et al., 2021).

In cases studying the effects of magnetosphere-ionosphere interaction on GICs, the geomagnetic field rate-of-change  $dB/dt$  is used as a proxy for GICs. This eliminates the

need to analyze geoelectric field or compute ground conductivity, since  $dB/dt$  will show the locations at which we expect to see large geoelectric fields that cause GICs (Ngwira et al., 2018; Dimmock et al., 2020). For observational data, we use  $dB/dt$  recorded by ground magnetometers as well as spacecraft data to uncover GIC drivers. However, observations also show extreme localization of these Geomagnetic Disturbances (GMDs), with  $dB/dt$  varying widely between magnetometers that are spaced within 100-200 km of each other (EPRI, 2020; Engebretson, Pilipenko, et al., 2019; Dimmock et al., 2019). As a result, Localized GMDs (LGMDs) prove extremely difficult to monitor routinely, and typical spacing between magnetometer stations is larger than the possible spatial scale of the variability in  $dB/dt$ . Current literature presents drivers of LGMDs through observations, and we aim to model and predict them using global magnetohydrodynamics (MHD) to replicate the locations and strengths of magnetic field fluctuations on the ground. However, current configurations of MHD have limitations, both known and unknown, making their use challenging (Welling et al., 2018; Welling, 2019). For example, fundamentally kinetic physical processes are excluded from MHD, making substorm effects at high latitudes unpredictable (Dimmock et al., 2021). In addition, prediction of LGMDs requires models that can capture these effects at faster-than-real-time, which can be computationally expensive. Ongoing efforts to study GMDs in global models include Pulkkinen et al. (2013), which presented a statistical analysis of the current ability to accurately predict GMDs based on an entire set of models, magnetometer stations, and events. While literature shows that models can meaningfully reproduce and predict some LGMDs, the accuracy, completeness, and usefulness of these models is limited by our understanding of the underlying physics that causes LGMDs and our ability to reproduce this physics in our models (Dimmock et al., 2021; Welling et al., 2017; Mukhopadhyay et al., 2020).

Table 1 presents the following information about individually identified drivers of LGMDs: Column one lists known drivers of LGMDs seen in observation; column two lists each driver's associated phenomenology; and column three lists current capability to reproduce LGMDs caused by each driver in global MHD models. Our capability ranges from strongly able to Unknown, where "Unknown" indicates that existing literature has not yet identified the phenomenon as a driver of LGMDs in global MHD models, and whether or not models in their current form can reproduce the driver has not been determined.

As pointed out in Dimmock et al. (2019), substorms are one of the known drivers of localized geomagnetic disturbances. Several of the phenomena in Table 1 are associated with substorms, and existing literature demonstrates connections between LGMDs and substorm signatures both in observation and models. On the observational side, Ngwira et al. (2018) examined spacecraft data from two events and drew a strong connection between LGMDs and multiple auroral processes that are associated with substorms. Engebretson, Steinmetz, et al. (2019) showed rapid geomagnetic variation following substorm onsets in Canada. EPRI (2020) showed LGMDs associated with auroral structures developed during later stages of substorms. Freeman et al. (2019) showed a connection between substorm dynamics and enhanced ground magnetic field in the U.K. On the modeling side, scientists have used global models to explore several of the phenomena listed in Table 1. Several of these use the Space Weather Modeling Framework (SWMF) (Tóth et al., 2005) and are directly related to this work. Haiducek et al. (2020) showed that the SWMF's ability to reproduce substorm signatures is statistically significant, but weak. Blake et al. (2021) explored the expansion of the equatorward boundary and used the SWMF to approximately reproduce this expansion, although they suggested higher-resolution simulations to better explore extreme events in the model.

Most relevant to this work are three papers that examine GICs in observation and in the SWMF during the September 7, 2017 event. Dimmock et al. (2019) compared GICs observed in Fennoscandia to a combination of ground conductivity models and geoelec-

**Table 1.** Drivers of LGMDs identified from existing literature, each with a phenomenology and documentation of our current capability to reproduce the given driver in global MHD models.

| Drivers of LGMDs                                                             | Phenomenology                                                                                | Capability in Global MHD                                                                          |
|------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|
| <b>Bursty Bulk Flows</b><br>(Wei et al., 2021)                               | Regional fast tail flows producing wedgelets (Birn et al., 2004)                             | Can reproduce<br>(Wiltberger et al., 2015)<br>(Garcia-Sage et al., 2015)<br>(Eshetu et al., 2019) |
| <b>Omega Bands</b><br>(Apatenkov et al., 2020)                               | Omega-shaped auroral structure formed from regional fast flows (Vokhmyanin et al., 2021)     | Unknown                                                                                           |
| <b>Pulsating Aurora</b><br>(Zou et al., 2021)                                | Formed from wave-particle interaction during substorms (Nishimura et al., 2020)              | Unknown                                                                                           |
| <b>Poleward Boundary Intensification</b><br>(Nishimura et al., 2013)         | Ionospheric manifestation of distant reconnection (Ohtani & Yoshikawa, 2016)                 | Can reproduce; unclear if possible locally (Blake et al., 2021)                                   |
| <b>Auroral Streamers</b><br>(Nishimura et al., 2011)<br>(Lyons et al., 2021) | Narrow auroral flow propagating toward equatorward boundary (Sergeev et al., 2004)           | Unknown                                                                                           |
| <b>Expansion of auroral bulge</b><br>(Ngwira et al., 2018)                   | Intensification of westward electrojet due to substorm current wedge (Viljanen et al., 2006) | Can weakly reproduce (Haiducek et al., 2020)<br>(Yang et al., 2012)                               |

122 tric field models to show ground conductivity’s importance on the accuracy of the model.  
 123 Dimmock et al. (2020) defines useful metrics for identifying localized dB/dt occurrences,  
 124 connects ionospheric processes to localized dB/dt, and emphasizes the importance of us-  
 125 ing local rather than global metrics to predict regional variability. Dimmock et al. (2021)  
 126 evaluated the SWMF’s ability to reproduce auroral indices and magnetic field data dur-  
 127 ing the same event, and noted that higher resolution simulations performed significantly  
 128 better.

129 A notable takeaway from these studies is that ionospheric fluctuations and substorms  
 130 are significant drivers of LGMDs, and there is not a clear picture of how well global MHD  
 131 models capture these phenomena on spatial scales that translate usefully to the ground.  
 132 However, a detailed comparison of high resolution model output to observation can give  
 133 insight into which drivers of LGMDs are captured with global MHD models, which drivers  
 134 are not captured, and what changes we must make to our models to improve overall pre-  
 135 diction skill. In this study, we present an analysis of the Sept 7, 2017 storm that follows  
 136 from the processes in Dimmock et al. (2020) and Dimmock et al. (2021), using high-resolution  
 137 SWMF model results. Section 2 describes the high-resolution SWMF setup, defines the  
 138 metrics we use to evaluate SWMF performance, and divides the event into separate time  
 139 periods. Section 3 compares metrics and model features in each of the different periods  
 140 and uses SWMF output features to draw conclusions about the drivers of LGMDs and  
 141 the model performance of the SWMF. Section 4 concludes with additional open ques-  
 142 tions and suggested methods for improvements in the data-model comparison.

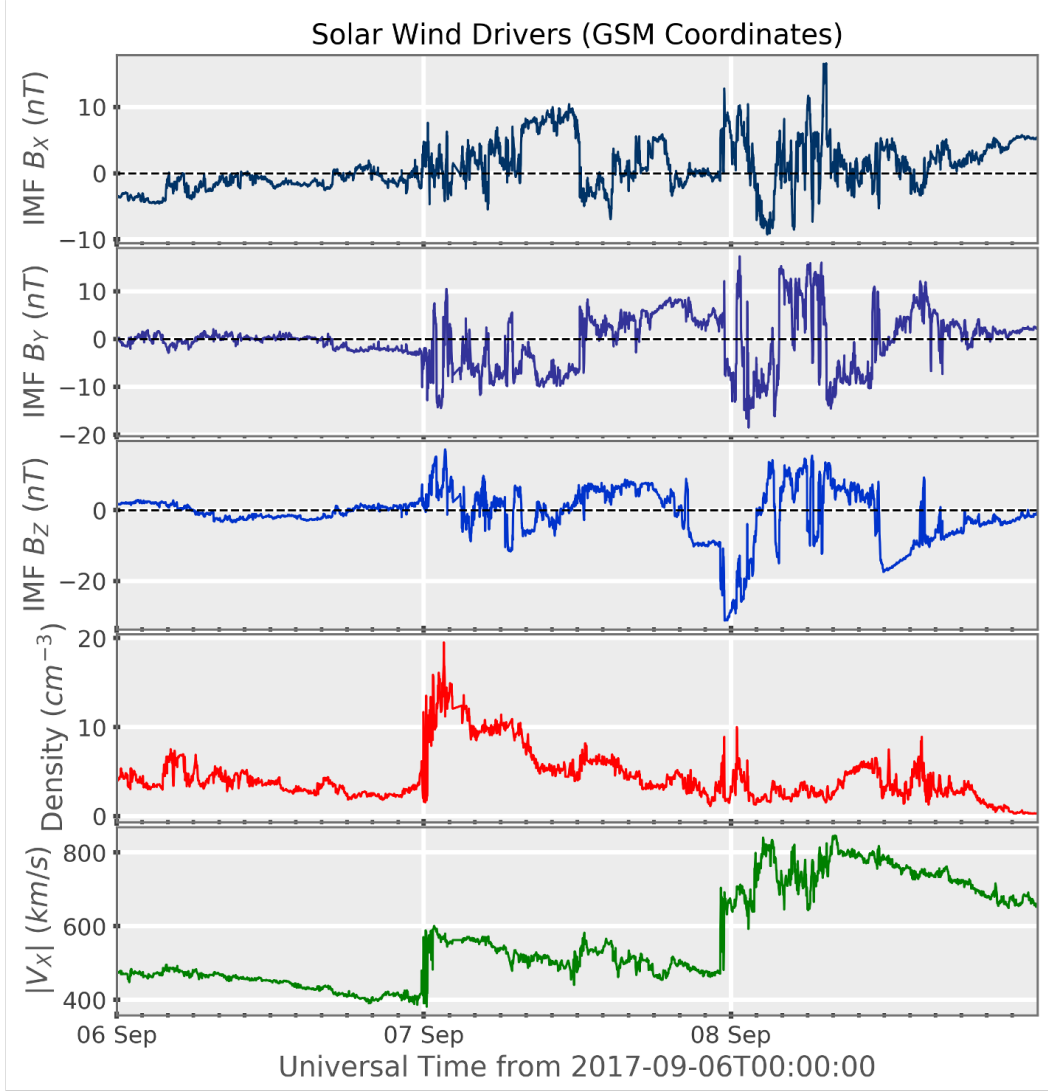


**Figure 1.** SWMF inputs for the September 6-8, 2017 event are solar IMF, density, and solar wind speed. Data are from OMNI.

## 2 Methodology

### 2.1 Model and Data Setup

In this study we use a high-resolution configuration of the Space Weather Modeling Framework (SWMF) (Tóth et al., 2012; Gombosi et al., 2023), which couples three physical models that describe the magnetosphere-ionosphere system. The Block Adaptive Tree Solar-Wind Roe Upwind Scheme (BATS-R-US) (Powell et al., 1999) uses ideal magnetohydrodynamic equations to model the global magnetosphere and has a block-adaptive grid that models regions of interest with higher spatial resolution. The Ridley Ionosphere Model (RIM) (Ridley et al., 2004) is a shell ionosphere calculated by solving 2-D Ohm's Law. The Rice Convection Model (RCM) (Wolf et al., 1982) is a drift model of the inner magnetosphere. As the model progresses in time, the three models run independently for small time periods, stop to exchange variable information, and continue running with updated coupled values.

Figure 1 shows the upstream solar wind conditions taken from OMNI that we use as the inputs to the SWMF for the September 6-8, 2017 event, which is a relevant storm that has been examined by previous studies for its significance to GICs (Dimmock et al., 2019, 2021; Piersanti et al., 2019). We specify F10.7 flux in the model configuration and use it as a proxy for EUV radiation to set conductance. SWMF output is a rich set of relevant magnetospheric and ionospheric variables at an output frequency of one minute. In this study, we use a configuration of the SWMF slightly modified from the operational Space Weather Prediction Center (SWPC) setup. Dimmock et al. (2021) analyzed three increasingly high-resolution grid configurations of the SWMF and showed that the highest resolution configuration most closely matched observation. In this work we present results matching the highest resolution configuration shown in Dimmock et al. (2021), with a minimum cell separation of  $1/16$ th  $R_E$ , to capture the most detailed magnetospheric structure. Ionospheric structure is resolved to 1-degree by 1-degree. This level of detail maps near-body structures to less than 1-degree spacing on the ground. More detail about the grid configuration can be found in Welling and Liemohn (2014).

SWMF output includes a grid of virtual magnetometers that we can use to compare to real-life magnetometer data. These virtual magnetometers use Biot-Savart integrals to calculate magnetic perturbations from four different current sources - Hall currents, Pedersen currents, field-aligned currents, and currents from anywhere in the MHD region of the simulation (Yu & Ridley, 2008). The real-life data that we compare to the SWMF virtual magnetometers comes from the IMAGE magnetometer network (Tanskanen, 2009). Dimmock et al. (2020) uses the same set of magnetometers in Fennoscandia, grouped into Subset 1 and Subset 2. Subset 1 contains 4 magnetometers at geographic latitudes from 75 to 80 degrees. Subset 2 contains 8 magnetometers at geographic latitudes from 65 to 70 degrees. We use the magnetometer data from Subset 2, because although the stations sit at lower latitudes, they provide a better fit to the observational data for this study. Subset 2 magnetometers are separated from each other by approximately 100 kilometers and form a total area of approximately 500 by 200 kilometers. Table 2 lists the stations along with their geographic latitudes and longitudes.

**Table 2.** List of stations from IMAGE magnetometer network used in this study. This list corresponds to Subset 2 from Dimmock et al. (2020). Coordinates are geographic east.

| Station     | Code | GLat (°) | GLon (°) |
|-------------|------|----------|----------|
| Abisko      | ABK  | 68.35    | 18.822   |
| Kevo        | KEV  | 69.76    | 27.07    |
| Kilpisjärvi | KIL  | 69.06    | 20.77    |
| Kiruna      | KIR  | 67.84    | 20.42    |
| Masi        | MAS  | 69.46    | 23.07    |
| Muonio      | MUO  | 68.02    | 25.53    |
| Pello       | PEL  | 66.90    | 24.08    |
| Tromsø      | TRO  | 69.66    | 18.94    |

## 2.2 Event and Metrics

In this study we focus on LGMDs in the space weather event during September 6-8, 2017. This event features complex interaction between two Interplanetary Coronal Mass Ejections (ICMEs) that caused localized GIC activity on the ground. This storm, shown in Figure 1, is of particular interest because it is characterized by a collection of different features present in the solar wind conditions, including two sudden storm commencements and two instances of southward-turning IMF  $B_z$ . The storm begins on Septem-

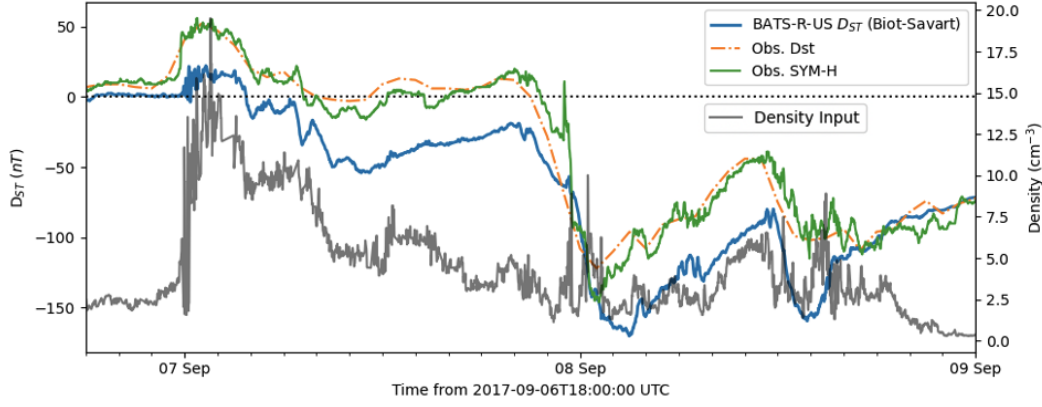


**Figure 2.** Comparison between SWMF Dst, observed Dst/SYM-H, and density input shows a two-hour time shift between model and observation that translates to a shift between model and observational RSD comparison.

ber 6 and its effects continue through September 7 and 8. The first sudden storm commencement occurs at midnight on the 7th, and the second occurs at midnight on the 8th. In both cases the solar wind speed jumps by 200 km/s at the time of the commencement. The most prominent instances of southward-turning IMF  $B_z$  occur at midnight on the 8th, and noon on the 8th.<sup>1</sup> There is evidence of substorm activity following both the first shock and the second (Clilverd et al., 2018; Dimmock et al., 2019).

Storm-time indices calculated from the SWMF output can indicate the overall performance of the run when compared to their observed counterparts. Figure 2 shows observed and modeled Dst, observed SYM-H, and the solar wind number density (an input to the model). Overall, the model captures the dynamics of the storm well, and modeled Dst consistently follows observed Dst/SYM-H with a RMSE of 33.5 nT between BATS-R-US Dst and observed SYM-H. The minimum value of Observed SYM-H reaches -122 nT and the minimum BATS-R-US Dst reaches -170 nT. We note that the initial positive jump in modeled Dst, which is calculated at 1-minute resolution, occurs approximately two hours after the observed jump in Sym-H, which is also measured at one-minute resolution. In addition, we note that the initial jump in the density happens simultaneously with the Dst from BATS-R-US, indicating that the input to the model has a time delay as well. This delay comes from a combination of error in propagating data from a point measurement near L1 toward Earth, and inadequate characterization of the Earth-impacting solar wind from a point measurement. These types of error have been previously documented (Borovsky, 2018; O’Brien et al., 2023) and can manifest as time delays and uncertainty in the model results (Morley et al., 2018).

To begin quantifying the model’s ability to capture LGMDs, we adopt the metric Region-to-Specific Difference (RSD) from Dimmock et al. (2020) and calculate RSD for  $dB/dt$  at each 1 minute interval during the event using Equation 1.

$$RSD_{dB/dt} = \max\left(\left|\frac{dB_H}{dt} - \frac{d\overline{B_H}}{dt}\right|\right) \quad (1)$$

To determine the value of RSD for  $dB/dt$  at a given timestep for the set of magnetometers listed in Table 2, we first calculate  $dB_H/dt$  for that timestep at each magnetometer location, where  $dB_H/dt$  is the horizontal component of the change in magnetic field at a particular location. We then calculate the average  $dB_H/dt$  of the entire

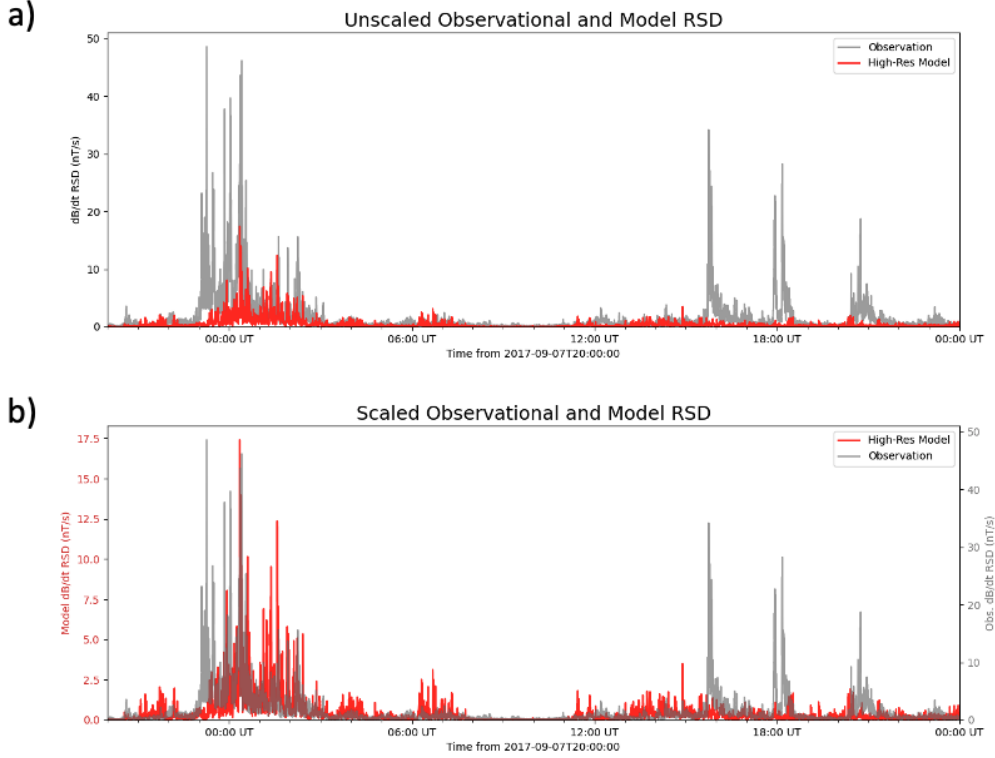


**Figure 3.** Region-to-Specific Difference (RSD) for the entire September 2017 event. Panel *a* shows the comparison between model and observational data with both model and observation on the same scale. Panel *b* shows the comparison between model and observational data, with model RSD scaled to match the observational data. RSD calculated from IMAGE magnetometer station data is in gray, and RSD calculated from the SWMF virtual magnetometer output is shown in red.

set of stations and subtract it from the  $dB_H/dt$  of each individual station. The maximum value in this set is the RSD for  $dB/dt$  at that single timestep. Because RSD compares  $dB/dt$  recorded by a magnetometer to the average  $dB/dt$  of the other magnetometers in the set, RSD spikes when a single magnetometer yields a much different value than all the others in the set, indicating that an LGMD has occurred. RSD is particularly useful because it examines LGMDs in relation to the ground magnetometer sites, rather than pinpointing exact locations of LGMDs on the ground in the simulation. This creates a more direct comparison between model and data.

In addition to calculating RSD for observational magnetometer data, we can calculate RSD for the virtual magnetometers in our model output to see how well our model can reproduce the spikes in RSD that indicate LGMDs. Figure 3a shows the unscaled comparison between virtual magnetometer stations and real-world magnetometer readings. We can note several things from this initial comparison of observed versus modeled RSD. First, the model captures activity in the first half of the event, from September 7, 23:00 UTC to September 8, 03:00 UTC, but fails to capture the RSD spikes between September 8, 15:00 UTC to September 8, 22:00 UTC in the second half of the run. Second, the model does not reproduce RSD spikes with the same magnitude as observation. The observed spikes with the highest amplitudes reach up to nearly 50 nT/s, whereas the modeled RSD spikes hit their top amplitude at nearly 20 nT/s. Third, we see that

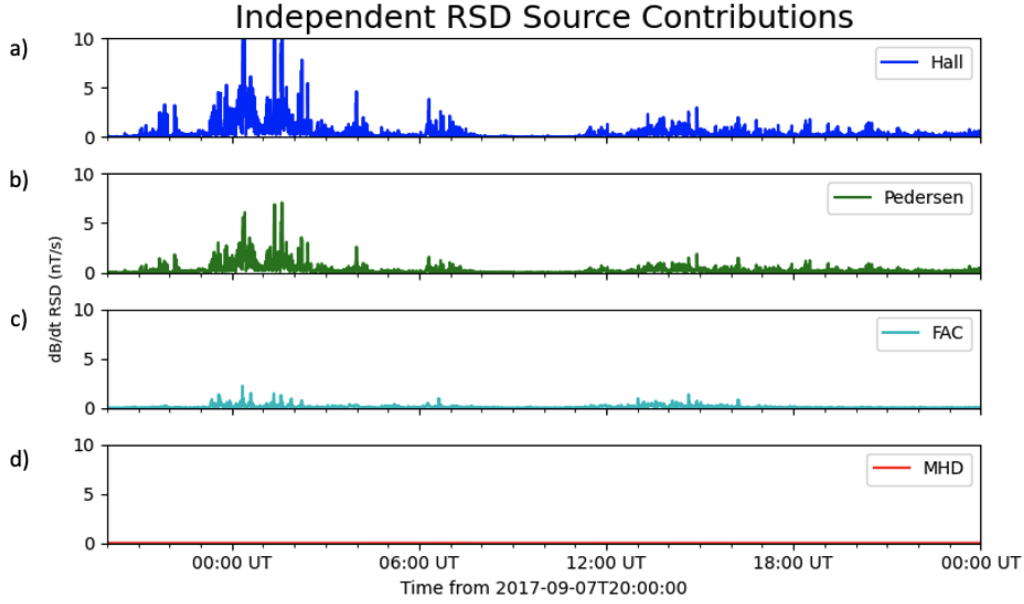


**Figure 4.** Region-to-Specific Difference (RSD) for the entire September 2017 event split by each current source used in the model to calculate  $\text{dB}/\text{dt}$  RSD using in Biot-Savart integrals. Panel *a* shows the contribution from the Hall currents, Panel *b* shows the contribution from the Pedersen currents, Panel *c* shows the contribution from the field-aligned currents, and Panel *d* shows the contribution from the MHD currents.

the background RSD for the model matches fairly well with observation in the unscaled version on the comparison, but when model results are scaled to observation as in Figure 3b, the background amplitudes are higher than observed RSD.

Figure 3b shows the clearest example of the effects of the time shift between model and observation seen in Figure 2. When the model results are scaled to match observation, we see the strongest model RSD peaks centered around September 8, 00:30 UT appearing approximately 1.5 hours after the strongest observed peaks in RSD, which matches the time shift seen in Figure 2.

In Figure 4, we break down the modeled  $\text{dB}/\text{dt}$  RSD by contribution from each Biot-Savart integral source to get indicators about the potential drivers of LGMDs (Welling, 2019). We see in Figure 4a that the Hall currents contribute most to the total, Pedersen and Field-Aligned Currents (FAC) contribute moderate amounts as shown in Figures 4b and 4c, and the MHD current contribution shown in 4d is negligible. This provides an initial indication of which regions are most important to driving RSD spikes in the model.

Besides examining RSD on the ground, we can calculate RSD for state variables anywhere along the magnetic field lines mapped through the 3-D model domain. In the SWMF, BATS-R-US uses tracing to map magnetic field lines from the ground, through the ionosphere, and into the magnetosphere. Tracing allows us to follow along field lines from magnetometer locations on the ground and differentiate the sources of ground perturbations from the ionosphere and magnetosphere. In this work we show comparisons with the two most relevant variables - horizontal currents in the ionosphere and vorticity in the tail. Horizontal currents, consisting of the Hall and Pedersen currents, are relevant because they are the top contributors to the modeled RSD seen in the breakdown in Figure 4. Vorticity is important because it can provide information about the field-

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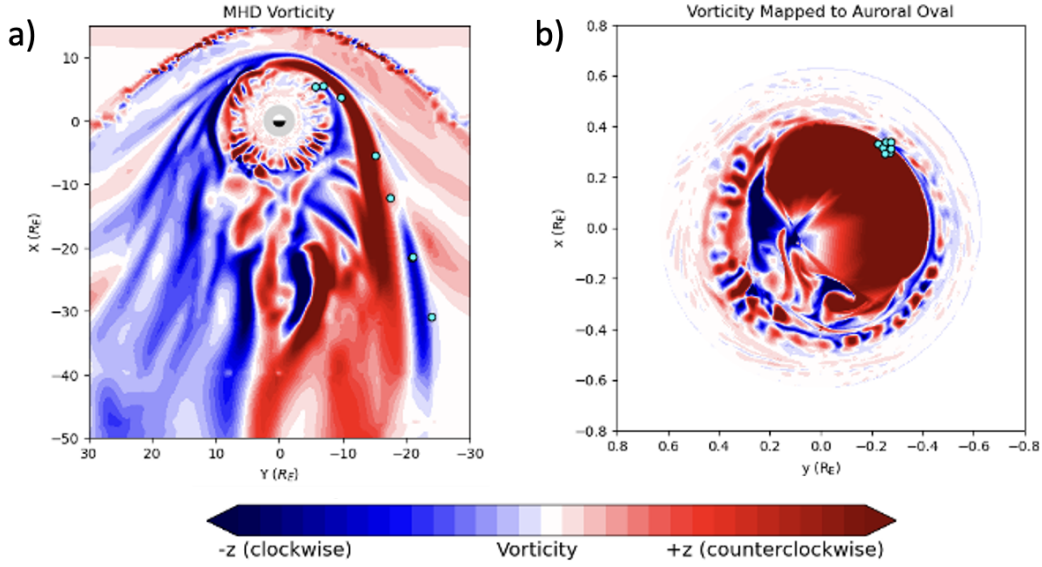


**Figure 5.** Vorticity contours with teal dots showing locations of magnetometer stations mapped from the ground along magnetic field lines. Panel *a* shows vorticity in the equatorial plane and panel *b* shows vorticity in the northern hemisphere. We see a spread of the stations down the tail as the station locations are caught in the shear flows along the magnetosheath.

aligned currents, which are the third contributor to the RSD source breakdown in Figure 4c. Because of the frozen-in flux theorem, we can use the equation  $\mu_0 J = \nabla \times \vec{B} \propto \nabla \times \vec{u}$  to relate the curl of the magnetic field to the vorticity, which is the curl of the velocity. So to examine how the field-aligned currents are related to LGMDs, we extract the vorticity in the equatorial plane at the mapped field line locations ( $RSD_{tail}$ ). To examine Hall and Pedersen currents, we extract the RSD of the horizontal currents in the ionosphere at the locations of the magnetometer stations mapped along field lines ( $RSD_{iono}$ ). We then compare  $RSD_{tail}$  and  $RSD_{iono}$  throughout the storm to  $RSD_{dB/dt}$  on the ground to gain insight into which ionospheric and the magnetospheric sources drive which periods of LGMDs in the model.

Following the station locations along field lines also allows us to track how far apart the field lines deviate from each other as they reach the equatorial plane. Figure 5 shows the effect of field lines spreading apart from each other when they are traced back to the magnetosphere. Figure 5a shows a slice through the X-Y equatorial plane at  $Z=0$ , looking down on Earth from above. Figure 5b shows the northern hemisphere. The color-bar indicates vorticity strength and direction, with red contours indicating vorticity coming out of the page in the +Z direction, and blue contours indicating vorticity entering the page in the -Z direction. The teal dots in Figure 5b indicate the station locations on the ground, and the teal dots in Figure 5a indicate where those station locations map along field lines. We see that for this specific epoch of the model output, the station locations map to vastly disparate locations in the tail. We call this separation of the field lines "station spread," and we quantify the amount of station spread at any given timestep in time by subtracting the minimum distance between stations from the maximum. The existence of station spread indicates that larger dynamics in the magnetosphere can map down to small locations on the ground, meaning that all LGMDs are not necessarily caused by small spatial-scale structure.

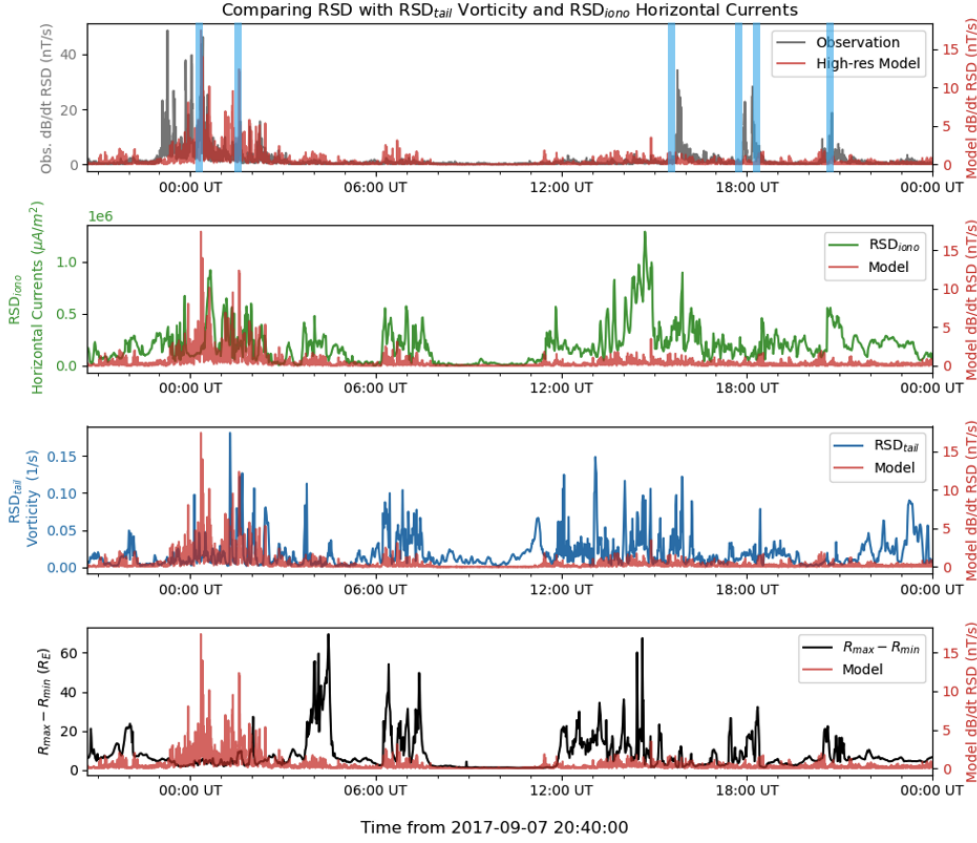


**Figure 6.** Comparing model RSD to four different values and metrics. Panel a) compares model RSD to observational RSD and shows blue lines where substorms have been identified in observation. Panel b) compares model RSD to  $RSD_{iono}$  calculated for horizontal currents in the ionosphere, panel c) compares model RSD to  $RSD_{tail}$  calculated for vorticity in the equatorial plane, and panel d) compares model RSD to "station spread", calculated using  $R_{max} - R_{min}$ .

### 3 Results

We can now use the metrics defined in the previous section to more closely examine the entire September 7, 2017 event to quantify SWMF capability to reproduce LGMDs and theorize drivers of LGMDs in the model. Figure 6 shows the comparison among these metrics in different regions of the simulation over the entire event, as well as the substorms identified from observation both in Clilverd et al. (2018) and from the SuperMAG list created from Forsyth et al. (2015) during times when the stations were on the night-side. Figure 6a shows modeled and observed RSD for dB/dt on the ground. Figure 6b compares modeled dB/dt RSD and  $RSD_{iono}$  for the horizontal currents in the ionosphere. Figure 6c shows modeled dB/dt RSD and  $RSD_{tail}$  of the vorticity in a slice through the magnetosphere like the one shown in Figure 5.

In Figure 6d we compare modeled dB/dt RSD to the station spread metric calculated by subtracting the minimum spatial separation between any two stations from the maximum spatial separation between any two stations. Looking at the overall behavior of RSD in horizontal currents, vorticity, and station spread, we see periods of activity coinciding with the Dst drops in Figure 2 around September 8, 00:00 UT and September 8, 12:00 UT. Note that 6a compares model and observation, so the time shift dis-

cussed in the methodology is present in this comparison. Figures 6b, 6c, and 6d compare model values only, so there is no time shift present in these plots.

To quantify both model performance and causes of individual RSD spikes, we examine two shorter time periods within the event. Part A of the event covers September 7, 22:00 UTC through September 8, 09:00 UTC, and Part B covers September 8, 13:00 UTC through September 9, 00:00 UTC. Figure 7 shows Part A of the event. Part A is characterized by a period of clear correlation between dB/dt RSD spikes in the model and in observation from September 7, 23:00 UTC to September 8, 03:00 UTC, seen in Figure 7a. Figures 7b-d show comparisons between the modeled dB/dt RSD on the ground and the modeled RSD calculated in other regions of the simulation. In Figure 7b we see strong correlation between modeled RSD and RSD\_iono calculated for the horizontal currents in the ionosphere. In Figure 7c we note some correlation between modeled dB/dt RSD and RSD\_tail calculated for the vorticity in the tail. In 7d we see little to no station spread in the region of large RSD spikes, however between September 8, 03:00 UTC to September 8, 08:00 UTC we see peaks in station spread corresponding to peaks in both RSD\_tail and RSD\_iono, with very slight peaks in the modeled RSD on the ground. These peaks in station spread indicate periods of time during which the complex magnetic field structure traced in the model causes large-scale structures in the tail to map down to small spatial regions on the ground, indicating that large-scale phenomena in the magnetosphere can drive LGMDs.

Figure 8 shows Part B of the event. During this period of time we see three prominent spikes in observed dB/dt RSD, none of which are reproduced in the model RSD on the ground shown in Figure 8a. Taking into account the time shift between observation and model and comparing the observed RSD to the horizontal currents, vorticity, and station spread shown in 8B, 8C, and 8D respectively, we see some correlation with horizontal currents, faint correlation with vorticity, and clear correlation with station spread for two out of the three spikes.

Because Part B of the storm is associated with strong substorm activity (Dimmock et al., 2021; Clilverd et al., 2018), we examine this period in the context of observable substorm signatures in the model. Studies of modeling substorms in global MHD show that we are able to capture substorm activity in a significant way starting with early efforts and continuing into the present. Lyon et al. (1998) shows global MHD reproducing polar cap flux values seen in observation during a substorm, and while there are differences between observation and simulation, it is clear a global picture of substorm activity can be obtained from MHD. Haiducek et al. (2020) has demonstrated that MHD can reproduce key ground-based signatures of substorms, such as AL-negative bays and mid-latitude signatures, although often with weaker amplitudes than in observation.

For this particular storm, the model does not show the manifestation of substorm activity in Part B as LGMDs on the ground. We examine other parts of the model to look for substorm signatures, particularly around September 8, 18:00 UT where the second peak in Figure 8a can be seen in observational dB/dt RSD but not in the model RSD on the ground. The top panel of Figure 9 shows a slice through the X-Z plane of the magnetosphere at the time of this disturbance on September 8, 18:42 UT. The contours illustrate thermal pressure, which is strongest in the ring current and plasmashet but minimal throughout the lobes. The thick red lines illustrate the last-closed magnetic field lines; light black lines illustrate other magnetic field lines traced through the plane. These field lines show the clear development of a substorm expansion: a near-Earth reconnection line around  $20R_E$  downtail and the spiraling field lines corresponding to a plasmoid. In subsequent minutes, the plasmoid is released and the newly reconnected closed field lines dipolarize. This is a textbook example of tail dynamics during a substorm (Hones, 1979) and they occur in conjunction with the real-world substorm signatures. In the bottom panel of Figure 9 we show a timeseries of the inclination angle calculated at various points in the tail. Near the orange line that coincides with the exact time in the top

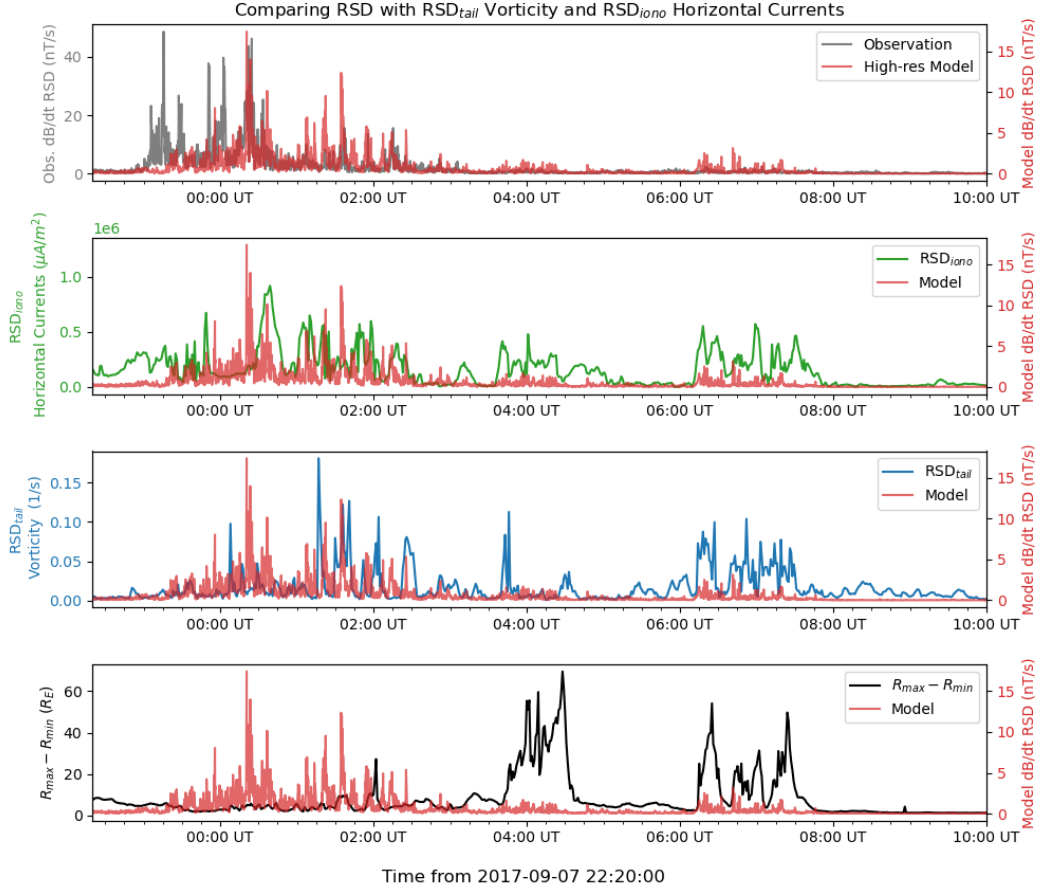


**Figure 7.** Same as Figure 6 but zoomed in on Part A of the September 2017 event (September 7, 23:00 UTC to September 8, 03:00 UTC). We see a closer view of the correlation between modeled RSD and horizontal currents in the main part of the storm.

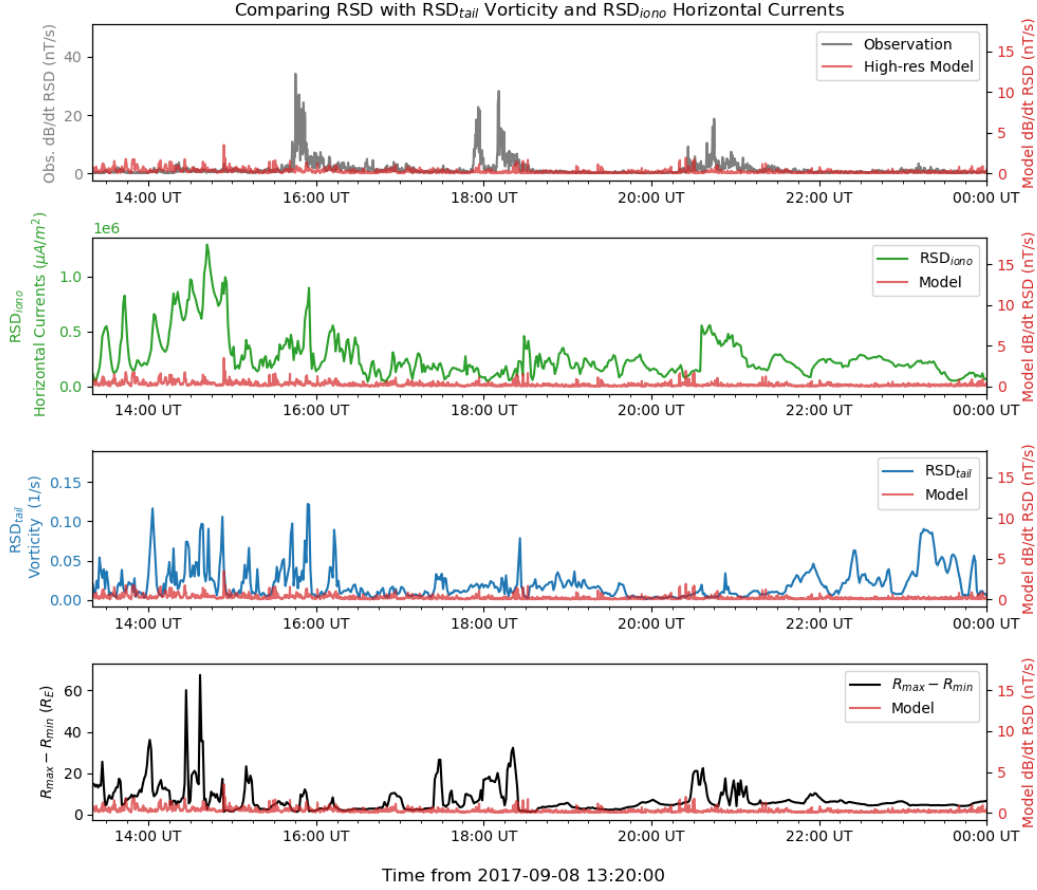


**Figure 8.** Same as Figure 6 but zoomed in on Part B of the September 2017 event (September 8, 13:00 UTC through September 9, 00:00 UTC). Part B shows the three RSD peaks associated with substorm activity, and only weak correlations with RSD<sub>iono</sub>, RSD<sub>tail</sub>, and station spread.

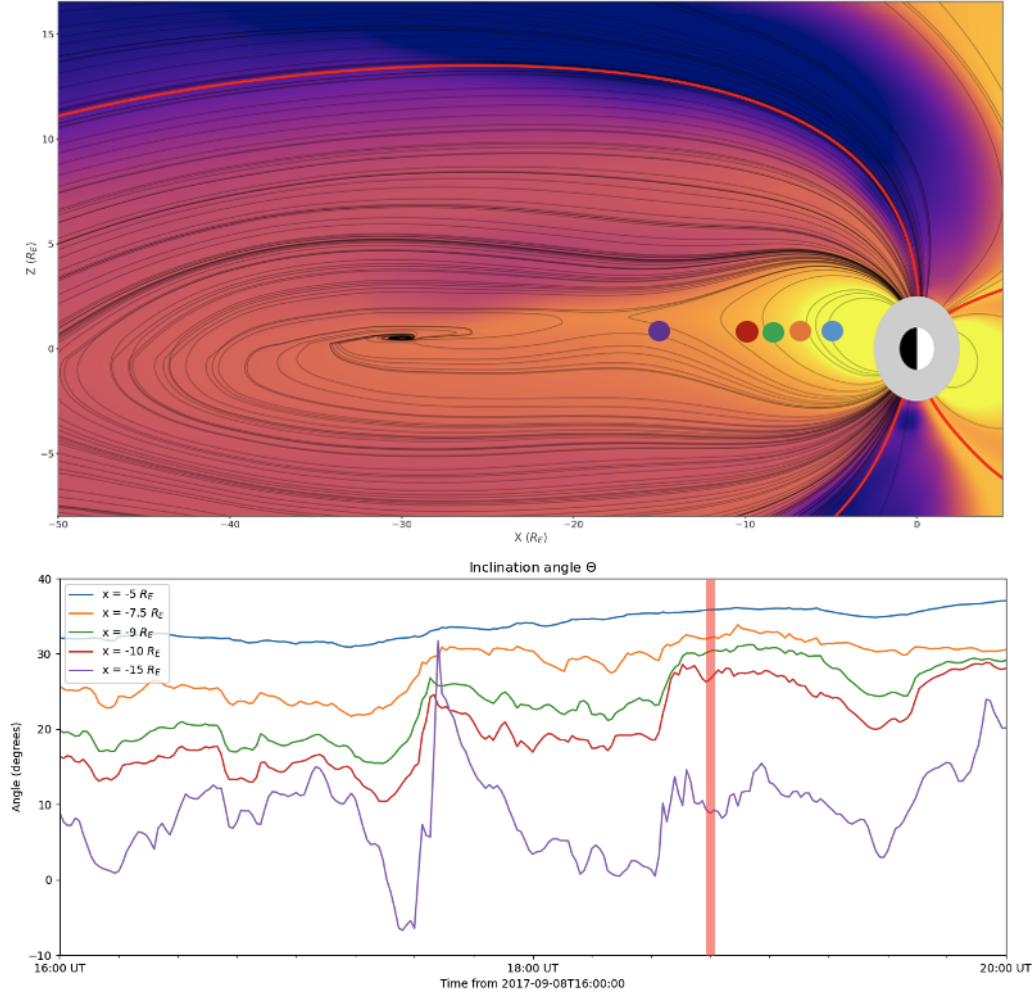


**Figure 9.** Magnetic field lines in an x-z slice of the magnetosphere during September 8, 18:42 UT. In the top panel we see plasmoid release/dipolarization indicating the presence of substorm signatures in the model. The colored dots correspond with the x location of the colored curves in the bottom panel. In the bottom panel at the orange line indicating the exact time of the top panel, we see the inclination angle increases further downtail, but becomes less prominent closer to Earth. This indicates that the energy transfer associated with the substorm does not translate down to the ground the way that observed reality indicates.

panel, we see that the inclination angle increases more drastically downtail, but is very slight close to Earth. Despite good model-observation association, the model produces only weak ground signatures and a slight LGMD event. A discussion of the possible reasons that the model fails translate the tail dynamics into a clear ground signature is presented in the next section.

#### 4 Discussion and Conclusions

Our analysis of the September 7, 2017 event leads us to several broad conclusions both about the drivers of LGMDs in the model during this event and about the ability of the SWMF to reproduce LGMDs. Firstly, we have shown that we can reproduce the period of increased LGMD activity seen in the first part of the run. By examining the

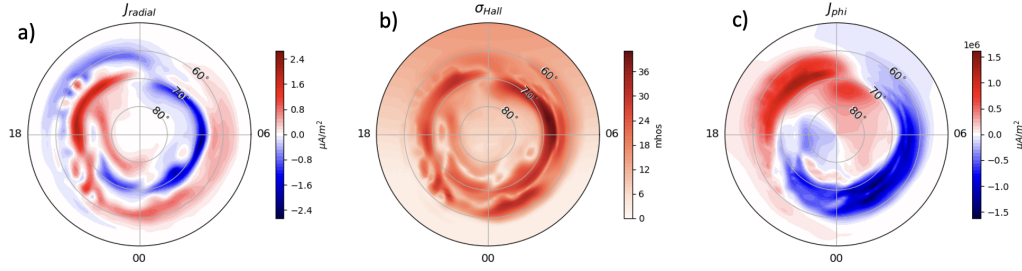


**Figure 10.** FAC, Hall conductance, and horizontal currents from the Ridley Ionosphere Model using the legacy conductance model.

model output, we see that the main drivers of RSD during this period are small spatial scale magnetospheric and ionospheric activity.

Secondly, several times during this event we see a clear correlation between station spread, magnetospheric vorticity, and horizontal ionospheric currents, indicating that some of the drivers of LGMDs are accompanied by station spread. Because points at such disparate locations in the magnetosphere can map to adjacent points on the ground, some of the LGMDs may be caused not by small-scale structure in the tail, but by large-scale storm dynamics in the magnetosphere that map to small-scale features on the ground. Thirdly, from this study we can also clearly note the limitations of the model regarding LGMDs. The amplitudes of RSD peaks are lower in the model than in reality, and we cannot capture large-amplitude RSD peaks in the second half of the event. We can hypothesize various causes for these deficiencies in the model, and propose model improvements that will directly address these deficiencies.

A likely reason behind the lower LGMD magnitude in the model is the empirical conductance model employed in these simulations (Mukhopadhyay et al., 2020, 2022). Ionospheric conductance remains an outstanding challenge for global MHD simulations, especially concerning predictions of ground magnetic perturbations (Welling et al., 2017; Welling, 2019; Mukhopadhyay et al., 2021). The conductance model employed here is an empirical relationship between conductance and local FAC strength. The auroral oval location is fit to upward FAC and additional conductance term is applied broadly over the oval. The result is a conductance pattern that is smooth and spatially broad, allowing horizontal currents to close over a wide area. This means that FACs driven by small scale features in the magnetosphere (for example, the localization of vorticity or flow shears illustrated in Figures 6 and 7) can disperse once they arrive at the ionosphere as their closure path is broad. Real world auroral features and, therefore, conductance channels, can be narrow and complex. FACs closing through these conductance bands form narrow electrojets, concentrating current to smaller areas.

So long as the basic empirical conductance model is used, many mechanisms for generating LGMDs in the SWMF will be circumvented. With the current conductance model, these currents become "smeared" across the ionosphere, giving the false impression that flow channels and other ionosphere phenomena are more spread out than in observed reality. This causes RSD in the model to be weaker, which is reflected in the amplitude difference between model RSD and observed RSD. An example of this is shown in Figure 10. 10a shows the field-aligned currents in the northern hemisphere at the same epoch as Figure 9 - September 8, 18:42 UT. We see that the SWMF resolves these currents well, showing good localized structure during enhanced ionospheric activity. In Figure 10b, we see Hall conductance calculated using the empirical conductance model. In Figure 10c, we see the horizontal currents in the ionosphere. While the SWMF captures

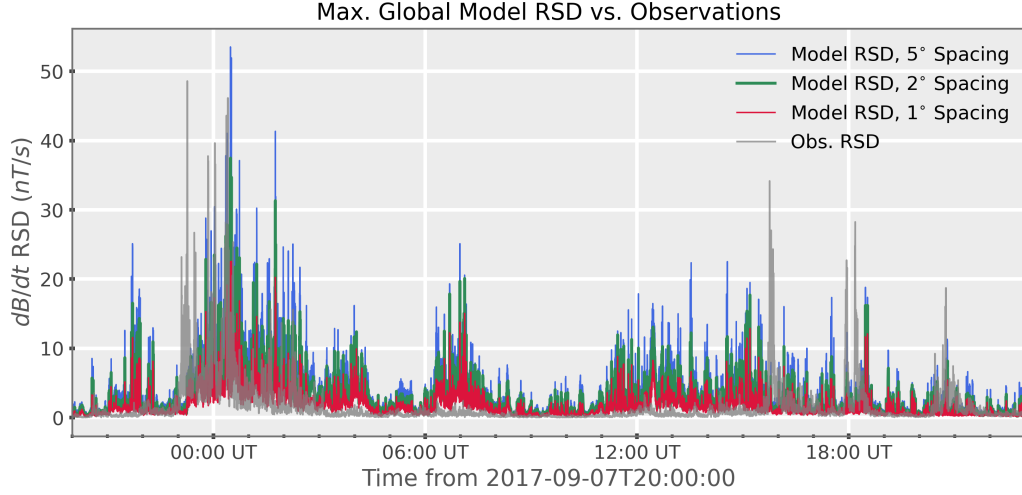


**Figure 11.**  $dB/dt$  RSD as observed (light gray line) and maximum global RSD from the simulation result using a  $1^\circ \times 1^\circ$  stencil (red line), a  $2^\circ \times 2^\circ$  stencil (green line), and a  $5^\circ \times 5^\circ$  stencil (blue line).

the approximate shape of the horizontal currents, we can clearly see the smearing that occurs as a result of the conductance. While these diffuse currents can be useful in observing global phenomena, localized features are much more difficult to resolve. Transitioning from the legacy empirical conductance model to an advanced physics-based approach (Mukhopadhyay et al., 2022) that retains small scale structure will be a critical next step in LGMD research.

Another explanation for the RSD spikes not present in the model is the possibility that the model does capture them, but not in the precise locations we are examining. Reproducing LGMDs requires that the model precisely captures the precise location of the source of LGMDs, both in the magnetosphere and the ionosphere. Small discrepancies in source location can greatly degrade data-model comparisons, even though the physics of the model may have performed admirably overall.

To explore the potential of this issue, a global maximum  $dB/dt$  RSD was calculated from the model. Virtual magnetometers were placed at a  $1^\circ \times 1^\circ$  latitude-longitude spacing across the entire northern hemisphere. A 4-point,  $1^\circ \times 1^\circ$  stencil was used to calculate RSD in one location. This stencil was then shifted by  $1^\circ$  in longitude and RSD was calculated again. This process was repeated over the full range of longitudes, then the stencil was shifted  $1^\circ$  in latitude and the longitude range scanned again. Once the stencil has been shifted across the entire northern hemisphere, the maximum RSD was saved and the process repeated for all points.

Figure 11 shows the result of this process. The red line is the global RSD from the entire northern hemisphere; the gray line is the observations-based RSD for reference. Compared to the model RSD drawn only from the stations listed in Table 2, there is substantially more LGMD activity. RSD spikes are more frequent in time and have a much higher typical amplitude, now rivaling the amplitudes of the observations-based values. There is extensive LGMD activity outside of the periods where such activity was observed, but this is not surprising as the model RSD values in this figure represent activity anywhere across the globe compared to the limited range represented by the magnetometers used in the observational set. Notably, there is much more LGMD activity during the

three main substorm related spikes, with a significant RSD spike occurring near the observed spikes near 18:00UT. This figure demonstrates that the SWMF is indeed capable of producing significant localization of GMD activity, including activity related to substorms. However, there is much work remaining to improve the location of such spikes to better represent real-world activity.

While the model RSD magnitudes in Figure 11 better correspond to those from the observations, the largest values are still not achieved. This leaves open the question that model may not be capturing LGMD development on the same scale as the real world. To investigate this further, the process used to create the red line in Figure 11 was repeated, but with progressively larger stencil sizes that include more points for each RSD calculation. For example, a  $3^\circ \times 3^\circ$  stencil would include  $3 \times 3 = 9$  virtual magnetometer points simultaneously. Each stencil was still only shifted  $1^\circ$  per iteration. Stencil sizes from  $1^\circ$  to  $5^\circ$  were used to see at what point RSD magnitude stopped growing, indicating that the stencil is now larger than typical GMD spatial scale sizes. The green and blue lines in Figure 11 show the global RSD results for  $2^\circ$  and  $5^\circ$  stencil sizes, respectively. Extending the stencil size from  $1^\circ$  to  $2^\circ$  (red to green line) dramatically increases the resulting RSD magnitude, indicating that model activity is better characterized on  $2^\circ$  latitude/longitude scales. This is consistent with scale sizes noted in Engebretson, Pilipenko, et al. (2019) and EPRI (2020). These scales show much better agreement with the observed magnitudes overall, especially early in the event simulation. Beyond this size, amplitudes change far more modestly. The results for  $5^\circ$  stencil sizes (blue line) are very similar to the  $2^\circ$  spacing, indicating that most activity is captured at the finer stencil size. Overall, this comparison demonstrates that the SWMF is capturing smaller scale GMD dynamics, but further work may be required to drive this down to observed scales. This may include further refining the magnetosphere and ionosphere numerical grid or employing better auroral physics as described above.

Finally, this work contributes to the discussion on substorm signatures in global MHD. The SWMF fails to capture three RSD spikes during a period of substorm activity, and although we do see substorm signatures in the model, we do not see these effects translate into LGMDs at the locations we are observing. Historically, the SWMF can capture ionospheric convection and accurately reproduce magnetic field geometry (Welling, 2019). However, we know that the tail reconnection rate in the SWMF is less than in reality which could be a factor in the missing RSD spikes.

Next steps in this study will involve replacing the empirical conductance calculation in the SWMF with a physics-based conductance calculation, the MAGnetosphere Ionosphere Thermosphere (MAGNIT) model (Mukhopadhyay et al., 2022). Because the prediction of LGMDs relies on the location accuracy of ionospheric currents, implementing MAGNIT will improve both the accuracy and amplitude of LGMD predictions. Improvements from MAGNIT may also shed light on the issue of substorm energy transfer to the ground. An additional next step for this work is to couple a ground conductivity model to the high-resolution SWMF output and use the same metrics to quantify improvements. Many papers including Dimmock et al. (2021) and Marshalko et al. (2021) use ground conductivity in Fennoscandia and show correlation to observed GICs when coupling ground conductivity to model results.

## Open Research Section

The SWMF and all components used for this study are openly available at <https://github.com/MSTEM-QUDA/SWMF>. All input and configuration files for the simulations performed in this study as well as the output files from the simulation are stored in a single dataset (Vandegriff, 2023) and can be obtained via <https://doi.org/10.5281/zenodo.10080494>. We acknowledge use of NASA/GSFC's Space Physics Data Facility's OMNIWeb service, and OMNI data (King & Papitashvili, 2020). IMAGE data are available

at <https://space.fmi.fi/image/www/?page=home>. SuperMAG substorm lists are available at <https://supermag.jhuapl.edu/info/>.

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