



RESEARCH ARTICLE

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Key Points:

- ADELPHI, SWMF, low-resolution OpenGGCM with RCM showed more accurate and precise CPCP than LFM-MIX and all types of high-resolution OpenGGCM
- Inclusion of RCM in high-resolution OpenGGCM improved CPCP accuracy, reduced HIJH, and improved HIJH correlations with observed AE
- Ovation Prime showed better HPI in terms of accuracy (RMSE, PE) and bias but ADELPHI showed better precision and data-model correlation

Supporting Information:

Supporting Information may be found in the online version of this article.

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Intercomparison of Model Determinations of Auroral Electrodynamic Parameters

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Abstract Contributing to the objectives of the Committee on Space Research (COSPAR) International Space Weather Action Teams (ISWAT) Auroral Precipitation and High Latitude Electrodynamics (AuroraPHILE) group, various methods and models are compared for determining the auroral electrodynamic parameters during geomagnetically active conditions. Parameters used for comparisons include Cross Polar Cap Potential (CPCP), Hemispherically Integrated Joule Heating (HIJH), and Hemispheric Power Input (HPI). Models tested include Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE) Derived Electrodynamics of the High Latitude Ionosphere (ADELPHI), Lyon-Fedder-Mobarry (LFM) - Magnetosphere Ionosphere Coupler/Solver (MIX), Space Weather Modeling Framework (SWMF), Open Geospace General Circulation Model (OpenGGCM), and Ovation Prime. Modeled CPCP values are compared with the observations from the Super Dual Auroral Radar Network (SuperDARN) and the Defense Meteorological Satellite Program (DMSP). The performance of OpenGGCM is further scrutinized by varying model resolutions. The effects of coupling with the Rice Convection Model (RCM) are also observed. The results showed large and inconsistent differences in the auroral parameters across models. In particular, LFM-MIX and higher-resolution OpenGGCM without RCM generally showed higher CPCP and HIJH than the other models. Low-resolution OpenGGCM with RCM, ADELPHI, and SWMF provided more accurate CPCP. The inclusion of RCM generally improves OpenGGCM model performance. HPI values from ADELPHI were usually higher than those from Ovation Prime and DMSP data. The modeled auroral parameters were moderately correlated with the observations. Modeled HIJH values were also moderately correlated with Auroral Electrojet (AE). Solstitial interhemispheric asymmetries in CPCP and HIJH were observed and explained by varying ionospheric conductances.

Plain Language Summary The incoming solar wind interacts with Earth's magnetic field, creating the magnetosphere, a region that energizes particles and stores electric and magnetic energy. Large solar disturbances and enhanced solar wind conditions cause electric currents and charged particle precipitation in the ionosphere at high latitudes. The charged particle precipitation produces the aurora in the northern and southern polar regions, which heats the atmosphere and modifies the ionospheric electric fields, currents, and conductivities. The currents can, in turn, result in frictional heating of the atmosphere. These disturbances affect satellite orbits and satellite-based communication and navigation systems. The energetic particles can create hazards to spacecraft surfaces and electronics. Accurate estimation of these auroral parameters is important in order to mitigate these problems. Due to limited global observations worldwide, model predicted auroral parameters become essential. In this regard, the determination of model accuracies in different geophysical conditions becomes very important. This paper examines the performance of several commonly used models during geomagnetically disturbed conditions using available observations. The objective is to provide the space weather research and operations community a comprehensive quantitative information about model accuracies in specifying auroral parameters.

1. Introduction

A major focus in understanding the space weather impacts of geomagnetic disturbances is accurate specification of auroral electrodynamics parameters in the high latitude ionosphere. To this end, the Auroral Precipitation and High Latitude Electrodynamics (AuroraPHILE) group was formed by the Committee on Space Research (COSPAR) as one of the International Space Weather Action Teams (ISWAT) under the Geomagnetic Disturbance Cluster group (team ID G1-03). The major objective of this group is to quantify the accuracies and reliabilities of space weather models in specifying auroral electrodynamics and energy inputs (Robinson et al., 2019). These models simulate the complex physical behaviors that take place due to interactions between

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the solar wind and Interplanetary Magnetic Field (IMF) and Earth's magnetosphere, ionosphere, and thermosphere (M-I-T), which is very challenging. The parameters simulated include energetic particle fluxes, the electric fields, Cross Polar Cap Potential (CPCP), electric current systems, atmospheric Joule heating, ionospheric conductivities, and auroral and polar cap boundaries. Specification and prediction of these parameters are essential in order to mitigate the adverse effects of space weather events on electric power grids, satellites, and telecommunications. Excellent reviews on the societal impacts of space weather events are available from Boteler (2001), Eastwood, Biffis, et al. (2017), Bruinsma et al. (2023), and Opgenoorth et al. (2024). Atmospheric Joule heating at high latitudes during geomagnetically disturbed periods results in satellite drag variations caused by expansion of the thermosphere, traveling atmospheric disturbances, and changes in global neutral wind circulation, atmospheric composition, and plasma transport. These also cause changes in global ionization, which affect satellite-based navigation and spacecraft control systems all over the world. Another auroral parameter, CPCP, indicates the amount of electrodynamic coupling between the solar wind and Earth's magnetosphere at high latitudes (Doyle & Burke, 1983; Reiff et al., 1981). It is a dawn-to-dusk potential difference in the polar cap generated mainly by plasma convection and circulation between the dayside and nightside magnetosphere and ionosphere. Hemispheric Power Input (HPI) is an indicator of total power dissipation by auroral charged particle precipitation at high latitudes. Accurate and reliable predictions of Joule heating, CPCP, and energy input from precipitating energetic particles become essential for many space weather applications. A review of space-weather models, their present status, and future developments was provided by Eastwood, Nakamura, et al. (2017). Variabilities of magnetospheric and ionospheric current systems in different space-weather conditions were elaborated by Milan et al. (2017). In addition to the direct impact of auroral precipitation and energy inputs, electric fields and currents derived from them are also used to set boundary conditions and drive global space weather models. This can help accurate simulation of magnetospheric and ionospheric interactions. The effects of these boundary conditions can be found in Goodman (1995), Ridley et al. (2004), and Merkin and Lyon (2010).

Performance evaluations of different space-weather models have also been reported earlier. Raeder et al. (2001) observed global model performance using ground-based and satellite data in a substorm event. Yu and Ridley (2008) observed the Space Weather Modeling Framework (SWMF) performance using ground-based magnetic perturbation data. Wang et al. (2008) showed the performance of SWMF regarding Field Aligned Current (FAC) and CPCP using satellite data. Pulkkinen et al. (2010) compared the variations in Earth's magnetic field strength measured by ground magnetometer stations and geostationary satellites with SWMF and Open Geospace General Circulation Model (OpenGGCM) results during four geomagnetic storm events. Pulkkinen et al. (2011) also observed model performance in specifying ground-based magnetic perturbations in the northern hemisphere. Korth et al. (2011) used Iridium communication satellite data to assess the performance of SWMF for FAC prediction. Zhang et al. (2011) used the Lyon-Fedder-Mobarry Magnetosphere Ionosphere Coupler/Solver (LFM-MIX) to quantify several ionospheric parameters, including FAC and CPCP. Gordeev et al. (2013) observed the performance of the Grand Unified Magnetosphere–Ionosphere Coupling Simulation (GUMICS)-4 model for predicting different ionospheric and magnetospheric parameters. Honkonen et al. (2013) compared different components of the Earth's magnetic field calculated by Block-Adaptive-Tree-Solarwind-Roe-Upwind-Scheme (BATS-R-US), GUMICS-4, LFM, OpenGGCM with those measured by Cluster 1, Geotail and Wind satellite data. They also analyzed CPCP derived from these models, comparing them with the Super Dual Auroral Radar Network (SuperDARN) observations. They compared MHD model-derived magnetopause standoff distances with the same derived from empirical models. Mukhopadhyay et al. (2021) also observed the performance of LFM-MIX, SWMF, OpenGGCM, and different empirical models for CPCP and magnetopause distance. Gordeev et al. (2015) observed MHD model performance for synthetic space weather events with results from empirical models using linear fits. Kleiber et al. (2016) observed FAC using the LFM-MIX model alongside Iridium satellite derivations. Ridley et al. (2016) studied different model performances for the Earth's magnetic field strength at different satellite orbits and ranked them accordingly. Welling (2019) provided a comprehensive overview of recent advances in different MHD models and their limitations using data-model comparisons for Geomagnetically Induced Currents (GIC). Orr et al. (2023) compared the performances of different electric field models during 7 and 8 September 2017. Florczak et al. (2023) compared ground magnetic field perturbations from the UK network with results from SWMF, LFM-MIX, and OpenGGCM during 17 and 18 March 2015, and 7 and 8 September 2017. Performance evaluation of Joule heating from different models was also reported in the literature, such as Baumjohann and Kamide (1984), Palmroth et al. (2004), and Bagheri and Lopez (2023).

In the present paper, CPCP, Hemispherically Integrated Joule Heating (HIJH), and HPI from several models are compared during selected geomagnetically disturbed events. The models used for CPCP and HIJH comparison are Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE) Derived Electrodynamics of the High Latitude Ionosphere (ADELPHI) (Robinson et al., 2021), LFM-MIX (Goodrich et al., 2004; Lyon et al., 2004; Merkin & Lyon, 2010; Wiltberger et al., 2015), SWMF (Gombosi et al., 2021; Powell et al., 1999; Tóth et al., 2005, 2012), and different versions of OpenGGCM (Raeder et al., 1996, 1998). The models used for HPI comparison are ADELPHI and Ovation Prime (Newell et al., 2009, 2010, 2014). Modeled CPCP are compared with SuperDARN and Defense Meteorological Satellite Program (DMSP) data. Modeled HPI are also compared with DMSP data. In the absence of observations, modeled HIJH performance has been assessed differently, as described in Section 1.1.

The present work extends previous model assessments in several ways. We have provided a comprehensive statistical analysis of model performance by evaluating accuracy, precision, bias, correlations with observations and observed Auroral Electrojet (AE), and standard deviations of modeled outputs. Statistics regarding accuracy involve Root Mean Square Error (RMSE), Prediction Efficiency (PE), maximum amplitude ratio, and percentage time instances for model overestimation/underestimation. The model resolutions and versions used in our paper are different from those in other papers. One unique feature of this paper is the use of different versions of OpenGGCM in order to examine the effects of varying resolutions and the addition of an inner magnetospheric model to a global magnetosphere model (OpenGGCM). The performance assessment of ADELPHI and the use of DMSP data for the evaluation of modeled CPCP and HPI performance are some of the other unique features of our study. We have shown the effects of ionospheric conductances on modeled CPCP, HIJH, radial current densities, and their solstitial interhemispheric asymmetries due to solar radiation. Moreover, we have compared modeled radial current densities with the same from AMPERE observations.

The paper is organized as follows. Sections 1.1–1.3 describes the models, data, and geomagnetically active events used in this study. Section 2 presents the assessment methodology used to compare the model outputs to available observations and with each other. The quantitative results of the comparisons are described in Section 3. Detailed discussions related to model performance, including contributions from model resolution, inner magnetosphere model, ionospheric conductance, and the observed solstitial interhemispheric asymmetry, are provided in Section 4. The conclusions are summarized in Section 5.

1.1. Models and Data Used and Brief Descriptions of Geomagnetically Disturbed Events

1.1.1. ADELPHI

ADELPHI is based on the observations of FAC using data from the Iridium satellite constellation of 66 satellites at an altitude of 780 km in six equally spaced polar orbits at an inclination angle of 86° (Anderson et al., 2014; Waters et al., 2020). The satellites measure the magnetic field perturbations caused by the FAC. These measurements are used to characterize global FAC every 2 min from the data accumulated over 10 min (Anderson et al., 2000; Waters et al., 2001). ADELPHI is based on statistical correlations between FAC and energy fluxes from Robinson et al. (2018) and between FAC and conductances from Robinson et al. (2020). The methodology for calculating the electric potential, electric fields, and horizontal currents from maps of FAC and conductances is described by Robinson et al. (2021). The model results were validated by comparison with the SuperMAG magnetic indices.

1.1.2. LFM-MIX

The LFM model provides the solution of magnetohydrodynamic (MHD) equations (Lyon et al., 2004) related to the solar wind interactions with the Earth's magnetosphere. The MIX model provides information related to the inner boundary conditions (Merkin & Lyon, 2010). The MHD equations consist of equations of mass, momentum, energy conservation, and electromagnetic induction. MIX calculates high-latitude particle precipitation from MHD plasma parameters (Fedder et al., 1995) to derive conductances. It obtains the electric fields and currents in the ionosphere from FAC mapped from the magnetosphere into the ionosphere. The model operates on a distorted spherical grid in Solar Magnetic (SM) coordinates. The LFM-MIX model inputs are the solar wind velocity, plasma density, interplanetary magnetic field strength, orientation, and the geomagnetic dipole tilt angle. It generates time-dependent outputs such as magnetospheric MHD parameters, ionospheric currents, potentials,

flux intensities of energetic particles, and ionospheric conductivities. Our study did not include an inner magnetospheric model such as the Rice Convection Model (RCM) with LFM-MIX.

LFM-MIX has recently been upgraded to a more improved and robust version named Grid Agnostic MHD for Extended Research Applications (GAMERA) (Sorathia et al., 2020; Zhang et al., 2019). It retains the same fundamental numerical algorithms from LFM. However, it provides further numerical upgrades and limits dependence on external libraries. Overall, it is the most optimized version so far. GAMERA is also a part of the Multiscale Atmosphere-Geospace Environment Model (MAGE) designed by the Center for Geospace Storms (CGS), a NASA Drive Center (Sorathia et al., 2023). With the continuing ISWAT-G1 objectives, the performance evaluations of GAMERA will be carried out in the subsequent papers.

1.1.3. SWMF

SWMF is a modeling framework comprising several models, such as BATS-R-US, RCM, and Ridley Ionosphere Model (RIM). It is designed at the Center for Space Environment Modeling (CSEM), University of Michigan. BATS-R-US solves MHD equations outside of $2.5 R_E$ on an adaptive block-based grid in order to resolve structures at high resolution in the near-Earth magnetosphere and on internal boundaries such as shocks (Powell et al., 1999; Tóth et al., 2005). The model is enhanced in the inner magnetosphere by RCM (De Zeeuw et al., 2004) to track drift-kinetic effects. The RCM model was developed at Rice University (Sazykin et al., 2002; Wolf et al., 2007). The system is closed in the ionosphere by the RIM model (Ridley et al., 2001). BATSRUS, RCM, and RIM are coupled through the SWMF framework. The model takes solar wind speed and IMF components as model inputs and plasma pressure, velocity, electric fields, currents, ionospheric Hall and Pedersen conductances, and electric potentials in the ionosphere as outputs. We have used SWMF coupled with RCM and Radiation Belt Environment (RBE) (Fok et al., 2014) in this study.

1.1.4. OpenGGCM

The OpenGGCM model calculates magnetospheric MHD properties (plasma density, temperature, velocity, magnetic field, and electric currents) outside of $2.5 R_E$ on a stretched cartesian grid (Raeder et al., 1996, 1998). The model considers the Earth's dipole with fixed orientation over time during simulations. Ionospheric conductances can be specified empirically (Raeder et al., 1996), or the model can be coupled with the Coupled Thermosphere Ionosphere Model (CTIM) (Fuller-Rowell, Rees, et al., 1996) to provide ionosphere conductances and electric potentials. We have used OpenGGCM with lower and higher resolutions and with and without RCM in order to observe their effects.

1.1.5. Ovation Prime

Ovation Prime is an empirical model designed by Patrick Newell and his colleagues from Johns Hopkins Applied Physics Laboratory (JHU-APL) using 11 years of energetic particle precipitation data from DMSP (Newell et al., 2009, 2010). The binning and sorting of the data distinguish between discrete and diffuse auroral precipitation to specify mean precipitation patterns more accurately. HPI is calculated from the resulting maps of precipitating energy flux. The model needs solar wind data to predict particle precipitation and the resulting HPI. Ovation Prime is further upgraded using the Global UltraViolet Imager (GUVI) data from the TIMED satellite. The new version also removes salt-and-pepper noise and ensures more seamless interpolation to eliminate data gaps occurring after midnight (Newell et al., 2014).

1.1.6. Data Sets Used

For CPCP observations, we have used SuperDARN and DMSP data. SuperDARN is an international radar network located in high latitudes in both hemispheres (Ruohoniemi & Baker, 1998). DMSP is a constellation of polar, sun-synchronous satellites that orbit Earth at an average altitude of 850 km. For CPCP comparisons, data from DMSP satellites F16–F19 are used. For CPCP, DMSP data is available for 9 March 2012 only. Modeled HPI is also compared with DMSP observations. DMSP HPI is calculated by mapping orbital particle fluxes with climatological maps using the relations given in Evans (1987). DMSP HPI was also used previously by Zhang and Paxton (2008). Descriptions of the DMSP HPI data can be found at https://dmsp.bc.edu/html2/dmspssj4_hp.html. We have also used AMPERE radial current density data to evaluate the model performance.

1.2. Model Run Specifications

1.2.1. Simulation Grid Specifications

For LFM-MIX, we have used the version 2_1_5. The resolution of grid cells for LFM_MIX runs in this paper for all events was $106 \times 96 \times 128$ on a distorted spherical grid arrangement similar to Florczak et al. (2023). $106 \times 96 \times 128$ means 106 radial shells (similar to radial points in a spherical grid), 96 latitudinal points (similar to θ in a spherical grid), and 128 azimuthal points (similar to φ in a spherical grid). LFM-MIX grid positions are arranged on shells that are spherical near the Earth and ellipsoidal further out. It creates a cylindrical outline for the outer boundary, axisymmetric around the SM X-axis. The cylinder extends from $-350.5 R_E$ to $30.0 R_E$ in the X-direction and has a radius of $130.2 R_E$ in the Y-Z plane (domain size). The radial resolution is non-uniform, with the finest spacing near the inner boundary and the dayside magnetopause and coarser spacing in the outer regions. Latitudinal resolution varies from uniform at the near-Earth boundary to variable further away from the Earth (to concentrate grid resolution near the X-axis on the dayside and nightside). The azimuthal resolution (in degrees) is uniform, with an angular spacing of $360^\circ/128 = 2.8125^\circ$ in the azimuthal direction. The radial spacing and physical azimuthal spacing of the model in different locations are as follows.

- *Near the Inner Boundary* ($X = 2.2 R_E$, $Y = 0$, $Z = 0$):
 - Radial spacing (dr): $0.1919 R_E$
 - Physical azimuthal spacing ($r \cdot d\theta_{\text{grid}}$): $0.0398 R_E$
- *At Magnetopause Distances* ($X = 10 R_E$, $Y = 0$, $Z = 0$):
 - Radial spacing (dr): $0.1605 R_E$
 - Physical azimuthal spacing ($r \cdot d\theta_{\text{grid}}$): $0.1741 R_E$
- *At Magnetotail Distances* ($X = -30 R_E$, $Y = 0$, $Z = 0$):
 - Radial spacing (dr): $1.0740 R_E$
 - Physical azimuthal spacing ($r \cdot d\theta_{\text{grid}}$): $0.4153 R_E$

The details of this simulation grid can be found on the Community Coordinated Modeling Center (CCMC) webpage at the link https://ccmc.gsfc.nasa.gov/requests/grid_LFM.php. The ionosphere electrodynamics grid spacing for LFM-MIX is $1^\circ \times 1^\circ$ (with additional positions at 0.1° , 0.25° , and 0.5° degrees in latitude from the magnetic poles).

For SWMF, we have used the 20180525 version with 18,558,976 cells. The SWMF grid comprises blocks of constant spacing in cartesian GSM coordinates. It has the finest resolution of $1/8 R_E$ or $0.125 R_E$ near the Earth and the dayside magnetopause. It has coarser cells further away from the inner magnetosphere. The simulation box extends from $-255 R_E$ to $33 R_E$ in the X-direction and $-128 R_E$ to $128 R_E$ in the Y and Z directions in GSM coordinates (domain size). The resolutions at different locations are mentioned below.

- *Near the Inner Boundary* ($X = 2.5 R_E$, $Y = 0$, $Z = 0$):
 - Cell size: $0.125 R_E$ in all directions (X, Y, Z).
- *At Magnetopause Distances* ($X = 10 R_E$, $Y = 0$, $Z = 0$):
 - Cell size: $0.125 R_E$ in all directions (X, Y, Z).
- *At Magnetotail Distances* ($X = -30 R_E$, $Y = 0$, $Z = 0$):
 - Cell size: $0.25 R_E$ in all directions (X, Y, Z).

The details of the simulation grid for SWMF are also obtained from the CCMC website: https://ccmc.gsfc.nasa.gov/requests/grid_BATSRUS.php. The ionosphere electrodynamics grid spacing for SWMF is 1° in latitude and 2° in longitude.

We have used three different types of OpenGGCM runs of version 5.0. They are (i) OpenGGCM with a lower resolution of 3,150,000 cells (with a wider simulation box of 5,816,320 cells) coupled with RCM (referred to as “Low-Resolution OpenGGCM with RCM” henceforth in this paper), (ii) OpenGGCM with higher resolution of dayside emphasis grid with 23,681,600 cells coupled with RCM (referred to as ‘High-Resolution OpenGGCM with RCM’ henceforth in this paper) and (iii) OpenGGCM with same higher resolution of dayside emphasis grid with 23,681,600 cells without RCM (referred to as ‘High-Resolution OpenGGCM without RCM’ henceforth in this paper). This is done in order to observe the effects of (i) varying resolution or simulation grid and (ii) the effects of coupling with an inner magnetospheric model to a global magnetosphere model.

For OpenGGCM, the grid is stretched Cartesian in GSE coordinates with varying resolutions (Raeder et al., 1996, 1998), with the finest near the Earth and the dayside magnetopause. The grid extends from $-350 R_E$ to $33 R_E$ in the X -direction and -96 to $96 R_E$ in the Y and Z directions (domain size). The details of the resolutions are given below.

1. Low-Resolution OpenGGCM with RCM

- *Near the Inner Boundary* ($X = 2.5 R_E$, $Y = 0$, $Z = 0$):
 - X : $0.2548 R_E$
 - Y : $0.3000 R_E$
 - Z : $0.3000 R_E$
- *At Magnetopause Distances* ($X = 10 R_E$, $Y = 0$, $Z = 0$)
 - X : $0.2395 R_E$
 - Y : $0.3000 R_E$
 - Z : $0.3000 R_E$
- *At Magnetotail Distances* ($X = -30 R_E$, $Y = 0$, $Z = 0$):
 - X : $0.5325 R_E$
 - Y : $0.3000 R_E$
 - Z : $0.3000 R_E$

2. High-Resolution OpenGGCM (with and without RCM)

- *Near the Inner Boundary* ($X = 2.5 R_E$, $Y = 0$, $Z = 0$):
 - X : $0.1180 R_E$
 - Y : $0.2000 R_E$
 - Z : $0.2000 R_E$
- *At Magnetopause Distances* ($X = 10 R_E$, $Y = 0$, $Z = 0$)
 - X : $0.0977 R_E$
 - Y : $0.2000 R_E$
 - Z : $0.2000 R_E$
- *At Magnetotail Distances* ($X = -30 R_E$, $Y = 0$, $Z = 0$):
 - X : $0.4784 R_E$
 - Y : $0.2000 R_E$
 - Z : $0.2000 R_E$

The details of OpenGGCM simulation grids are available on the CCMC website: https://ccmc.gsfc.nasa.gov/requests/grid_OpenGGCM.php. The ionosphere electrodynamics grid spacing for OpenGGCM is 0.5° in latitude and 3° in longitude.

1.2.2. Ionospheric Conductances From Models

Ionospheric conductance is an important part of a model that controls how models predict ionospheric electrodynamics. The dayside conductance is mainly determined by solar illuminance, which varies with the solar zenith angle and from solar maximum to minimum. The other important contributor to ionospheric conductance is auroral precipitation. For all models studied here, the ionospheric conductance includes contributions from both solar radiation and auroral precipitation.

For ADELPHI, solar radiation driven conductance was determined from empirical relations with F10.7 and solar zenith angle (Robinson & Vondrak, 1984). The auroral precipitation-driven conductance uses empirical relations between AMPERE-driven FAC and ionospheric conductances estimated from the Poker Flat Incoherent Scatter Radar (PFISR) electron density profiles at an altitude range of 80–200 km (Robinson et al., 2020). Linear fit coefficients were provided for the relations between upward and downward FAC and height-integrated Hall and Pedersen conductances for different bins of magnetic local times.

Conductance from LFM-MIX also includes contributions from solar illumination and auroral particle precipitation (Wiltberger et al., 2004, 2009; Zhang et al., 2011). The solar radiation-driven conductance is determined using the Assimilative Mapping of Ionospheric Electrodynamics (AMIE) EUV conductance algorithm (Richmond, 1992; Richmond & Kamide, 1988; Richmond et al., 1998). The spatial and temporal solar radiation-driven conductance profiles are calculated using F10.7 and solar zenith angle. Conductance from auroral precipitation was determined from integrated precipitating electron flux and average energy using the empirical formula from Robinson et al. (1987). The precipitation flux and average energy were determined by the methodology described

by Fedder et al. (1995). The version at CCMC used the conduction model given by Wiltberger et al. (2009). Recently, significant improvements have been made in calculating these parameters, especially diffuse, monoenergetic, broadband, and cusp precipitations with different energy levels (Zhang et al., 2015). This paper replaces the linear Knight (1973) relation with non-linear relations from Fridman and Lemaire (1980) for diffuse, monoenergetic, and direct entry cusp precipitations for electrons. They also incorporated a diffuse precipitation boundary mechanism, which removed higher fluxes from lower latitudes. However, these are not included in the version available in CCMC.

Auroral conductance from SWMF is empirically derived from FACs by an exponential equation inside 60°–90° MLAT (Mukhopadhyay et al., 2020; Ridley et al., 2004). It also has contributions from solar radiation (Moen & Brekke, 1993; Ridley et al., 2004). This contribution includes conductances due to solar EUV, terminator scattering of solar radiation, and conductances from nightside starlight. The model also considers contributions from polar rain and variations from different seasons.

OpenGGCM uses a magnetosphere-ionosphere coupling mechanism that maps FACs to the ionosphere and calculates ionospheric conductances empirically from auroral precipitation (Raeder et al., 1998). This method calculates conductances from solar radiation (F10.7 and solar zenith angle) and isotropic pitch angle diffuse auroral electron precipitation. The auroral integrated precipitation flux and average energy are used to calculate conductance using the height-integrated Hall and Pedersen conductance formula by Robinson et al. (1987). This method is mentioned as ‘auroral’ conductance in the CCMC webpage. Conductances from OpenGGCM can also be calculated using the Coupled Thermosphere-Ionosphere Model (CTIM) (Fuller-Rowell, Rees, et al., 1996).

From the CCMC page, we have used the auroral conductance option for all models to maintain consistency. The auroral conductance option for all models includes conductances from solar radiation and auroral precipitation. We have also maintained fixed simulation grids for each model for all the events in this paper. The time resolutions used in this paper from CCMC output files are typically 1–4 min. All CCMC-based model outputs can be found using the model run numbers (Table S1 in Supporting Information S1) at ccmc.gsfc.nasa.gov.

1.3. Selected Geomagnetically Disturbed Events

The geomagnetically disturbed periods or events selected in this paper are 22 July 2004; 9 March 2012; 17 March 2013; 17 March 2015; 22–23 June 2015; and 7–9 September 2017. These events are chosen to thoroughly test model performance by including different seasons and covering two solar cycles. Solar and geomagnetic parameters during these events are summarized in Table S2 and Figures S1–S6 in Supporting Information S1. These geomagnetic storms originated from CMEs and were associated with high-speed solar wind. Among the selected storms, 22 July 2004, was the weakest (minimum SYMH: −97 nT). The strongest storm was on 17 March 2015 (minimum SYMH: −234 nT), followed by 22–23 June 2015 (minimum SYMH: −208 nT). These storms have been examined in previous studies (e.g., Astafyeva et al., 2015; Lin et al., 2019; Nava et al., 2016; Piersanti et al., 2017; Sur et al., 2021, 2022; Tsurutani et al., 2014; Yasyukevich et al., 2018; Zhu et al., 2022).

2. Assessment Methodology

We have compared the performance accuracies of different models in a comprehensive manner utilizing several metrics described by Pulkkinen et al. (2011) and Liemohn et al. (2021). The latter emphasized using more metrics and not being confined only to RMSE. In this section, the statistical methods used in this paper are described. These are used to compare model results with observations, and between models when observations are not available. The following metrics are used in the paper.

- (i) We have observed any possible data-model correlations and correlations with geomagnetic indices using the Pearson R coefficient. The definition is shown below.

$$\text{Pearson } R = \frac{\sum(a_n - a')(b_n - b')}{\sqrt{\sum(a_n - a')^2(b_n - b')^2}} \quad (1)$$

where a_n is the n th observation/input or geomagnetic variables, b_n is the n th modeled output, and a' and b' are the mean of all a_n and b_n , respectively. The ideal value for the Pearson R coefficient is 1. A correlation is considered good for $R \geq 0.7$ for general magnetospheric applications (Liemohn et al., 2021).

- (ii) Accuracy: We have performed Root Mean Squared Error (RMSE), Prediction Efficiency (PE), and maximum amplitude ratio similar to Pulkkinen et al. (2011). While RMSE is a popular choice for accuracy analysis, PE is also used by Pulkkinen et al. (2011), Honkonen et al. (2013), and Gordeev et al. (2015). These metrics are defined as follows.

$$\text{RMSE} = \sqrt{\frac{\sum (a_n - b_n)^2}{N}} \quad (2)$$

$$\text{PE} = 1 - \frac{1}{N} \frac{\sum (a_n - b_n)^2}{\text{variance of observed data}} \quad (3)$$

Similar to Equation 1, a_n is the n th observation/input, and b_n is the n th modeled output. N is the number of data points. RMSE should be as small as possible. The ideal value for PE is 1. The maximum amplitude ratio is the ratio between maximum amplitudes from the model and observation for a particular event.

Apart from these metrics, we have also observed how many times modeled outputs fall into the range of observation (in percentage of total time). The range is calculated to be inside $\pm 20\%$ of the magnitude of observation. The corresponding model outputs are inspected to determine whether they lie inside the ranges or they overestimate/underestimate. While RMSE and PE provide information on how modeled outputs are closer to observation, the maximum amplitude ratio and percentage time instances for model overestimation/underestimation measure whether the model generally overpredicts or underpredicts the same.

- (iii) Precision: We have observed model precision by $P_{\sigma, \text{ratio}}$ (Liemohn et al., 2021). $P_{\sigma, \text{ratio}}$ indicates how the spread of modeled output is close to the same from the observation. $P_{\sigma, \text{ratio}}$ is calculated by taking the ratio of the standard deviation (σ) of the modeled output and the same from the observation. The ideal value is 1. $P_{\sigma, \text{ratio}} > 1$ indicates modeled output overpredicts the spread of observation, and $P_{\sigma, \text{ratio}} < 1$ indicates the opposite.
- (iv) Bias: We have observed whether modeled outputs systematically overestimate or underestimate the observation (Liemohn et al., 2021). It is calculated by subtracting the event-wise median of modeled outputs and the same from observation. The ideal value is 0. Bias > 0 and bias < 0 indicate systematic overestimation and underestimation of the observation by the model, respectively. We have used median instead of mean in order to eliminate the effects of data skewness, if present.

2.1. Cross Polar Cap Potential (CPCP)

For CPCP, we have compared results from ADELPHI, LFM-MIX, SWMF, and OpenGGCM with SuperDARN and DMSP (only for 9 March 2012) data during the events mentioned in Section 1.3. Modeled CPCP was obtained by taking differences between maximum and minimum potentials from one hemisphere. We have used OpenGGCM with lower (coupled with RCM) and higher (with and without RCM) resolutions (Section 1.2.1). We have performed comprehensive statistical analyses, as described below. For DMSP, we have calculated the following metrics with a resolution of 1 hr.

- (i) Data-model correlation: The data-model association indicates whether the model results follow the trend of the observation and whether they diverge throughout the range. This is calculated using the Pearson R coefficient (Equation 1).
- (ii) Accuracy: We have performed accuracy analysis using RMSE (Equation 2), PE (Equation 3), maximum amplitude ratio, and percentage time instant of model overestimation/underestimation using all available observations. We have also observed how CPCP RMSE varies with geomagnetic activity (SYM).
- (iii) Precision and bias: We have observed model precision ($P_{\sigma, \text{ratio}}$) and bias when compared with all available observations.

2.2. Hemispherically Integrated Joule Heating (HIJH)

We have compared HIJH values from the same models used to assess CPCP performance. In the absence of observations, we have conducted the following statistical analyses.

- (i) We have observed the event-specific standard deviations from all modeled HIJH values.

- (ii) We have used the Pearson R coefficient (Equation 1) to observe any possible correlations between HIJH and observed AE during all events.

2.3. Hemispheric Power Input (HPI)

We have observed the performances of HPI from ADELPHI and Ovation Prime with respect to DMSP data. We have conducted statistical studies such as (i) Data-model correlation analysis (Equation 1), (ii) Accuracy: RMSE (Equation 2), PE (Equation 3), maximum amplitude ratio and percentage time instances for model over-estimation/underestimation, (iii) Precision ($P_{\sigma, \text{ratio}}$), and (iv) Bias.

We have also observed how the models demonstrate the interhemispheric asymmetry in the modeled CPCP and HIJH. We have limited this study by focusing on solstitial asymmetry due to solar radiation. We have used different metric values to determine the sensitivity of the models to this type of asymmetry.

3. Results and Analysis

3.1. Cross Polar Cap Potential Comparison

CPCP from ADELPHI, LFM-MIX, SWMF, and different versions of OpenGGCM are compared with SuperDARN data for the six selected storm periods (Figures 1 and 2). ADELPHI model outputs were unavailable for 22 July 2004, and 7–9 September 2017. The results from high-resolution OpenGGCM with RCM during 22–23 June 2015, were also unavailable because the run crashed in CCMC several times. This could be due to the large FAC at the equatorward boundary during strong driving conditions. These can cause numerical instabilities, and a slowdown of the MHD model runs, especially for higher-resolution models. The CPCP comparisons showed that the model results were relatively consistent except for LFM-MIX and high-resolution OpenGGCM without RCM. LFM-MIX and high-resolution OpenGGCM without RCM showed higher CPCP values for all dates except 9 March 2012. The maximum values from LFM-MIX and high-resolution OpenGGCM without RCM combining both hemispheres were 871.74 and 798.60 kV, respectively. These were seen on 17 March 2015, and 22–23 June 2015, respectively, with both corresponding to the most disturbed events. Except for 9 March 2012, high-resolution OpenGGCM with RCM provided lower and more accurate values (with respect to observation) than those from high-resolution OpenGGCM without RCM. This shows the importance of incorporating an inner magnetosphere model with OpenGGCM (details in Section 4.1). Low-resolution OpenGGCM with RCM performed better than high-resolution versions in most cases. ADELPHI and low-resolution OpenGGCM with RCM showed relatively higher CPCP than those from SWMF and SuperDARN. SWMF provided lower CPCP values on 22 July 2004, and 9 March 2012, but relatively higher values during the other periods. The comparisons also show that CPCP determined from SuperDARN were generally lower than those obtained from models and DMSP data (only available for 9 March 2012).

When compared with DMSP data, the ADELPHI CPCP values agreed with DMSP CPCP variations during most periods, especially in the northern hemisphere. The DMSP peaks were higher than ADELPHI in the southern hemisphere. LFM-MIX and OpenGGCM (low-resolution with RCM and high-resolution without RCM) CPCP values were also consistent with ADELPHI and DMSP on 9 March 2012. High-resolution OpenGGCM with RCM overestimated the observed CPCP (both SuperDARN and DMSP) in the northern hemisphere. SWMF underestimated DMSP CPCP in both hemispheres. When DMSP CPCP data from more dates become available, a more comprehensive validation of CPCP values can be undertaken.

3.1.1. Data-Model Correlation or Association Analysis

We have observed Pearson R data-model correlations between SuperDARN (as well as DMSP on 9 March 2012) and modeled CPCP during all periods (Table 1). Liemohn et al. (2021) emphasized that $R \geq 0.7$ is desired for magnetospheric applications. We have also considered this threshold as indicative of a good correlation. In Table 1, Pearson $R \geq 0.7$ from all models are shown in bold. Upon analyzing the correlations with SuperDARN data using the Pearson R coefficient, it was observed that SWMF and LFM-MIX exhibited good correlations ($R \geq 0.7$) with observations during most cases, followed by ADELPHI. SWMF had the highest correlation (0.89) in the northern hemisphere on 22 July 2004 (Table 1). The low-resolution OpenGGCM with RCM had the worst correlation with data. On a few occasions, the values were negative, indicating moderate anti-correlation. No significant improvement was observed in data-model correlations after incorporating RCM in high-resolution

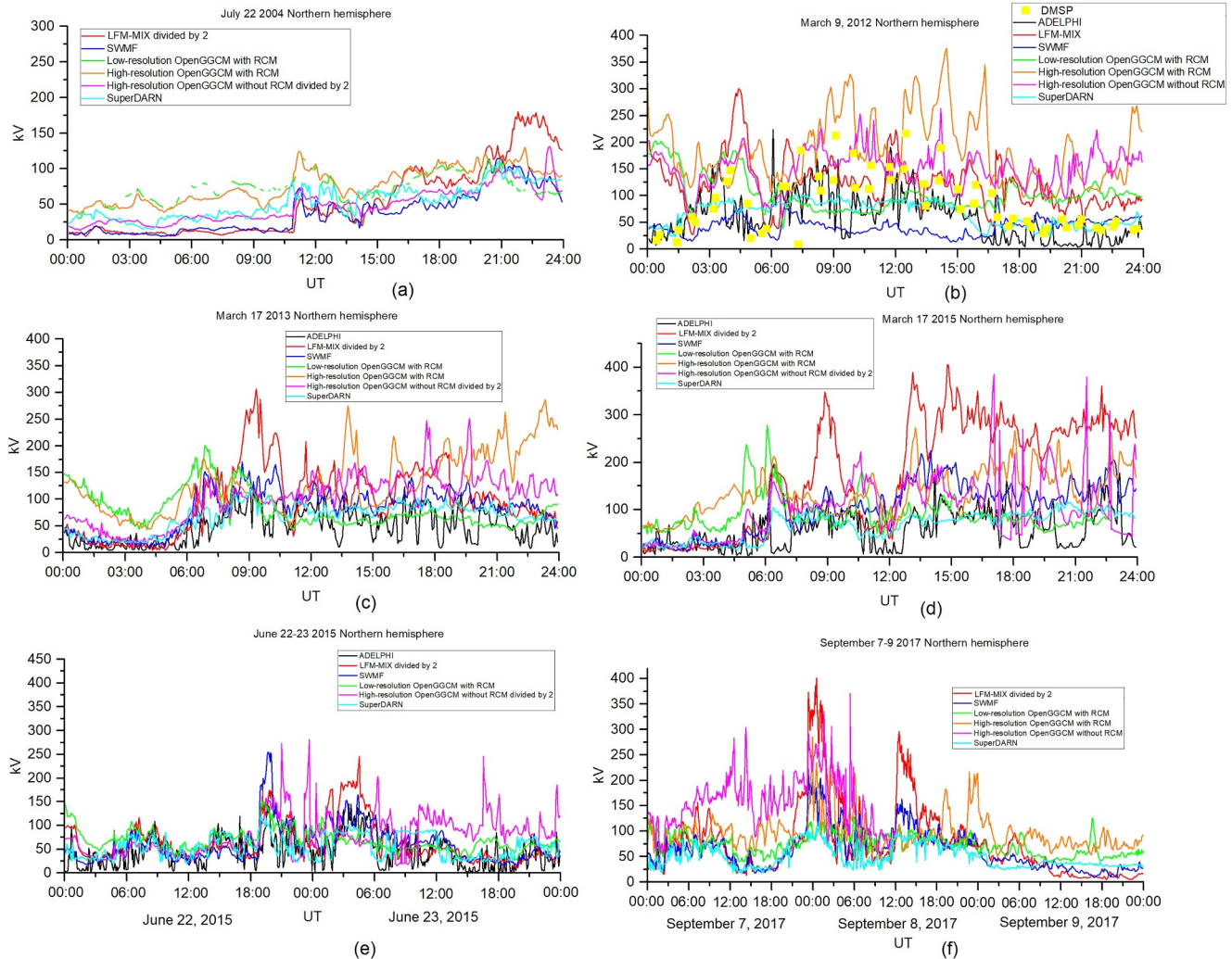


Figure 1. (a–f) Comparisons of CPCP from the northern hemisphere from different models, and SuperDARN and DMSP data during different selected events.

OpenGGCM when compared with SuperDARN data. Overall, OpenGGCM shows poor correlations irrespective of version. For 9 March 2012, $R \geq 0.7$ was observed only from ADELPHI outputs when compared with both SuperDARN (only from the northern hemisphere) and DMSP data.

It should be noted that time lags may exist between the observation and the model simulations. Model outputs may exhibit good correlations with observations when a specific time lag is considered, which may not be present if the correlation is calculated with no time lag. For this reason, multiple statistical metrics are used in this paper to assess different model performances comprehensively.

3.1.2. Accuracy Analysis

By analyzing RMSE, PE, percentage time instances for overestimation/underestimation, and maximum amplitude studies from all six events, we can extract important features from different models regarding their relative accuracies (Tables 2–4). When compared with SuperDARN data, LFM-MIX consistently provided higher CPCP values than the other models for all cases except for 9 March 2012. The maximum amplitude ratio from LFM-MIX varied between 2.56 and 7.12 after combining both hemispheres. Its maximum RMSE and maximum negative PE were 373.47 kV and -159.08 , respectively, on 17 March 2015, indicating poor accuracy. Additionally, LFM-MIX overestimates CPCP by near or more than 80% for every event except 22 July 2004. High-resolution OpenGGCM without RCM also showed very high CPCP values in most cases. The maximum RMSE, negative PE, and amplitude ratio from high-resolution OpenGGCM without RCM were 253.19 kV, -151.34 , and 8.58, respectively

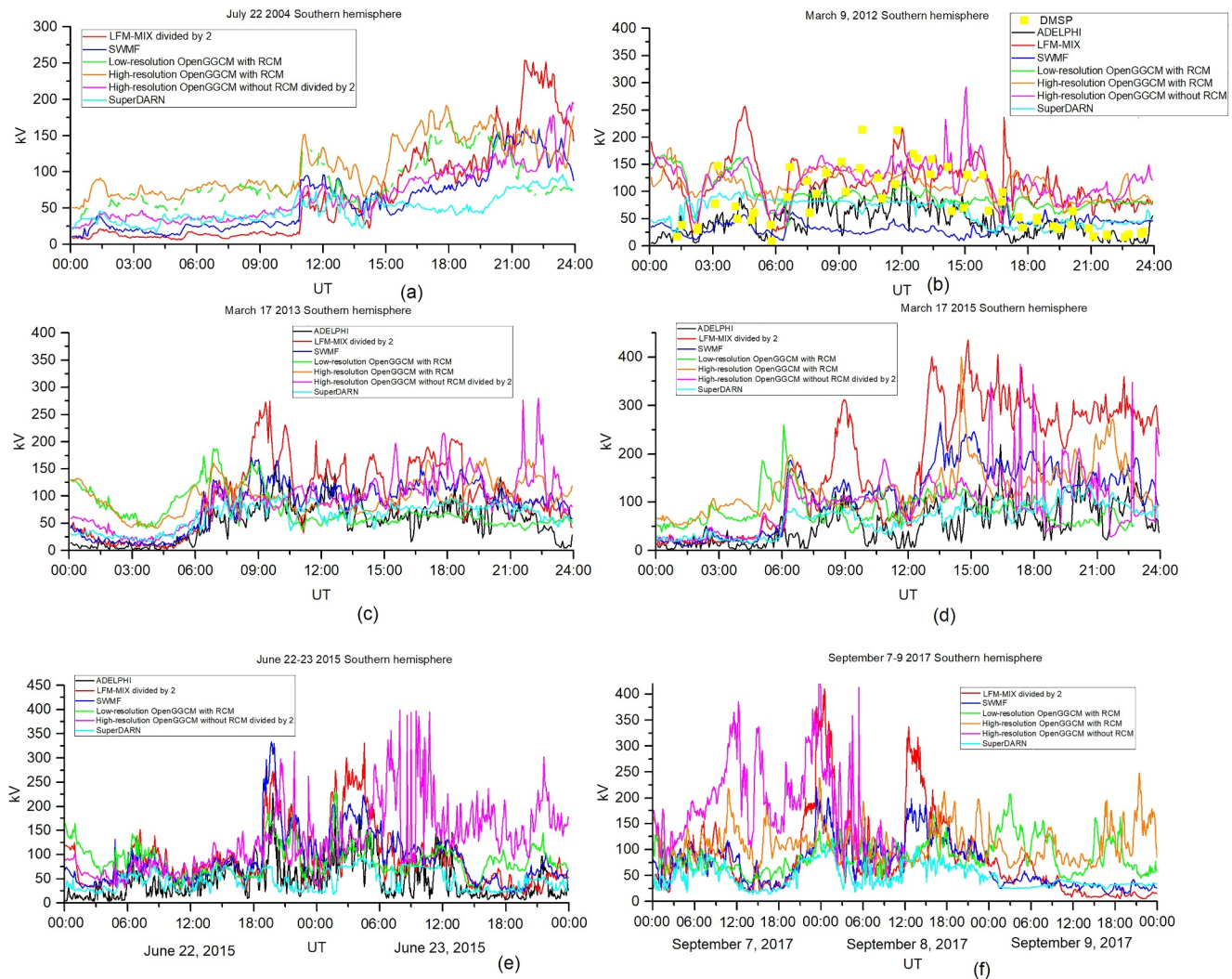


Figure 2. (a–f) Comparisons of CPCP from the southern hemisphere from different models, and SuperDARN and DMSP data during different selected events.

(from the southern hemisphere during 22–23 June 2015). ADELPHI RMSE values were around 30 kV for almost all events. The CPCP values from ADELPHI were also within the range during 22%–32% of the total time instances for all events. Its maximum amplitude ratio varied between 1.12 and 2.45, combining both hemispheres. SWMF RMSE values were typically around 20–40 kV except on 17 March 2015, and 22–23 June 2015 (southern hemisphere). During 22 July 2004, and 22–23 June 2015, higher CPCP values were observed, especially from the southern hemisphere, which might be associated with solstitial interhemispheric asymmetry (Sections 3.4 and 4.3). Overall, ADELPHI and SWMF provided the least RMSE and best PE when compared with SuperDARN data. The PE values were negative for almost all models, indicating that model performances regarding CPCP were poor overall and that SuperDARN generally yields lower values than the models. The underestimation of CPCP from SuperDARN might be explained by its lower spatial coverage in the southern hemisphere (Nishitani et al., 2019), where the data interpolation might produce lower values. The underestimation by SuperDARN can also be attributed to the refractive index in the scattering region (Gillies et al., 2009). The inferred ionospheric velocities may be underestimated, resulting in lower CPCP values. Drayton et al. (2005), Mori et al. (2012), and Wu et al. (2015) also reported underestimation of CPCP from SuperDARN. PE improved for all models when compared with DMSP data on 9 March 2012, which might also indicate the limitations of SuperDARN data.

In most cases, low-resolution OpenGGCM with RCM provided more accurate predictions (RMSE, PE, maximum amplitude ratio, and percentage time instances for model overestimation/underestimation) than OpenGGCM

Table 1
Correlations Between Data and Modeled CPCP

Correlations between data and modeled CPCP						
SuperDARN data						
	ADELPHI	LFM-MIX	SWMF	Low-resolution OpenGGCM with RCM	High-resolution OpenGGCM with RCM	High-resolution OpenGGCM without RCM
Northern hemisphere						
22 July 2004		0.84	0.89	0.47	0.82	0.85
9 March 2012	0.71	0.32	−0.13	−0.26	0.24	0.08
17 March 2013	0.66	0.77	0.83	−0.13	0.39	0.73
17 March 2015	0.45	0.86	0.80	−0.08	0.52	0.47
22–23 June 2015	0.49	0.43	0.51	0.24		0.05
7–9 September 2017		0.78	0.75	0.49	0.28	0.33
Southern hemisphere						
22 July 2004		0.81	0.84	0.29	0.55	0.76
9 March 2012	0.53	0.29	−0.30	0.26	0.33	0.25
17 March 2013	0.74	0.73	0.83	−0.05	0.45	0.65
17 March 2015	0.67	0.82	0.76	−0.01	0.62	0.51
22–23 June 2015	0.50	0.46	0.45	0.19		0.11
7–9 September 2017		0.79	0.75	0.07	0.10	0.24
DMSP data, 9 March 2012						
Northern hemisphere	0.72	0.49	−0.11	−0.45	0.49	0.45
Southern hemisphere	0.75	0.10	−0.49	−0.15	0.55	0.25

Note. Ideal value is 1, $0.7 \leq \text{values} \leq 1$ shown in bold.

higher-resolution versions (regardless of the inclusion of RCM). High-resolution versions of OpenGGCM overestimated SuperDARN CPCP by almost more than 75% during all events, which indicates that the low-resolution OpenGGCM with RCM can provide better performance than the higher-resolution versions. A possible explanation for this is provided in Section 4.2. The inclusion of an inner magnetospheric model significantly improved all accuracy metrics for all events except 9 March 2012. For example, the RMSE decreased from 178.32 to 80.65 kV in the northern hemisphere and from 163.85 to 71.34 kV in the southern hemisphere on 17 March 2015, when compared with SuperDARN data. The percentage time instances of overestimation were always over 90% for high-resolution OpenGGCM without RCM. Those decreased significantly for the same version after the inclusion of RCM (e.g., it reduced from 99.72% to 75.14% in the southern hemisphere on 17 March 2013). The maximum amplitude ratio decreased from 6.58 to 2.34 in the northern hemisphere and 5.60 to 2.91 in the southern hemisphere on 17 March 2015.

Similar features were observed when compared with DMSP data on 9 March 2012. The modeled responses on 9 March 2012, were different from those obtained during other events. For example, LFM-MIX RMSE values were lower than those from SWMF in both hemispheres. The maximum amplitude ratio was also very close to 1 for LFM-MIX in the southern hemisphere. High-resolution OpenGGCM with RCM showed higher RMSE and poorer maximum amplitude ratio than the same without RCM from the northern hemisphere. ADELPHI showed more accurate performance in terms of RMSE and PE than the other models, especially from the northern hemisphere, where the values were inside the range of DMSP by about 34.78%. CPCP from High-resolution OpenGGCM without RCM was also within range by 34.78% from the northern hemisphere.

We have also inspected whether the RMSE values with respect to SuperDARN data from different models have any correlations with geomagnetic activity. RMSE from all models except low-resolution OpenGGCM with RCM appeared to be correlated with maximum negative SYMH for all events (Figure 3). RMSE from all models

Table 2
RMSE and PE From CPCP of Different Models

SuperDARN data	RMSE (kV)					
	ADELPHI	LFM-MIX	SWMF	Low-resolution OpenGGCM with RCM	High-resolution OpenGGCM with RCM	High-resolution OpenGGCM without RCM
Northern hemisphere						
22 July 2004		96.59	20.88	28.31	26.66	52.45
9 March 2012	32.37	72.87	37.12	58.39	133.24	92.96
17 March 2013	30.44	166.44	26.01	46.40	81.64	153.75
17 March 2015	37.36	357.99	52.74	55.81	80.65	178.32
22–23 June 2015	30.53	106.66	35.19	31.19		134.01
7–9 September 2017		164.00	29.14	31.04	56.47	80.93
Southern hemisphere						
22 July 2004		149.28	30.90	51.65	65.73	106.06
9 March 2012	31.03	67.02	39.93	42.29	55.13	68.93
17 March 2013	25.94	172.73	33.62	41.86	44.22	143.48
17 March 2015	32.03	373.47	67.51	51.28	71.34	163.85
22–23 June 2015	32.83	176.61	66.64	54.26		253.19
7–9 September 2017		181.30	38.34	53.69	74.37	109.41
DMSP data, 9 March 2012						
Northern hemisphere	42.68	57.41	66.13	72.09	107.08	76.53
Southern hemisphere	49.71	68.86	70.55	61.52	54.27	66.47
SuperDARN data	PE					
	ADELPHI	LFM-MIX	SWMF	Low-resolution OpenGGCM with RCM	High-resolution OpenGGCM with RCM	High-resolution OpenGGCM without RCM
Northern hemisphere						
22 July 2004		−16.65	0.18	−0.52	−0.34	−4.20
9 March 2012	−1.15	−9.91	−1.83	−6.00	−35.47	−16.75
17 March 2013	−0.48	−43.22	−0.08	−2.44	−9.64	−36.73
17 March 2015	−0.74	−159.08	−2.47	−2.89	−7.12	−38.72
22–23 June 2015	−0.61	−18.61	−1.13	−0.68		−29.96
7–9 September 2017		−54.23	−0.74	−0.98	−5.55	−12.45
Southern hemisphere						
22 July 2004		−67.33	−1.93	−7.18	−12.25	−33.50
9 March 2012	−0.99	−8.30	−2.30	−2.70	−5.29	−8.83
17 March 2013	−0.23	−53.44	−1.06	−2.20	−2.57	−36.56
17 March 2015	−0.08	−145.34	−3.78	−1.76	−4.34	−27.17
22–23 June 2015	−1.56	−73.12	−9.55	−6.00		−151.34
7–9 September 2017		−65.52	−1.98	−4.83	−10.19	−23.23
DMSP data, 9 March 2012						
Northern hemisphere	0.16	−0.52	−1.01	−1.39	−4.28	−1.70
Southern hemisphere	−0.01	−0.93	−1.03	−0.54	−0.20	−0.80

Note. RMSE: Ideal value is as low as possible, lowest value per event is shown in bold, PE: Ideal value is 1, value closest to 1 per event is shown in bold.

Table 3
Maximum Amplitude Ratio From CPCP of Different Models

Maximum CPCP amplitude ratio between models and SuperDARN data						
	ADELPHI	LFM-MIX	SWMF	Low-resolution OpenGGCM with RCM	High-resolution OpenGGCM with RCM	High-resolution OpenGGCM without RCM
Northern hemisphere						
22 July 2004		3.25	1.03	1.03	1.18	2.37
9 March 2012	2.17	2.92	0.98	1.97	3.65	2.55
17 March 2013	1.12	5.15	1.43	1.69	2.41	4.24
17 March 2015	1.58	6.92	1.93	2.38	2.34	6.58
22–23 June 2015	1.27	4.16	2.16	1.28		4.76
7–9 September 2017		6.71	1.87	1.08	2.39	3.11
Southern hemisphere						
22 July 2004		5.27	1.66	1.77	1.99	4.07
9 March 2012	1.37	2.56	1.07	1.67	2.26	2.9
17 March 2013	1.49	5.22	1.63	1.79	1.63	5.31
17 March 2015	1.6	6.34	1.93	1.89	2.91	5.60
22–23 June 2015	2.45	7.12	3.58	2.47		8.58
7–9 September 2017		6.65	1.79	1.69	2.01	3.96
Maximum CPCP amplitude ratio between models and DMSP data						
9 March 2012						
Northern hemisphere	0.75	1.21	0.41	1.14	1.60	1.13
Southern hemisphere	0.51	1.00	0.29	0.89	0.83	0.87

Note. Ideal value is 1, $0.7 \leq \text{values} \leq 1.3$ are shown in bold.

became significantly higher during 22–23 June 2015, (minimum SYMH = −208 nT) and/or 17 March 2015 (minimum SYMH = −234 nT). This shows that the performance worsened with geomagnetic storm intensities for all models except low-resolution OpenGGCM with RCM. All models showed higher RMSE from the southern hemisphere than that from the northern hemisphere during solstitial events (22 July 2004, and 22–23 June 2015), indicating their ability to simulate solstitial interhemispheric asymmetry (Section 3.4).

3.1.3. Precision Analysis

LFM-MIX and high-resolution OpenGGCM without RCM showed wider spreads than SuperDARN data. Maximum $P_{\sigma, \text{ratio}}$ from LFM-MIX and high-resolution OpenGGCM without RCM were 8.27 (17 March 2015) and 6.71 (22–23 June 2015), respectively (Table 5). Both were observed during the two most intense geomagnetically disturbed events. Low-resolution OpenGGCM with RCM provided $P_{\sigma, \text{ratio}}$ nearer to 1 in most cases than higher-resolution OpenGGCM (with and without RCM). ADELPHI provided $P_{\sigma, \text{ratio}}$ much closer to 1. The inclusion of an inner magnetosphere model (RCM) in high-resolution OpenGGCM improves the precision of the model with respect to observation. However, low-resolution OpenGGCM with RCM provided the most improved spread/precision among all versions of OpenGGCM. When compared with DMSP spread, high-resolution OpenGGCM with RCM, LFM-MIX, ADELPHI, and low-resolution OpenGGCM with RCM provided better agreement in the northern hemisphere. Almost all models showed better precision when compared with DMSP than those from SuperDARN.

3.1.4. Bias Analysis

When compared with SuperDARN data, LFM-MIX and high-resolution OpenGGCM without RCM exhibited very high positive bias values, indicating systematic overestimation of the observation during all events, except in the northern hemisphere on 22 July 2004 (Table 5). In contrast, ADELPHI systematically underestimates the

Table 4
Modeled CPCP Percentage Time Instances to Be Inside Range or Overestimate/Underestimate

Percentage instances (SuperDARN data)	Inside range	Overestimate	Underestimate	Inside range	Overestimate	Underestimate
22 July 2004	Northern hemisphere			Southern hemisphere		
LFM-MIX	19.27	50.56	30.17	23.46	51.40	25.14
SWMF	30.45	1.40	68.16	19.55	43.30	37.15
Low-resolution OpenGGCM with RCM	29.11	60.34	10.55	16.46	81.86	1.69
High-resolution OpenGGCM with RCM	24.02	75.98	0.00	1.12	98.88	0.00
High-resolution OpenGGCM without RCM	7.54	91.62	0.84	0.56	99.44	0.00
9 March 2012	Northern hemisphere			Southern hemisphere		
ADELPHI	29.33	22.91	47.77	25.98	10.61	63.41
LFM-MIX	4.75	89.66	5.59	6.15	87.99	5.87
SWMF	24.02	15.36	60.61	22.91	11.73	65.36
Low-resolution OpenGGCM with RCM	31.28	62.29	6.42	27.65	68.44	3.91
High-resolution OpenGGCM with RCM	1.12	98.88	0.00	9.22	90.78	0.00
High-resolution OpenGGCM without RCM	6.42	93.02	0.56	4.19	90.22	5.59
17 March 2013	Northern hemisphere			Southern hemisphere		
ADELPHI	27.09	9.22	63.69	30.45	11.73	57.82
LFM-MIX	7.82	86.59	5.59	9.22	82.96	7.82
SWMF	46.09	41.62	12.29	19.27	58.38	22.35
Low-resolution OpenGGCM with RCM	24.02	38.83	37.15	27.65	39.11	33.24
High-resolution OpenGGCM with RCM	16.20	82.68	1.12	23.46	75.14	1.40
High-resolution OpenGGCM without RCM	0.28	99.72	0.00	0.28	99.72	0.00
17 March 2015	Northern hemisphere			Southern hemisphere		
ADELPHI	31.56	24.86	43.58	27.37	17.32	55.31
LFM-MIX	4.75	93.85	1.40	5.31	93.85	0.84
SWMF	19.55	73.46	6.98	18.72	72.91	8.38
Low-resolution OpenGGCM with RCM	29.03	54.55	16.42	18.71	59.06	22.22
High-resolution OpenGGCM with RCM	9.78	90.22	0.00	10.06	89.94	0.00
High-resolution OpenGGCM without RCM	7.54	92.18	0.28	4.47	93.85	1.68
22–23 June 2015	Northern hemisphere			Southern hemisphere		
ADELPHI	24.58	25.00	50.42	22.21	33.52	44.27
LFM-MIX	12.71	84.08	3.21	1.96	97.21	0.84
SWMF	28.35	31.15	40.50	13.83	84.36	1.82
Low-resolution OpenGGCM with RCM	25.42	56.70	17.88	15.50	82.96	1.54
High-resolution OpenGGCM with RCM						
High-resolution OpenGGCM without RCM	1.68	95.25	3.07	0.14	99.86	0.00
7–9 September 2017	Northern hemisphere			Southern hemisphere		
LFM-MIX	6.24	79.89	13.87	6.45	81.67	11.88
SWMF	32.96	45.90	21.14	24.79	64.83	10.38
Low-resolution OpenGGCM with RCM	26.63	71.32	2.05	21.42	77.92	0.65
High-resolution OpenGGCM with RCM	14.53	84.08	1.40	7.20	91.77	1.03
High-resolution OpenGGCM without RCM	3.89	95.93	0.19	2.05	97.02	0.93
	Northern hemisphere			Southern hemisphere		
Percentage instances, DMSP data, 9 March 2012	Inside range	Overestimate	Underestimate	Inside range	Overestimate	Underestimate
ADELPHI	34.78	4.35	60.87	17.39	8.70	73.91

Table 4
Continued

Percentage instances, DMSP data, 9 March 2012	Northern hemisphere			Southern hemisphere		
	Inside range	Overestimate	Underestimate	Inside range	Overestimate	Underestimate
LFM-MIX	17.39	78.26	4.35	21.74	60.87	17.39
SWMF	21.74	17.39	60.87	21.74	17.39	60.87
Low-resolution OpenGGCM with RCM	8.70	56.52	34.78	26.09	47.83	26.09
High-resolution OpenGGCM with RCM	13.04	86.96	0.00	30.43	65.22	4.35
High-resolution OpenGGCM without RCM	34.78	60.87	4.35	21.74	69.57	8.70

Note. Value maximum to be inside range is preferable. Maximum to be inside the range are shown in bold for each hemisphere per event.

same during all events. Combining both hemispheres, the low-resolution OpenGGCM with RCM showed better systematic bias values than the other models, including SWMF and ADELPHI. The inclusion of RCM with high-resolution OpenGGCM improved its performance regarding systematic bias values, except in the northern hemisphere on 9 March 2012. This was aligned with RMSE, PE, and maximum amplitude ratio. When compared with DMSP data, lesser bias was observed from LFM-MIX than those obtained when compared with SuperDARN data. This might be because DMSP values were higher than those from SuperDARN, which might be due to the limitation of SuperDARN (Section 3.1.2). Here also, low-resolution OpenGGCM with RCM showed better

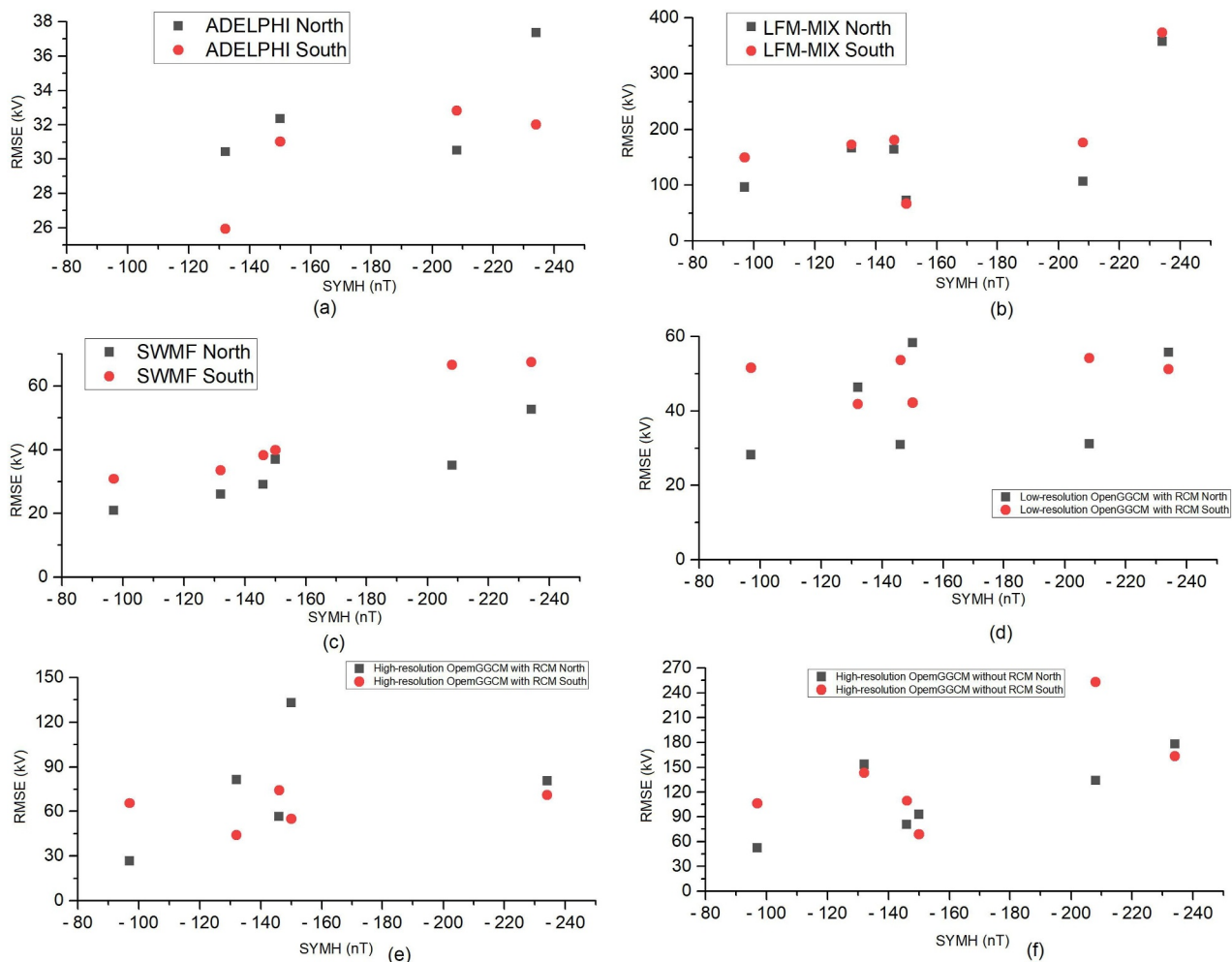


Figure 3. Variations of modeled CPCP RMSE with event-wise maximum negative SYMH.

Table 5
P_{σ, ratio} and Bias From CPCP of Different Models

SuperDARN data	Precision (<i>P_{σ, ratio}</i>)					
	ADELPHI	LFM-MIX	SWMF	Low-resolution OpenGGCM with RCM	High-resolution OpenGGCM with RCM	High-resolution OpenGGCM without RCM
Northern hemisphere						
22 July 2004		4.36	1.30	0.82	1.04	2.08
9 March 2012	1.96	2.14	0.68	1.53	2.85	1.58
17 March 2013	1.25	5.03	1.51	1.34	2.23	3.54
17 March 2015	1.35	8.27	1.92	1.28	1.68	4.41
22–23 June 2015	1.31	3.53	1.66	0.89		3.42
7–9 September 2017		6.59	1.77	0.89	1.50	2.40
Southern hemisphere						
22 July 2004		7.49	2.33	1.88	2.06	4.11
9 March 2012	1.25	1.93	0.59	1.21	1.09	1.59
17 March 2013	1.47	5.42	1.82	1.36	1.25	3.82
17 March 2015	1.28	7.94	2.08	1.06	1.63	3.86
22–23 June 2015	1.85	5.90	2.65	1.53		6.71
7–9 September 2017		7.05	1.92	1.37	1.54	3.69
DMSP data, 9 March 2012						
Northern hemisphere	0.77	0.80	0.28	0.72	1.13	0.59
Southern hemisphere	0.48	0.70	0.21	0.52	0.40	0.55
SuperDARN data	Bias (kV)					
	ADELPHI	LFM-MIX	SWMF	Low-resolution OpenGGCM with RCM	High-resolution OpenGGCM with RCM	High-resolution OpenGGCM without RCM
Northern hemisphere						
22 July 2004		19.51	−19.50	20.42	19.33	34.60
9 March 2012	−18.68	47.58	−31.23	21.78	96.75	82.40
17 March 2013	−28.12	107.48	13.91	−4.86	47.23	142.06
17 March 2015	−24.45	347.09	40.11	2.20	53.15	123.55
22–23 June 2015	−8.57	48.84	−1.86	12.91		95.90
7–9 September 2017		74.02	15.62	32.05	47.41	114.16
Southern hemisphere						
22 July 2004		44.92	2.83	31.94	45.32	68.07
9 March 2012	−33.05	40.47	−38.71	12.41	38.19	51.56
17 March 2013	−16.50	118.04	21.56	−10.43	23.13	114.49
17 March 2015	−23.12	354.26	58.19	7.68	43.86	126.45
22–23 June 2015	−5.78	106.13	36.56	40.40		193.55
7–9 September 2017		83.98	27.93	41.83	64.47	133.87
DMSP data, 9 March 2012						
Northern hemisphere	−24.94	38.63	−46.08	8.03	109.17	96.46
Southern hemisphere	−47.96	25.57	−57.37	−5.66	34.02	51.58

Note. *P_{σ, ratio}*: Ideal value is 1, 0.7 ≤ values ≤ 1.3 are shown in bold, Bias: Ideal value is 0, −30 ≤ values ≤ 30 are shown in bold.

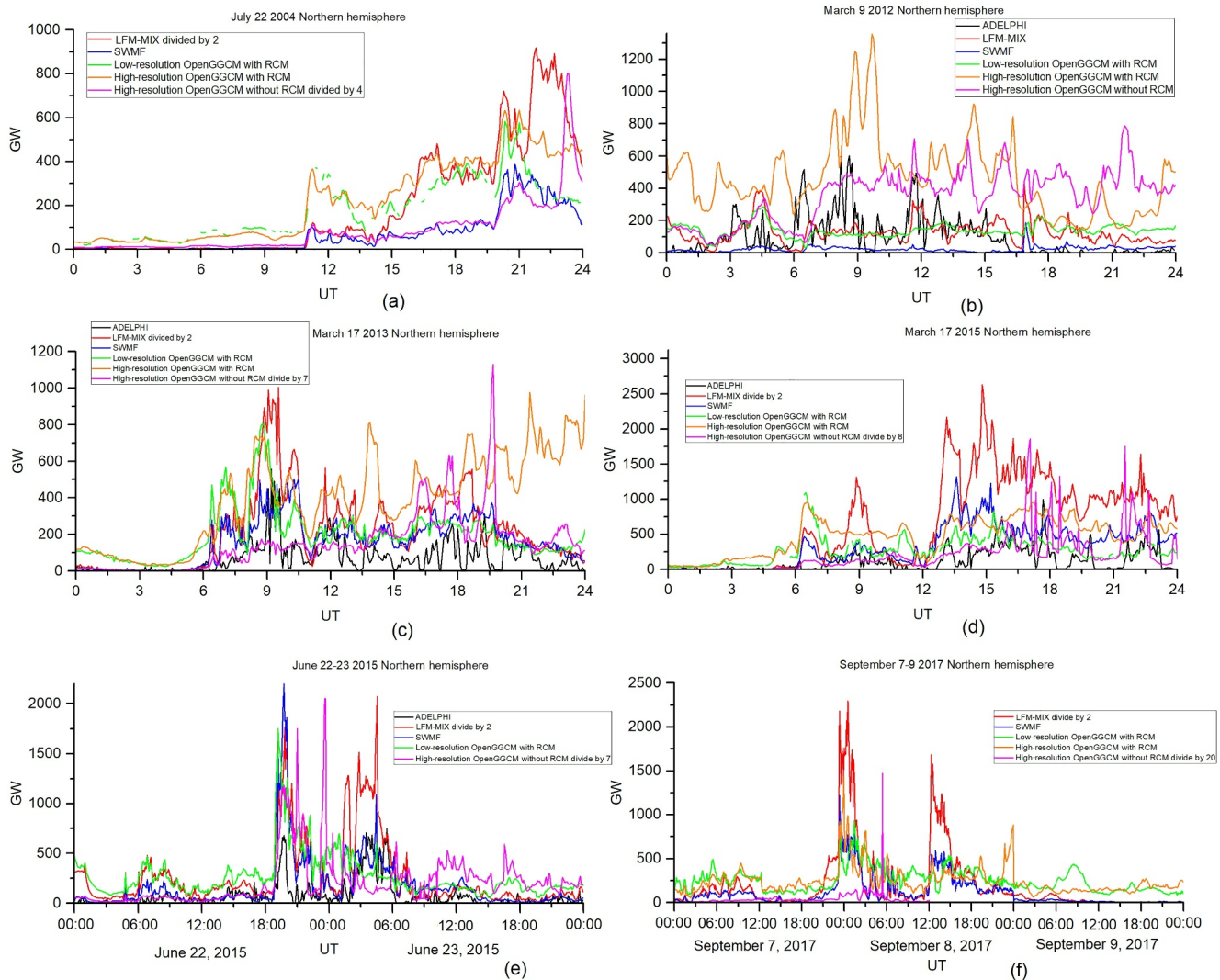


Figure 4. Comparisons of northern HIJH obtained from different models.

bias values than higher-resolution versions. These can be attributed to inaccuracies associated with higher resolutions (Section 4.2). Therefore, although low-resolution OpenGGCM with RCM showed poorer data-model correlations than the higher-resolution versions, it showed better accuracy, precision, and bias. Given that lower-resolution runs significantly save computational run times and resources, these results suggest using lower-resolution OpenGGCM with RCM over the higher-resolution versions.

3.2. HIJH Comparison

HIJH was calculated in two ways. In LFM-MIX, SWMF, and OpenGGCM, it is calculated by integrating the product of radial current density (J_r) and electric potential (Φ) over the hemisphere. ADELPHI integrates the product of the square of the electric field (E) and ionospheric height-integrated Pedersen conductivities (σ_P). It can be shown that the integral of $J_r \cdot \Phi$ over one hemisphere is equal to the hemispheric integral $\sigma_P \cdot |E|^2$ if we assume that the low-latitude boundary has either zero potential or zero perpendicular current density. The corresponding derivation can be found on the CCMC website https://ccmc.gsfc.nasa.gov/publicData/VIS-DOCS/JrPHI_hemispherically_integrated_JouleHeat.pdf. The integrated value is provided as $JrPHI_N$ or $JrPHI_S$ (for the northern and southern hemispheres, respectively) from the CCMC-based MHD model outputs.

The comparisons in Figures 4 and 5 demonstrate cases of both good agreements and large disparities in HIJH values determined from different models. LFM-MIX showed higher values than the other models. For example,

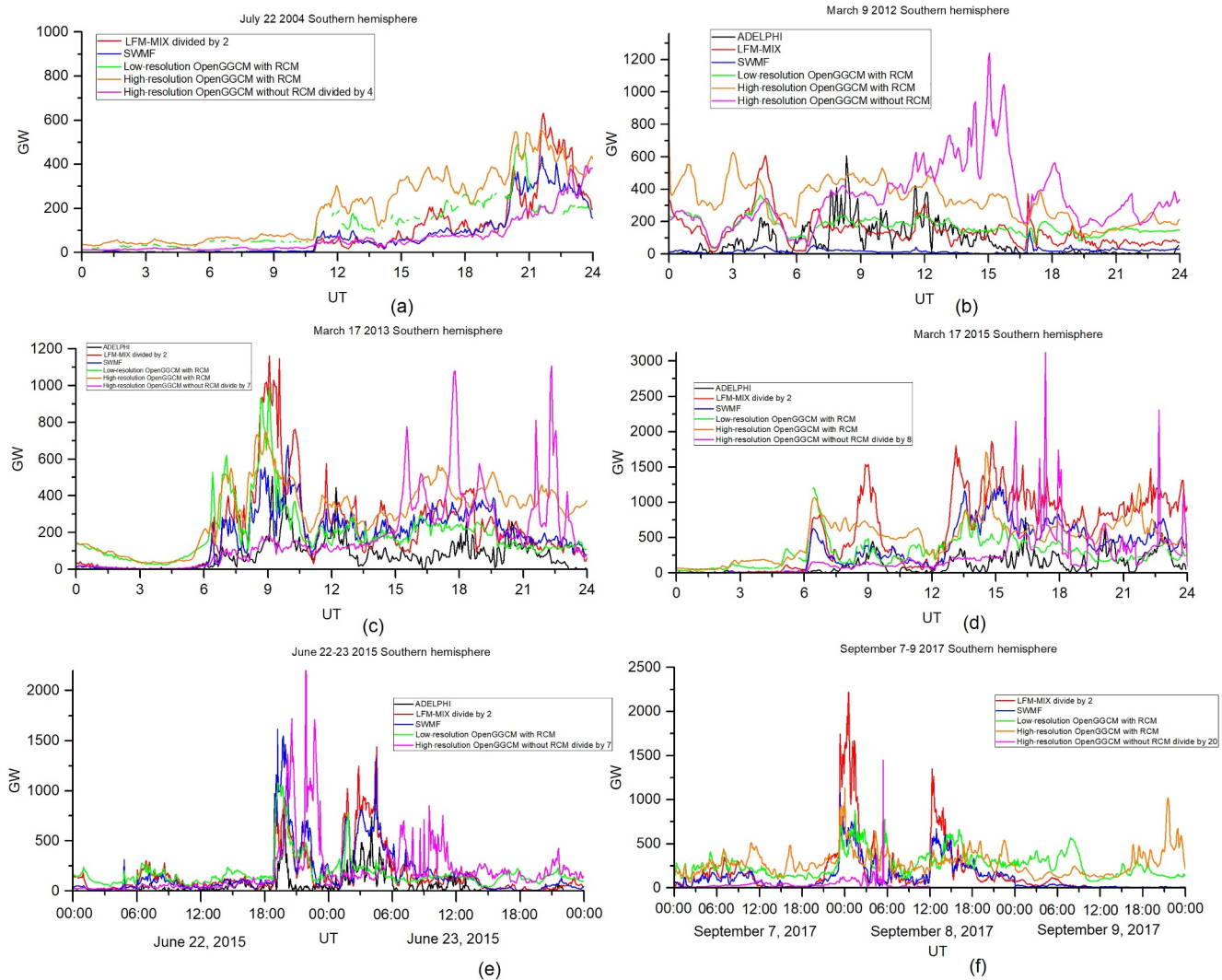


Figure 5. Comparisons of southern HIJH obtained from different models.

on 17 March 2015, the maximum values from LFM-MIX (5,260 GW, northern hemisphere, and 3,738 GW, southern hemisphere, at 14:48 UT) were much higher than the peak values from the other models. The exception was on 9 March 2012, when the LFM-MIX values were more consistent with those from the other models. Additionally, high-resolution OpenGGCM without RCM showed extremely large values, especially during periods with higher geomagnetic disturbances (e.g., maximum: $\sim 29,000$ GW during 7–9 September 2017). It consistently provided higher values than high-resolution OpenGGCM with RCM, except on 9 March 2012, similar to the CPCP results.

3.2.1. Standard Deviation of HIJH

In most cases, high-resolution OpenGGCM without RCM exhibited the highest spread or standard deviations in HIJH (maximum: 2622.21 GW) followed by LFM-MIX. Both models are not coupled with the inner magnetospheric model (RCM), which might have caused these larger spreads and higher magnitudes. The incorporation of RCM in OpenGGCM significantly reduced the spread of the HIJH. However, these values were still higher than low-resolution OpenGGCM with RCM. The maximum spreads from almost all models were found on 17 March 2015, when SYMH reached its maximum negative value (-234 nT). The maximum spread from low-resolution OpenGGCM with RCM was observed in the northern hemisphere during 22–23 June 2015, when the maximum

Table 6
Statistics Related to HIJH

Correlations between modeled hemispherically integrated Joule heating values and AE						
	ADELPHI	LFM-MIX	SWMF	Low-resolution OpenGGCM with RCM	High-resolution OpenGGCM with RCM	High-resolution OpenGGCM without RCM
Northern hemisphere						
22 July 2004		0.83	0.91	0.71	0.85	0.76
9 March 2012	0.59	0.38	−0.09	−0.07	0.54	0.02
17 March 2013	0.32	0.51	0.61	0.49	0.59	0.63
17 March 2015	0.31	0.75	0.76	0.39	0.66	0.40
22–23 June 2015	0.42	0.46	0.48	0.41		0.31
7–9 September 2017		0.25	0.19	−0.03	0.09	−0.12
Southern hemisphere						
22 July 2004		0.85	0.93	0.67	0.85	0.83
9 March 2012	0.63	0.45	−0.08	0.39	0.62	0.27
17 March 2013	0.35	0.42	0.65	0.41	0.74	0.53
17 March 2015	0.38	0.73	0.73	0.45	0.68	0.29
22–23 June 2015	0.45	0.46	0.53	0.45		0.28
7–9 September 2017		0.20	0.20	0.06	0.32	−0.11
Event-wise standard deviations of modeled hemispherically integrated Joule heatings (GW)						
Northern hemisphere						
22 July 2004		497.81	94.13	135.70	179.33	480.05
9 March 2012	122.00	72.15	16.84	39.71	228.24	156.55
17 March 2013	85.18	403.12	122.35	139.44	238.36	1029.90
17 March 2015	150.60	1222.32	282.17	182.33	252.82	2182.46
22–23 June 2015	134.69	671.21	268.53	219.10		1790.34
7–9 September 2017		712.57	156.11	130.52	151.18	1409.63
Southern hemisphere						
22 July 2004		277.42	106.56	103.16	155.98	336.39
9 March 2012	97.82	96.65	13.90	54.75	119.93	201.66
17 March 2013	79.66	437.32	135.41	151.36	168.01	1354.09
17 March 2015	133.66	981.40	305.36	200.57	279.52	2622.21
22–23 June 2015	103.68	453.13	252.34	151.28		1888.58
7–9 September 2017		622.29	154.52	137.70	141.53	1404.99

Note. For correlations between modeled HIJH and AE, ideal value is 1, $0.7 \leq \text{values} \leq 1$ are shown in bold.

negative SYMH was −208 nT (the second most intense geomagnetic storm event). This indicates that the spreads and the overall magnitudes of HIJH increased with geomagnetic storm intensity.

3.2.2. Correlation of AE and HIJH

Bagheri and Lopez (2023) observed correlations between AE and Joule heating from SWMF and empirical models using the linear fit technique. Baumjohann and Kamide (1984) calculated correlations between AE and northern hemispherically integrated Joule heating using Pearson R coefficients. They found correlations to be inside the range of 0.7–0.9. As mentioned in Section 3.1.1, an R -value of over 0.7 is desired (Liemohn et al., 2021). We have also assessed the correlations between observed AE and modeled HIJH using the Pearson R coefficient (Table 6) and considered a threshold of good correlation to be 0.7. The values ≥ 0.7 are shown in bold in Table 6. For ADELPHI, we have considered a 10-min average AE. The correlation coefficients for ADELPHI

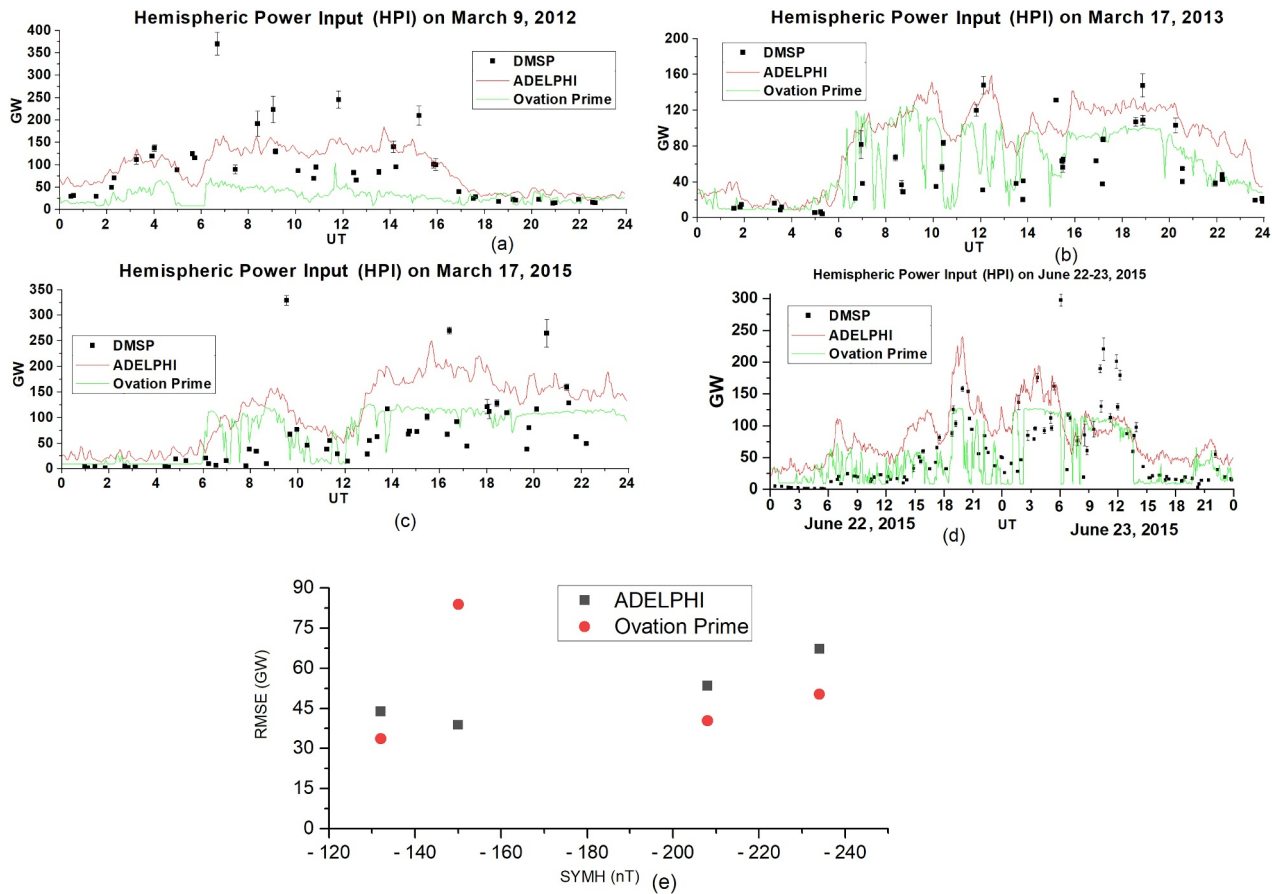


Figure 6. (a–d) Comparisons of HPI from ADELPHI and Ovation Prime models and DMSP data (e) Variations of modeled HPI RMSE with event-wise maximum negative SYMH.

vary between 0.31 and 0.59 in the northern hemisphere and 0.35 to 0.63 in the southern hemisphere, indicating moderate correlations. Higher correlations were found from LFM-MIX (maximum: 0.85) and all versions of high-resolution OpenGGCM. High-resolution OpenGGCM showed maximum correlation coefficients of 0.85 and 0.83 with and without RCM, respectively. Higher correlations were also observed from SWMF (maximum: 0.93). However, it showed negative correlations on 9 March 2012. Moderate correlations were observed from low-resolution OpenGGCM with RCM (maximum: 0.71). This means higher resolution increases its correlations with AE (if compared between versions including RCM). However, all OpenGGCM versions showed very low or negative correlations with AE during 7–9 September 2017. Low-resolution OpenGGCM with RCM also showed negative correlations with AE on 9 March 2012, from the northern hemisphere. In most cases, coupling with RCM improves correlations with AE for high-resolution OpenGGCM. Overall, SWMF, LFM-MIX, and high-resolution OpenGGCM with RCM provided good correlations ($R \geq 0.7$) during most cases.

In the absence of observations, we cannot perform crucial accuracy, precision, and bias analyses for HIJH. Therefore, event-wise standard deviations and correlations with observed AE become critical for model performance evaluations as they help us extract some interesting features. These features include the fact that higher correlations with AE were observed with the increments in resolutions and the inclusion of RCM in OpenGGCM.

3.3. HPI Comparison

HPI values from ADELPHI and Ovation Prime are compared with DMSP observations on 9 March 2012, 17 March 2013, 17 March 2015, and 22–23 June 2015 (Figure 6). All HPI statistics are summarized in Table 7. ADELPHI HPI values were generally higher than those from Ovation Prime, with greater differences on 9 March 2012, and 17 March 2015 (Figure 6).

Table 7
HPI Statistics

Data model correlations	ADELPHI	Ovation Prime	RMSE (GW)	ADELPHI	Ovation Prime
9 March 2012	0.82	0.66	9 March 2012	38.85	83.92
17 March 2013	0.79	0.59	17 March 2013	44.04	33.67
17 March 2015	0.69	0.64	17 March 2015	67.31	50.37
22–23 June 2015	0.66	0.74	22–23 June 2015	53.55	40.49
PE	ADELPHI	Ovation Prime	Maximum amplitude ratio	ADELPHI	Ovation Prime
9 March 2012	0.64	−0.66	9 March 2012	0.65	0.24
17 March 2013	−0.74	−0.01	17 March 2013	1.11	0.96
17 March 2015	−0.08	0.40	17 March 2015	0.76	0.44
22–23 June 2015	0.17	0.53	22–23 June 2015	0.68	0.42
Precision ($P_{\sigma, \text{ratio}}$)	ADELPHI	Ovation Prime	Bias (GW)	ADELPHI	Ovation Prime
9 March 2012	0.67	0.20	9 March 2012	15.50	−57.10
17 March 2013	1.21	1.04	17 March 2013	50.15	17.80
17 March 2015	0.96	0.69	17 March 2015	85.20	48.40
22–23 June 2015	0.72	0.71	22–23 June 2015	37.25	−9.60
HPI percentage time instances inside range or overestimate/underestimate statistics					
Percentage instances	Inside range		Overestimate		Underestimate
9 March 2012					
ADELPHI	26.09		56.52		17.39
Ovation Prime	13.04		13.04		73.91
17 March 2013					
ADELPHI	29.41		70.59		0.00
Ovation Prime	23.53		52.94		23.53
17 March 2015					
ADELPHI	8.70		86.96		4.35
Ovation Prime	13.04		60.87		26.09
22–23 June 2015					
ADELPHI	4.17		83.33		12.50
Ovation Prime	20.83		39.58		39.58

Note. Data-model correlation: (Ideal value is 1, $0.7 \leq \text{values} \leq 1$ are shown in bold). RMSE: Values as low is desirable (lowest value per event is shown in bold). PE: Value closer to 1 is desirable (value closest to 1 per event is shown in bold). Maximum amplitude ratio: (Ideal value is 1, $0.7 \leq \text{values} \leq 1.3$ are shown in bold). $P_{\sigma, \text{ratio}}$: (Ideal value is 1, $0.7 \leq \text{values} \leq 1.3$ are shown in bold). Bias: (Ideal value is 0, $-30 \leq \text{values} \leq 30$ are shown in bold). Percentage time instances inside range (value maximum to be inside range is preferable and shown in bold per event).

3.3.1. Data Model Correlation Analysis

ADELPHI showed near-good correlations (Pearson R closer or more than 0.7) with DMSP data during all events. For Ovation Prime, the values varied between 0.59 and 0.74. ADELPHI showed better correlations with observations than Ovation Prime during all events except for 22–23 June 2015. Good correlations ($R \geq 0.7$) from ADELPHI were observed on 9 March 2012, and 17 March 2013. Ovation Prime showed a good correlation ($R \geq 0.7$) during 22–23 June 2015.

3.3.2. Accuracy Analysis HPI

RMSE and PE from Ovation Prime were better than those from ADELPHI during all cases except 9 March 2012. Maximum RMSE from ADELPHI and Ovation Prime were 67.31 GW (17 March 2015) and 83.92 GW (9 March

2012), respectively. We have also calculated the percentage of time the model prediction falls inside the range of observation. Again, the range is defined to be the region inside $\pm 20\%$ of DMSP HPI data. It was found that ADELPHI overestimated DMSP values more than Ovation Prime. The maximum amplitude ratio values from ADELPHI were consistently higher than those from Ovation Prime. The maximum values from Ovation Prime were also lower than DMSP. ADELPHI maximum amplitude ratio varied between 0.65 and 1.11, combining all events. The same from Ovation Prime was 0.24–0.96. We have also observed the variation of RMSE with respect to maximum negative SYMH for different events. We have found gradual increments in RMSE for ADELPHI with increased geomagnetic disturbances (Figure 6e). Ovation Prime also showed the same except on 9 March 2012 (maximum negative SYMH: -150 nT), when it showed higher RMSE than the other events. This means model performance worsened with increased geomagnetic disturbances.

3.3.3. Spread and Bias Analysis

The spread or precision from ADELPHI was much closer to 1 than those from Ovation Prime, indicating better correspondence to the spread of the DMSP data during all cases except on 17 March 2013. Ovation Prime underpredicted the spread of the observations during the other events. The most accurate $P_{\sigma, \text{ratio}}$ from ADELPHI and Ovation Prime were 0.96 (17 March 2015) and 1.04 (17 March 2013), respectively. Both models underpredicted the spread of the data during all cases except 17 March 2013. The spreads from ADELPHI were always higher than those from Ovation Prime. From the bias calculation, it was found that ADELPHI always systematically overpredicted the DMSP data. Ovation Prime underpredicted the same on 9 March 2012, and 22–23 June 2015, and overpredicted on 17 March 2013, and 17 March 2015. The bias values were always higher for ADELPHI than those from Ovation Prime. The bias measurement also indicates that the HPI magnitudes from Ovation Prime were systematically closer to DMSP data than those from ADELPHI during all cases except 9 March 2012.

The maximum peaks from DMSP were higher than those from ADELPHI and Ovation Prime, though ADELPHI HPI were higher than those from DMSP during the majority of periods. It should be noted that the DMSP imaging data from which DMSP HPI was derived does not cover the entire auroral zone. A model is used to fill in the remaining sections of auroral oval particle precipitation empirically, possibly causing the smoothing out of localized intensities of particle precipitation, especially near midnight. On the other hand, ADELPHI HPI was derived from instantaneous AMPERE data. This could explain the lower DMSP HPI than those from ADELPHI during a majority of periods. The lower HPI values from Ovation Prime than those from ADELPHI can be explained by the fact that Ovation Prime is an empirical model based on averaging together many years of in situ measurements of DMSP energy flux using suitable magnetospheric coupling functions derived from solar wind parameters. In most cases, DMSP HPI values were also lower than ADELPHI (except peak values). This might explain why Ovation Prime HPI values were also lower than those from ADELPHI. This is also supported by better RMSE, PE, and bias from Ovation Prime than those from ADELPHI when compared with DMSP data. Being an empirical model, Ovation Prime might have averaged DMSP values causing less intense peak (maximum amplitude ratio) and lesser spread ($P_{\sigma, \text{ratio}}$) than those from ADELPHI. As already mentioned, ADELPHI was designed from instantaneous AMPERE FAC data and had a relatively higher data spread.

3.4. Solstitial Interhemispheric Asymmetry in CPCP and HIJH

Another indicator to assess model performance is how well these models demonstrate interhemispheric asymmetries. We have limited our study of interhemispheric asymmetry during solstice events to highlight the effects of varying solar radiation in the two hemispheres. Interhemispheric asymmetry was observed in CPCP from the model results during the solstice events studied in this paper. For example, the CPCP values from SWMF were higher in the southern hemisphere than those from the northern hemisphere almost during the entire day of 22 July 2004 (northern hemisphere maximum: 116 kV, at 20:26 UT, southern hemisphere maximum: 179 kV, at 22:16 UT).

Model results also showed that HIJH were typically higher in the sunlit hemisphere, especially from LFM-MIX and high-resolution OpenGGCM without RCM (22 July 2004, and 22–23 June 2015). For example, the maximum HIJH from LFM-MIX was 4,140 GW from the northern hemisphere and 2,877 GW from the southern hemisphere during 22–23 June 2015. Our objective is to observe how models can demonstrate solstitial interhemispheric asymmetry due to the changes in solar illumination between the summer and winter hemispheres. This is especially important for HIJH. In the absence of the observed HIJH, the ability to demonstrate the solstitial interhemispheric asymmetry in HIJH due to solar illumination could be an important indicator of model performance.

The solstitial interhemispheric asymmetry was also seen in CPCP statistics. With higher CPCP in the southern hemisphere from models and lesser interhemispheric asymmetry signatures obtained from SuperDARN data, almost all models exhibited higher RMSE, higher negative PE, higher percentage instances of overestimations of CPCP, and higher maximum amplitude ratio from the southern hemisphere than those from the northern hemisphere during solstice periods (Tables 2–4). For example, RMSE from LFM-MIX was 106.66 kV in the northern hemisphere and 176.61 kV in the southern hemisphere during 22–23 June 2015. The corresponding PE values were -18.61 and -73.12 respectively. The percentage time instances of overestimation also increased from 84.08% to 97.21% from the northern hemisphere to the southern hemisphere. Maximum amplitude ratio for LFM-MIX increased from 4.16 to 7.12 from the northern hemisphere to the southern hemisphere. A higher increment of maximum amplitude ratio was also observed from high-resolution OpenGGCM without RCM (from 4.76 to 8.58) during 22–23 June 2015. Solstitial interhemispheric asymmetry was also observed in precision/spread and bias analysis. For all models during these periods, $P_{\sigma, \text{ratio}}$ values were higher in the southern hemisphere than those from the northern hemisphere. Bias increased or it became positive from negative from the northern to the southern hemisphere. These changes in metrics were the lowest in ADELPHI.

4. Discussion

In this study, we have assessed various models in specifying auroral electrodynamic parameters using several metrics and tests to compare and quantify model performances. In the absence of observations (example: HIJH), we have observed whether modeled results are consistent with each other or not, how well they correlate with AE, and whether they can manifest features such as solstitial interhemispheric asymmetry in a physically realistic way. Here, we have interpreted these results using examples from specific time intervals.

4.1. Importance of Inner Magnetosphere Model

An important outcome of our study is the sensitivity of model results to the inclusion of an inner magnetosphere component such as the RCM. LFM-MIX and high-resolution OpenGGCM models (both without RCM) exhibited poorer RMSE, PE, $P_{\sigma, \text{ratio}}$, bias, and maximum amplitude ratio (for CPCP) than the other models. They also showed the largest magnitudes and standard deviations for HIJH. Coupling with RCM improves these statistical metrics and correlations between observed AE and modeled HIJH from high-resolution OpenGGCM. The effects of coupling an inner magnetosphere model to the global magnetospheric model have already been reported in several papers (e.g., Dredger, Lopez, Collado-Vega, Khurana, & Rastaetter, 2023; Dredger, Lopez, & Collado-Vega, 2023). However, the improvement of model performance after the incorporation of RCM is quantified here in greater detail.

In order to compare radial current densities and other parameters from different models, two representative cases during strong driving conditions with extremely high HIJH from high-resolution OpenGGCM without RCM were examined in detail. These are at 17:20 UT on 17 March 2015, mainly in the southern hemisphere (henceforth Example_1) and at 5:24 UT on 8 September 2017, in both hemispheres (henceforth Example_2). The HIJH values for these examples were $\sim 25,000$ GW (southern hemisphere) and $\sim 29,000$ GW (both hemispheres), respectively. We have compared modeled radial current densities between models for both instants. We have also compared the same with observed radial current densities from AMPERE (for Example_1 only as AMPERE data was unavailable during Example_2). All these comparisons are shown for Example_1 and Example_2 in Figures 7 and 9, respectively. Corresponding Joule distributions are shown in Figures 8 and 10, respectively. Height-integrated ionospheric Hall and Pedersen conductances during Example_2 are shown in Figures 11 and 12.

For both examples, LFM-MIX and especially all versions of OpenGGCM had stronger FAC than the other models and AMPERE data (Figures 7 and 9). Among them, LFM-MIX and low-resolution OpenGGCM with RCM had stronger FAC on the dayside. The dominant part of LFM-MIX ionospheric conductance was due to solar radiation (Figure 11). This ensured higher conductance on the dayside and subsequently higher dayside FAC due to stronger solar wind-magnetosphere coupling than that on the nightside. This agrees with Ridley et al. (2004). Stronger dayside FAC might cause higher CPCP from LFM-MIX. The Joule heating distribution from LFM-MIX was also greater near the dayside (slightly toward the dusk sector during Example_1), which was consistent with the stronger FACs at this location (Figures 7–10). The stronger dayside coupling, subsequent stronger dayside FAC, and higher CPCP can explain the relatively high HIJH from LFM-MIX for all events except 9 March 2012. This agrees with Slinker et al. (1999), Wiltberger et al. (2009), and Rastätter et al. (2016).

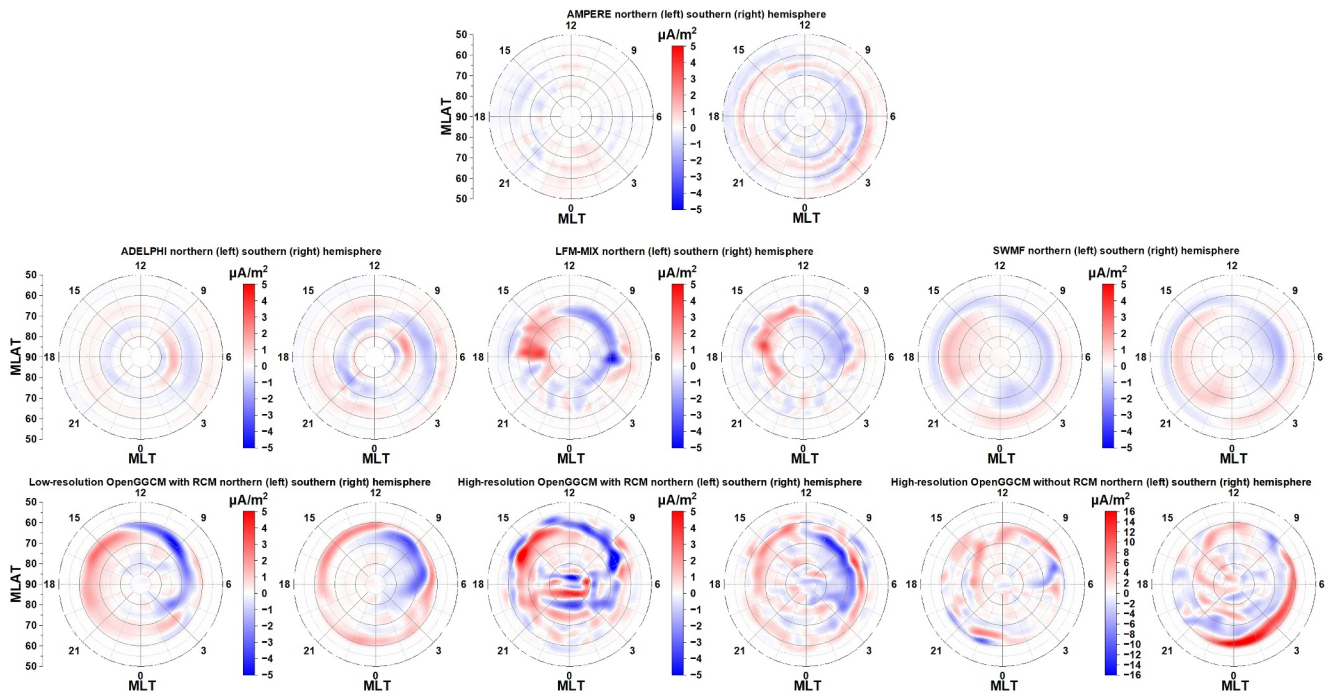


Figure 7. Radial current densities from AMPERE data and different models during 17:20 UT, 17 March 2015.

The magnitudes of radial current densities from the high-resolution OpenGGCM without RCM were much higher than AMPERE data and other models, especially in the southern hemisphere during Example_1 and in both hemispheres during Example_2 (maximum: $\sim 38 \mu\text{A/m}^2$ during Example_2). These were associated with extremely high HIJH values in both hemispheres. For Example_1, high-resolution OpenGGCM without RCM showed strong FACs from midnight to dawn in the southern hemisphere. These higher currents were possibly due to the Region 1 currents in the absence of shielding effects from the Region 2 currents from an inner magnetosphere model. In the presence of strong FACs, high-resolution OpenGGCM without RCM showed intense HIJH from the southern hemisphere during Example_1, where spatial Joule heating distribution also intensified in the midnight to dawn sector coincident with the strong FAC region. The absence of Region 2 currents pushed the Region 1 current to lower latitudes where it was saturated, causing intense Joule heating, which agrees with Richmond (2010). The shift of the radial current density was accompanied by the motion of the open-closed boundary to lower latitudes and FAC saturation, as it cannot expand any further to lower latitudes. Coupling with RCM reduces the Region 1

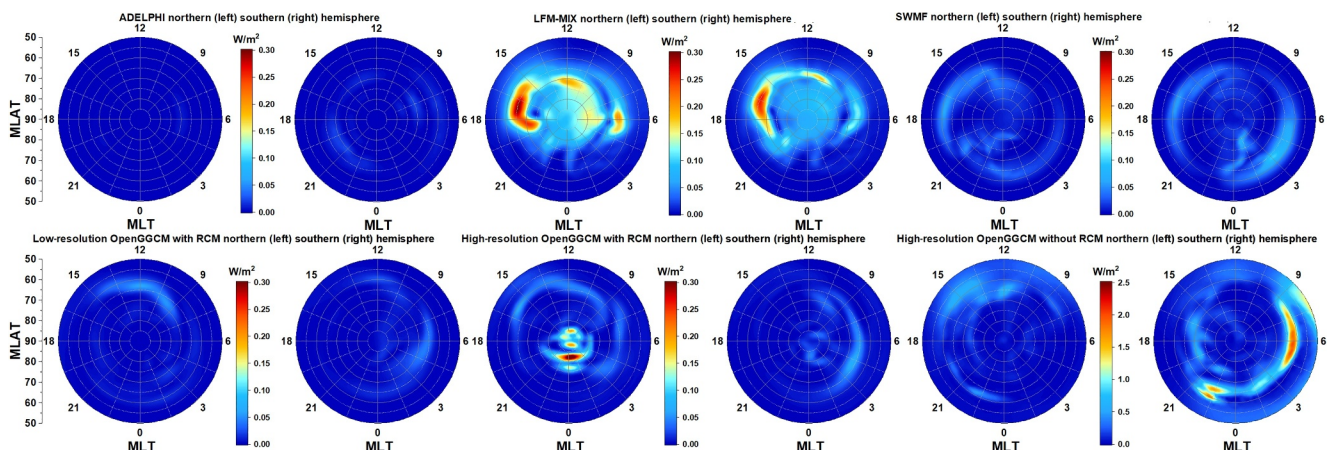


Figure 8. Joule heating distributions from different models during 17:20 UT, 17 March 2015.

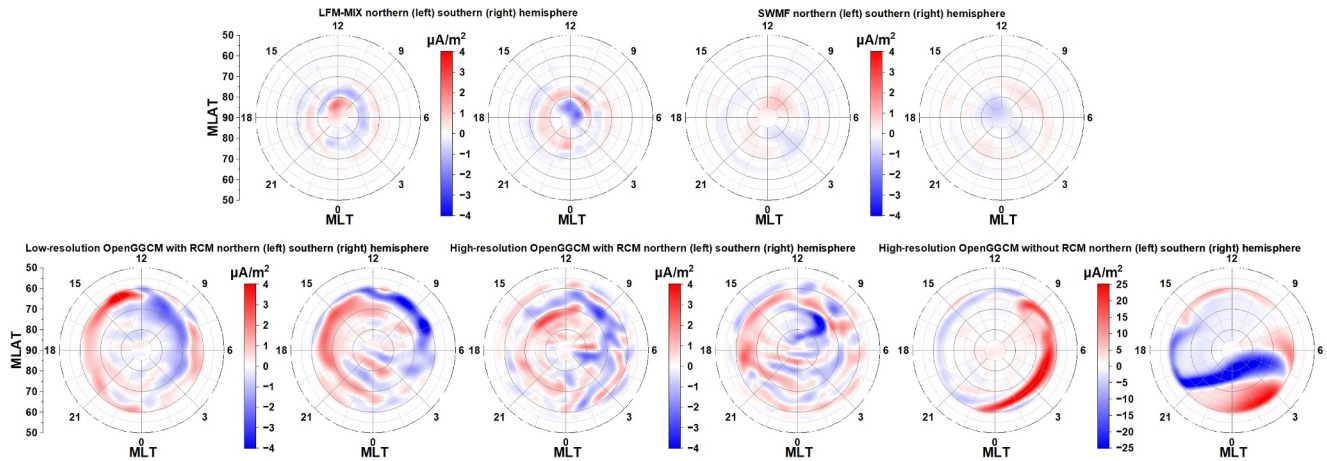


Figure 9. Radial current densities from different models during 5:24 UT, 8 September 2017.

FAC due to the presence of Region 2 currents, thus decreasing the overall HIJH (Figure 7). During Example_1, after coupling with RCM, the location of the maximum radial current density shifted from 60.5° MLAT to 64.5° MLAT in the northern hemisphere and 60.5° MLAT to 67° MLAT in the southern hemisphere. The latitudinal positions of maximum Joule heating distribution were shifted from 67° MLAT to 81.5° MLAT in the northern hemisphere and from 60° MLAT to 87.5° MLAT in the southern hemisphere (Figure 8). Therefore, high-resolution OpenGGCM with RCM showed maximum FAC and Joule heating distributions at much higher latitudes than the same from high-resolution OpenGGCM without RCM. This led to a significant reduction in CPCP, radial current density, and HIJH after coupling with RCM (Figures 1, 2, 4, and 5). During Example_2, the coupling with RCM in high-resolution OpenGGCM reduced maximum radial current density from ~38 to ~6 $\mu\text{A}/\text{m}^2$ in the southern hemisphere. However, all versions of OpenGGCM showed stronger FACs than SWMF and ADELPHI for both examples, which is consistent with their stronger ionospheric conductances due to auroral precipitation during Example_2 (Figures 11 and 12). These higher conductances were seen at relatively lower latitudes (~60° MLAT). Among all versions of OpenGGCM, ionospheric conductances were by far the largest for high-resolution OpenGGCM without RCM (maximum Hall conductances ~700 mhos). All versions of OpenGGCM also showed relatively higher current densities in lower latitudes than those from LFM-MIX and SWMF. For Example_2, maximum current densities from LFM-MIX and SWMF were seen at 84°–85° MLAT, while different versions of OpenGGCM showed maximum current densities around 62°–75° MLAT. This extremely high conductance, low latitude radial current densities with higher magnitudes, and higher CPCP (Figures 1 and 2) might explain the high HIJH, especially from high-resolution OpenGGCM without RCM.

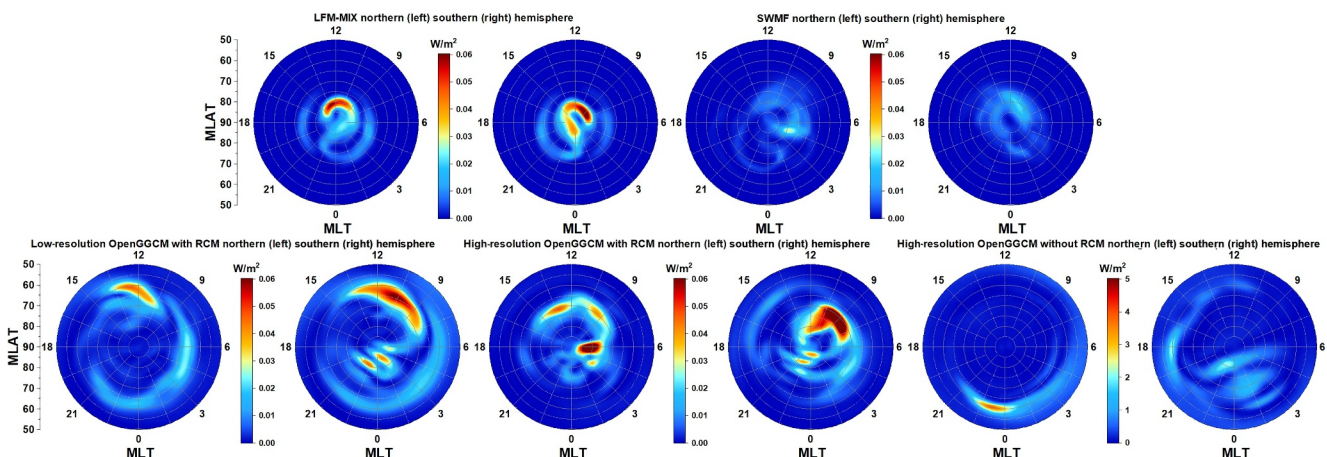


Figure 10. Joule heating distributions from different models during 5:24 UT, 8 September 2017.

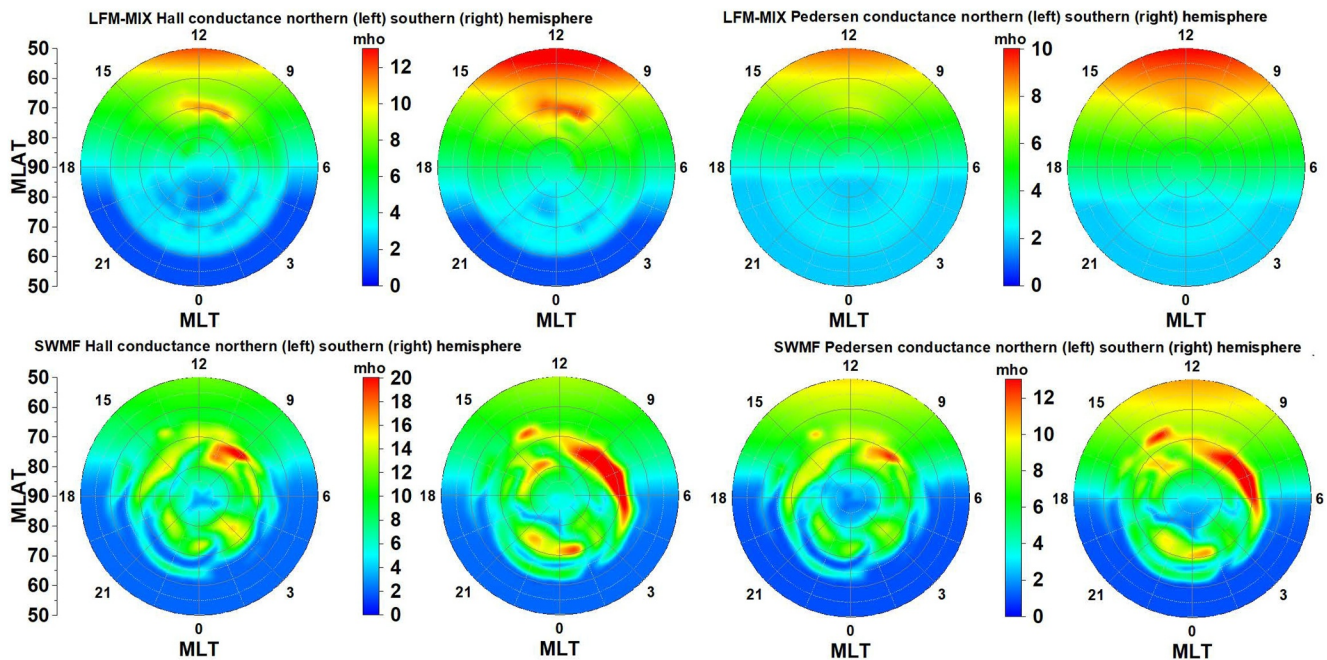


Figure 11. Ionospheric Hall and Pedersen conductances from LFM-MIX and SWMF during 5:24 UT, 8 September 2017.

Higher ionospheric conductances and radial current densities from high-resolution OpenGGCM without RCM relative to other models might also be explained by higher magnetopause erosion during geomagnetically disturbed periods (Dredger, Lopez, Collado-Vega, Khurana, & Rastaetter, 2023). We have observed noon-time magnetopause standoff distances during Example_2 from all models. The values from LFM-MIX, SWMF, and low-resolution OpenGGCM with RCM were 9.46 R_E , 8.84 R_E , and 5.81 R_E , respectively. The same from high-resolution OpenGGCM without RCM was 4.38 R_E . The inclusion of RCM shifted the distance to 10.19 R_E . This might explain the lower radial current densities, ionospheric conductances, CPCP, and HIJH from high-resolution OpenGGCM with RCM relative to those from the version without RCM. We have shown only one case of magnetospheric standoff distances to inspect the effects of inclusion of RCM, as this is beyond the scope of the present paper.

It should be noted that the high-resolution OpenGGCM without RCM showed higher CPCP and HIJH than the other models during all events except 9 March 2012. Sharp jumps were also observed in HIJH from high-resolution OpenGGCM without RCM in several cases during geomagnetically disturbed periods. These were associated with higher CPCP, radial current densities, and ionospheric conductances. The jumps could also be associated with numerical instabilities. However, these jumps were not isolated events and were seen frequently from high-resolution OpenGGCM without RCM (e.g., 17 March 2013, 17 March 2015, and 22–23 June 2015). Even without these sharp jumps, high-resolution OpenGGCM without RCM showed higher HIJH than the other models continuously during all events except 9 March 2012. These sudden jumps could also be associated with anomalous solar wind conditions. Therefore, these sudden jumps in high-resolution OpenGGCM without HIJH might be a physical process associated with the model or might also be associated with numerical instabilities, requiring further investigation. It has already been reported in Section 3.1 that the high-resolution OpenGGCM with RCM run for 22–23 June 2015 crashed in the CCMC portal, which could serve as evidence of possible numerical instabilities. However, sudden HIJH jumps were reduced after coupling with RCM.

The ionospheric conductances for the SWMF (Ridley et al., 2004) and ADELPHI (Robinson et al., 2020) models were designed empirically from FAC. They showed radial current densities closer to AMPERE data than LFM-MIX and all versions of OpenGGCM during Example_1. Rastaetter et al. (2016) mentioned that SWMF provided more realistic CPCP values. The present paper shows that CPCP from SWMF and ADELPHI were more accurate than LFM-MIX and different versions of OpenGGCM in most cases (especially from high-resolution OpenGGCM with or without RCM). Therefore, HIJH values from SWMF and ADELPHI can also be

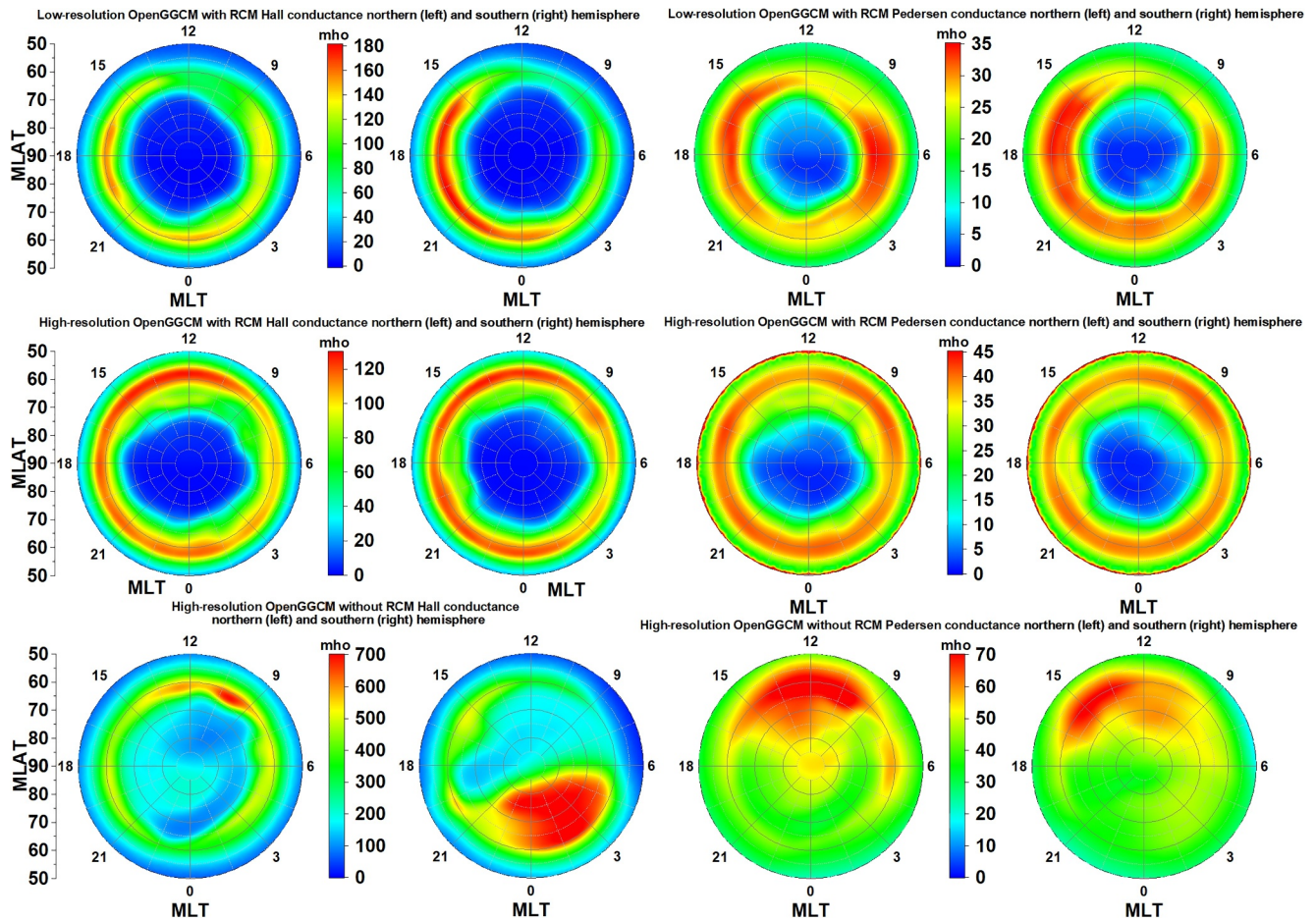


Figure 12. Same as Figure 11 for different versions of OpenGGCM.

considered realistic and can be used as benchmarks in the absence of observations. ADELPHI FACs agreed well with observed FACs because the model itself is fed by AMPERE FAC data. This also means its ability to capture small-scale variations is limited. FACs from AMPERE are typically less than $2 \mu\text{A}/\text{m}^2$, much smaller than those from the MHD models. This accounts for the smaller values for HIJH derived from ADELPHI.

4.2. Effects of Model Resolution

This study has shown that an increase in model resolution generally provides higher CPCP and HIJH for OpenGGCM (Figures 1, 2, 4, and 5). This agrees with Johnson and Heelis (2005), Deng and Ridley (2007), and Rastätter et al. (2016). The increase in Joule heating values with higher resolution is possibly due to improved ability to capture the small-scale particle precipitation and electric field variations that are the sources of intense atmospheric heating (Codrescu et al., 1995; Deng & Ridley, 2007; Lanchester et al., 2001) mainly during intense geomagnetically disturbed conditions. Higher-resolution OpenGGCM captured very small-scale structures of radial current density variations with higher magnitudes during Example_1 and Example_2 (Figures 7 and 9, respectively), which might contribute to the very high HIJH values. These structures were absent in the low-resolution OpenGGCM with RCM model simulations, probably because of spatial averaging (Lühr et al., 2004). Lu et al. (1995) and Rastätter et al. (2016) mentioned that higher resolution shifts magnetospheric energy to lower latitudes, causing model inaccuracy. This agrees with our observation of higher CPCP accuracies and lower HIJH from low-resolution OpenGGCM with RCM than the higher-resolution versions during most of the geomagnetic storm events (Figures 1, 2, 4, and 5 and Tables 2–4).

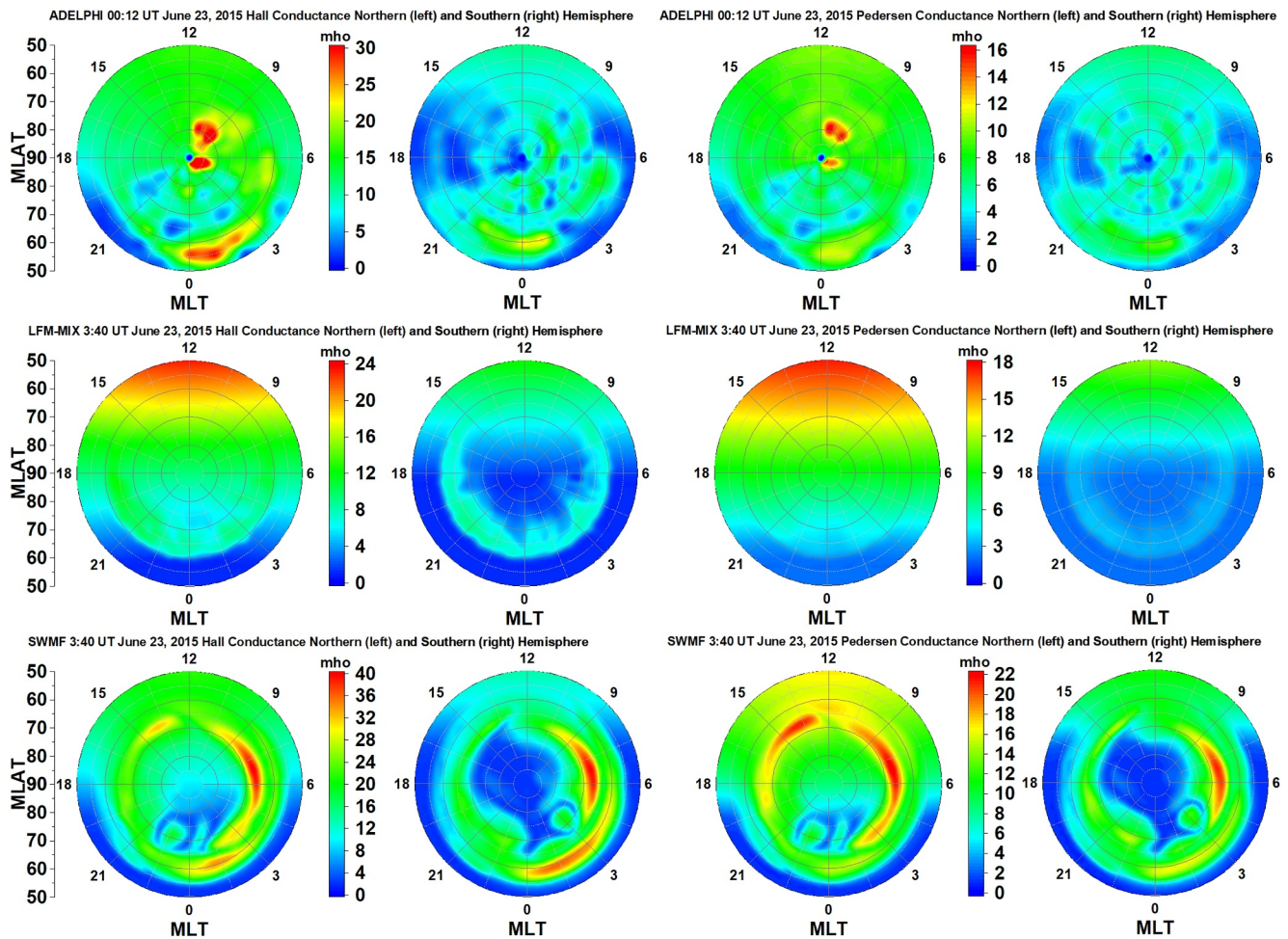


Figure 13. Ionospheric Hall and Pedersen conductances from ADELPHI, LFM-MIX, and SWMF during a geomagnetically disturbed solstice period (23 June 2015).

Capabilities of capturing small-scale structures in radial current densities by higher-resolution OpenGGCM might explain its increased HIJH correlations with AE. HIJH is related to the energy dissipated from magnetosphere-ionosphere currents, and it is highly dependent on the spatial distribution of electric fields and currents. High-resolution models can capture the detailed spatial structures of these electric fields and currents, leading to a better correlation with auroral electrojet currents.

4.3. Solstitial Interhemispheric Asymmetry

Another metric used in this study to assess model performance was the interhemispheric asymmetry in electrodynamic parameters during the solstice events. Fuller-Rowell, Codrescu, et al. (1996) and Hong et al. (2021) attributed these seasonal variations to differences in ionospheric conductances due to varying solar illumination. The higher conductances produced by solar illumination allow for more currents to flow in the sunlit hemisphere (Fuller-Rowell, Codrescu, et al., 1996). The frictional heating between ions and neutrals associated with these currents is reflected in higher HIJH. This interhemispheric asymmetry was observed on 22 July 2004, and 22–23 June 2015, from all models. The effects of solstitial interhemispheric asymmetry were also seen in the statistical results of model performances, especially from LFM-MIX and high-resolution OpenGGCM without RCM (Section 3.4).

Representative cases of ionospheric height-integrated Hall and Pedersen conductances from all available models are shown in Figures 13 and 14 during disturbed conditions on 23 June 2015. Ionospheric conductances from all models were higher in the sunlit northern hemisphere than in the southern hemisphere. The decrease in solar illumination-driven conductance in the southern winter hemisphere might explain the higher CPCP and lower

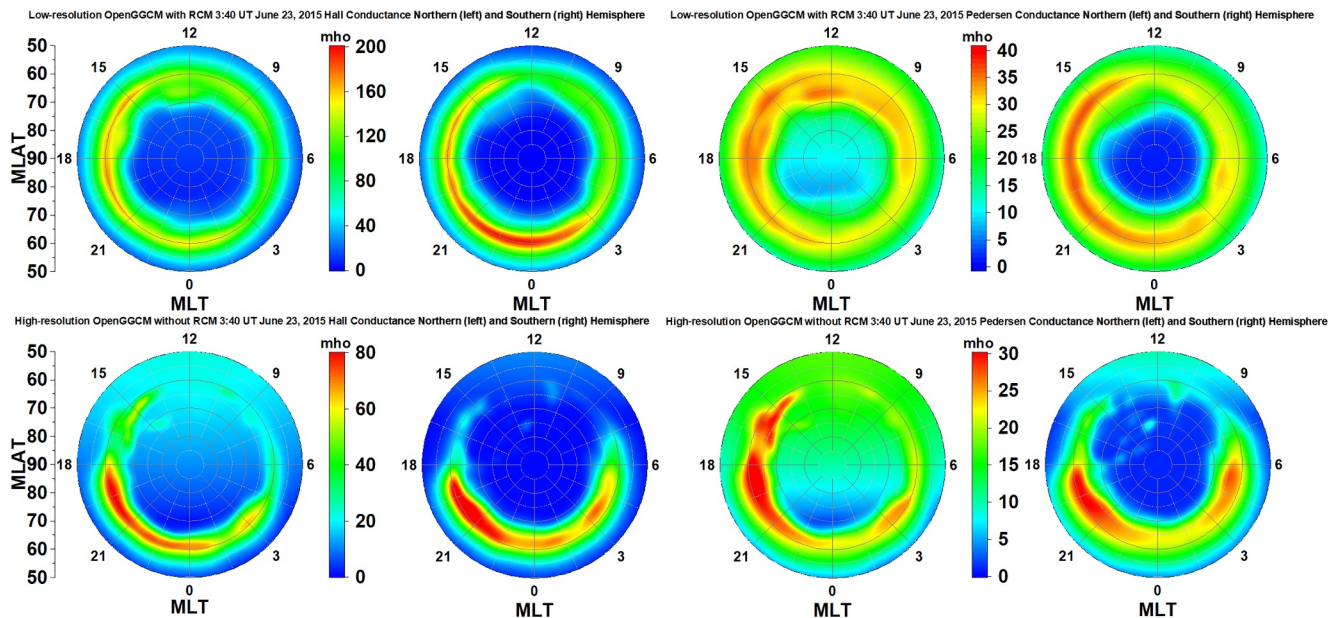


Figure 14. Same as Figure 13 for different available versions of OpenGGCM.

HIJH in the southern hemisphere than in the northern hemisphere for all models. Regarding magnitude, LFM-MIX had the lowest, and OpenGGCM (all versions) had the highest ionospheric Hall and Pedersen conductances compared to the other models. For OpenGGCM, the contribution from auroral precipitation to total conductance was higher than that from solar illumination (Figure 14). For SWMF, the contributions were of near similar magnitudes. For LFM-MIX, the conductance driven by solar illumination was larger than that from auroral precipitation. The dominant contribution of solar radiation-driven conductance over total conductance in LFM-MIX might be a possible reason for the higher solstitial interhemispheric asymmetry of CPCP and HIJH observed from this model than the other models.

The other possible factors for interhemispheric asymmetry in CPCP and Joule heating could be due to effects from IMF By (Hong et al., 2023; McHarg et al., 2005) and dipole tilt (varies by $\pm 10^\circ$ during equinox), and its diurnal variations (Cnossen et al., 2012; Cnossen & Richmond, 2012; Eggington et al., 2020; Lockwood et al., 2018). Other factors are offsets between geographic and geomagnetic poles (Förster & Cnossen, 2013; Laundal et al., 2017), differences in magnetic field strengths, asymmetric geomagnetic field (Hong et al., 2021; Laundal et al., 2017), and twisting of the magnetosphere during geomagnetically disturbed periods as a result of solar wind interactions (Østgaard et al., 2011). As mentioned in Section 3.4, we have limited the objective of this paper to observing whether models could demonstrate solstitial interhemispheric asymmetry due to changes in solar illumination. Discussions on other factors regarding interhemispheric asymmetry are planned to be presented in a separate focused paper as the continuing objectives of ISWAT.

5. Summary and Conclusions

This study provides a comprehensive performance analysis of different auroral parameter prediction models during adverse space weather conditions. The model predictions are compared with each other and with observations when available. In the absence of observations (e.g., HIJH), we have examined the extent to which the derived auroral parameters are correlated with solar and other geomagnetic parameters, such as AE, and their capabilities to address the solstitial interhemispheric asymmetry in auroral parameters due to solar radiation. Efforts to acquire more observations to compare with the model predicted values are still underway. These results will be reported later as a part of continuing AuroraPHILE group activities.

The overall results are summarized below.

1. LFM-MIX and high-resolution OpenGGCM without RCM showed higher CPCP than observations and other models during most events (RMSE, PE, percentage time instances of overestimation, and maximum

- amplitude ratio). These models also systematically overestimated the observations and their spread. However, CPCP from LFM-MIX (also from SWMF) was highly correlated with observations.
2. Negative PE from almost all models, when compared with SuperDARN, indicates poor CPCP performance from models. Different statistical metrics, including PE from modeled CPCP, were improved when compared with DMSP data. This may also be explained by the limitations of SuperDARN data.
 3. ADELPHI and SWMF CPCP showed the most accurate and precise predictions of CPCP. The correlation with DMSP CPCP data was maximum with ADELPHI outputs for the one day when these data were available.
 4. When compared with SuperDARN data, CPCP RMSE values from all models were correlated with geomagnetic activity except low-resolution OpenGGCM with RCM. Other metrics, such as PE and maximum amplitude ratio, were also correlated with geomagnetic disturbances. This means model performance worsened during higher geomagnetic activity except for low-resolution OpenGGCM with RCM. This may also point to systematic offsets in the SuperDARN data.
 5. LFM-MIX and high-resolution OpenGGCM without RCM showed relatively high HIJH values during all but one day (9 March 2012). This is consistent with their higher CPCP values. The magnitudes and spreads of HIJH were correlated with geomagnetic storm intensity.
 6. ADELPHI showed relatively lower HIJH values. This might be explained by its inability to capture small-scale radial current density variations and relatively smaller radial current density magnitudes.
 7. HIJH values from SWMF showed the highest correlations with observed AE, followed by LFM-MIX and high-resolution OpenGGCM with RCM. Other models showed moderate correlations with observed AE during most cases.
 8. In the absence of observations, HIJH from SWMF and ADELPHI may be considered the benchmarks as they provided more accurate CPCP and radial current density values.
 9. Performances of all models were more consistent on 9 March 2012, than during other events. It is unclear what aspect of this geomagnetic storm allowed for better agreement among the models than the other events. This needs further investigation.
 10. All models captured the expected solstitial interhemispheric asymmetry due to varying solar radiation, as they provided higher CPCP and lower HIJH from the winter hemisphere than those from the summer hemisphere. This was reflected in several performance metrics and is likely due to the higher ionospheric conductances from the sunlit northern hemisphere than those from the southern hemisphere. LFM-MIX and high-resolution OpenGGCM without RCM showed higher interhemispheric asymmetries in CPCP and HIJH than the other models.
 11. ADELPHI provided relatively higher HPI values than Ovation Prime. Ovation Prime had better RMSE, PE, and bias in most cases, but the peak values from ADELPHI were closer to DMSP data peak values than those from Ovation Prime.
 12. ADELPHI HPI values were well correlated with DMSP data during most cases ($R \geq 0.7$ or closer to 0.7).
 13. Modeled HPI RMSE values (both from ADELPHI and Ovation Prime) were correlated with geomagnetic disturbances. However, this indicates that the model performance worsened with increased geomagnetic disturbances. The only exception was on 9 March 2012, for Ovation Prime. On 9 March 2012, Ovation Prime showed higher RMSE values than during other geomagnetic disturbed events with higher intensities.

The effects of model resolution: The performance of lower and higher resolution versions of OpenGGCM in predicting CPCP and HIJH yielded the following results:

1. For CPCP, low-resolution OpenGGCM with RCM was more accurate, precise, and had less systematic bias from the observation than the higher-resolution version. However, low-resolution OpenGGCM with RCM showed weaker correlations with observed CPCP than the higher-resolution version.
2. As mentioned before in this section, correlations were found between event-wise CPCP RMSE and corresponding maximum negative SYMH from high-resolution OpenGGCM (with or without RCM). This indicated that the CPCP performance from high-resolution OpenGGCM worsened with higher geomagnetic activity. However, this correlation was absent in low-resolution OpenGGCM with RCM. This shows the performance of low-resolution OpenGGCM with RCM did not vary with geomagnetic storm intensities, which is a positive aspect for the low-resolution OpenGGCM with RCM.
3. Low-resolution OpenGGCM with RCM also provided lower HIJH. Higher resolution increased the correlation between HIJH and AE.

4. The radial current densities from low-resolution OpenGGCM with RCM were more accurate than those from high-resolution OpenGGCM as compared to AMPERE data.
5. The higher HIJH from higher-resolution versions could be due to the presence of spatially small-scale structures in radial currents, which were absent in the low-resolution version. However, inaccuracies could occur in the higher-resolution versions, as magnetospheric energy might shift to lower latitudes. This might cause saturation of FAC and numerical instabilities in model simulations. This could also be linked with higher magnetospheric erosion (especially for high-resolution OpenGGCM without RCM). But this needs more observations. However, the accuracies of these higher HIJH values could not be evaluated as we did not have observed HIJH.

The effects of incorporating an inner magnetospheric model into a global magnetosphere model: We have incorporated RCM with high-resolution OpenGGCM and compared its performance with that without RCM. The results are summarized below.

1. Coupling with RCM in OpenGGCM significantly reduced the overestimation of high-resolution OpenGGCM while predicting CPCP. It also improves its accuracy, precision, and bias.
2. Incorporation of RCM in high-resolution OpenGGCM reduced HIJH magnitudes (which might be more realistic) and event-wise standard deviations and increased the correlations with AE.
3. Incorporation of RCM reduces the radial current densities. The current densities after the incorporation of RCM were closer to AMPERE data.
4. The inclusion of RCM also shifts magnetospheric energy in terms of radial current density and Joule distribution toward higher latitudes (and subsequently preventing FAC saturation) by introducing region-2 currents to the system.
5. The inclusion of RCM reduced the magnetospheric erosion.
6. Including RCM reduced sudden jumps in HIJH during higher geomagnetically disturbed conditions, possibly arising due to numerical instabilities.

The effects of ionospheric conductances:

1. Ionospheric conductances from LFM-MIX have dominant contributions from solar radiation on the dayside. This might explain its stronger dayside FAC and stronger dayside coupling with the solar wind. This can also explain the relatively higher CPCP and HIJH from LFM-MIX.
2. Having stronger conductance contributions from dayside solar radiation may also explain higher solstitial interhemispheric asymmetry due to solar illuminance from LFM-MIX than the other models.
3. ADELPHI and SWMF showed lesser strength in FAC, and lesser Joule heating distributions. Ionospheric conductances from both models were calculated from empirical relations based on FAC (Ridley et al., 2004; Robinson et al., 2020). Radial current densities from both models were closer to AMPERE data than those from LFM-MIX and all versions of OpenGGCM.
4. Conductances from OpenGGCM were higher for all versions than the other models and occurred at relatively lower latitudes ($\sim 60^\circ$ MLAT) during disturbed conditions. This could also explain the relatively higher radial currents from all versions of OpenGGCM than the other models.
5. After incorporating RCM, extremely high conductance from the high-resolution OpenGGCM was reduced. This also reduced overall CPCP and HIJH and shifted magnetospheric energy toward higher latitudes.

Although it cannot be conclusively determined which model is superior, we can definitely categorize the model performances in terms of different metrics such as accuracy, precision, bias, and data-model correlations, correlations with geomagnetic parameters (between HIJH and AE), and their abilities to reproduce phenomena such as solstitial interhemispheric asymmetry. These types of studies are important for model developers on a regular basis to identify potential strengths and weaknesses of models and for users of space weather information who need to choose models for their applications. In the future, we expect to get DMSP CPCP data for the other events in order to validate the model performances with observations. The storm that occurred on 9 March 2012, must be further explored as this is the only one among all ISWAT events where all model performances for HIJH and CPCP from both hemispheres were consistent. The interrelations between modeled ionospheric conductances and modeled CPCP and HIJH are different from each other and need further investigation. Detailed inspection of interhemispheric asymmetries involving other factors is required. Those results will be presented in subsequent

papers as a part of continuing ISWAT G1-03 group activities. Future papers will also include performance evaluations of improved and newer models. In this paper, we have conducted a comprehensive statistical analysis that could be used as a benchmark for those studies.

Data Availability Statement

All CCMC-based model outputs (LFM-MIX, SWMF, OpenGGCM, Ovation Prime) can be found using the model run numbers (Table S1 in Supporting Information S1) on the CCMC website ccmc.gsfc.nasa.gov. IMF Bz, Solar wind speed, solar wind pressure, auroral electrojet, and SYMH are available from the website omniweb.gsfc.nasa.gov. All ADELPHI model outputs and CPCP from SuperDARN and DMSP (only on 9 March 2012) are made available online at Sur et al. (2024a). DMSP hemispheric power input data is available at the Madrigal database. The data are provided online at Sur et al. (2024b). We have also used AMPERE radial current density data from <https://ampere.jhuapl.edu> to compare the model performance.

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