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Key Points:

- WACCM-X runs coupled to the MAGE geospace model show 71.7%–121.7% higher Joule heating rates compared to empirical geomagnetic forcing
- Neutral density and Joule heating rate during storm recovery vary up to 50% between high- and coarse-resolution configurations
- MAGE-coupled WACCM-X runs show lower integrated O/N₂ ratios during and after the storm

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Impact of Magnetosphere Forcing and Model Resolution on Joule Heating Estimates in WACCM-X During the 24 August 2005 Storm

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Abstract We investigate the high-latitude Joule heating in a recently developed high-resolution configuration of the WACCM-X whole-atmosphere model coupled to the MAGE model. Model resolution and geomagnetic forcing effects during the severe ($K_p > 8$) geomagnetic storm on 24 August 2005 are analyzed, distinguishing storm peak and recovery conditions. The Joule heating energy in MAGE-coupled runs is 71.7%–121.7% higher compared to Heelis- and Weimer-driven WACCM-X runs, due to stronger convection electric fields. Due to the higher Joule heating, the column-integrated O/N₂ ratio is significantly lower in MAGE-coupled runs, potentially correcting a previously observed overestimation of the WACCM-X model. The distribution of modeled Joule heating rates with geomagnetic latitude is affected by the coupling to MAGE as well. The high-resolution model shows distinctly different thermospheric dynamics in response to the geomagnetic storm, leading to a lower neutral particle density over the polar region during storm recovery compared to the coarse-resolution model. The altered thermospheric dynamics causes a 50% higher Joule heating up to about 120 km and lower Joule heating at F region altitudes, in turn affecting the thermospheric neutral density. Despite the overall lower Joule heating rates in the high-resolution model run, the neutral gas heating rate is higher compared to the coarse-resolution run, leading to slightly lower O/N₂ ratios. The electron density is affected on meso-scales, especially in the area of the auroral oval, by the increase in model resolution, which causes strong local variations of Joule heating estimates between the high- and coarse-resolution model runs.

Plain Language Summary Resistive heating, also known as Joule heating, is the fundamental process of light bulbs. Interestingly, it is also of high importance for the interaction of the Earth system and its space environment. The Joule heating of the Earth's atmosphere above 100 km altitude occurs mainly at auroral latitudes and is a main source of so-called “space weather impacts” on human society. Two of the main challenges for space weather forecasts are the accurate modeling of the high-latitude electrodynamics, that is the currents responsible for Joule heating, and so-called meso-scale processes (atmospheric processes with a size of about 20–2,000 km), which are highly important for how the atmosphere reacts to Joule heating. A new high-resolution atmosphere-ionosphere model run coupled to a physical high-latitude electrodynamics model promises to improve on both of these problems. We investigate the model run more closely to distinguish the respective effects of physics-based modeling of high-latitude electrodynamics and the high-resolution model configuration. On a global scale, the modeling of high-latitude electrodynamics has a stronger impact on space weather modeling. However, the high-resolution model configuration significantly affects the thermospheric dynamics and the mesoscale ionosphere, both causing distinct changes to the representation of space weather processes as well.

1. Introduction

The modeling of geomagnetic energy input into the thermosphere-ionosphere (T-I) system by high-latitude Joule heating remains one of the major challenges for space weather predictions. Geomagnetic forcing by data assimilated convection patterns (Matsuo, 2020; Richmond & Kamide, 1988) was shown to agree better with local

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measurements (Günzkofer, Liu, Pham, et al., 2025, Günzkofer, Liu, Liu, et al., 2025) than empirical parameterizations (Heelis et al., 1982; Weimer, 1995, 2005). Recent efforts (e.g., Sorathia et al., 2023) were directed toward coupling a magnetohydrodynamic (MHD) model of the magnetosphere, such as the Grid Agnostic MHD for Extended Research Applications (GAMERA, Lyon et al., 2004; B. Zhang et al., 2019), with a T-I model. Physics-based geospace simulations, such as the Multiscale Atmosphere-Geospace Environment (MAGE), including GAMERA as the magnetosphere component, promise a more realistic geomagnetic forcing of the thermosphere-ionosphere, though a systematic validation remains to be done.

In addition to geomagnetic forcing, high-latitude ionospheric phenomena like polar plasma patches (Pokhotelov et al., 2021; Xiong et al., 2019) and auroral arcs (Krcelic et al., 2023) can cause a meso-scale ($\sim 20 - 2000$ km) variability of the Pedersen conductivity, thus affecting the Joule heating. Recently, a novel high-resolution configuration of the Whole Atmosphere Community Climate Model with thermosphere/ionosphere extension (WACCM-X, H. L. Liu, Lauritzen, Vitt, & Goldhaber, 2024) has been developed. This promises an improved representation of meso-scale processes. The direct resolution of gravity waves in high-resolution model runs has been shown to affect the thermospheric circulation (H. L. Liu, Lauritzen, & Vitt, 2024; H. L. Liu, 2025). Associated wind and density changes might also affect the Joule heating estimate. For a detailed discussion of the physical processes resolved in high-resolution WACCM-X runs and the associated numerical issues, we refer to H. L. Liu, Lauritzen, Vitt, and Goldhaber (2024).

In this paper, we analyze a MAGE-driven high-resolution (HR) WACCM-X simulation of the severe geomagnetic storm on 24 August 2005 (maximum Kp 9–; maximum auroral electrojet index $AE \approx 2200$ nT at around 10:00 UT). This event was previously studied by Crowley et al. (2010), Pham et al. (2022), and Wilder et al. (2012). Most notably, Pham et al. (2022) investigated this storm with a version of the MAGE model, which included TIE-GCM for the T-I component. However, their main focus was on atmospheric density disturbances in comparison to CHAMP satellite measurements. The focus of this paper is to assess the impact that these recent model developments (the coupling to a magnetosphere model and the high-resolution model configuration, see Section 2) have on the high-latitude Joule heating.

Joule heating occurs due to Pedersen currents and has a distinct maximum at about 110–130 km altitude (Baloukidis et al., 2023; Günzkofer et al., 2024). However, Joule heating has a thermospheric impact in a broad range of altitudes, and this paper investigates the range of 90–300 km altitude. The local Joule heating rate is

$$q_J = \sigma_P (\vec{E} + \vec{U}_N \times \vec{B})^2 \quad (1)$$

where σ_P is the Pedersen conductivity, $\vec{E}$ the convection electric field, $\vec{U}_N$ the neutral wind vector, and $\vec{B}$ the Earth's magnetic field. The Pedersen conductivity is

$$\sigma_P = \left(\frac{\nu_{en}}{\nu_{en}^2 + \omega_e^2} + \frac{m_e}{m_i} \frac{\nu_{in}}{\nu_{in}^2 + \omega_i^2} \right) \frac{N_e e^2}{m_e} \quad (2)$$

with the ion/electron-neutral collision frequencies $\nu_{in/en}$ (assuming the empirical relations given in Kelly (2009)), ion/electron gyrofrequencies $\omega_{i/e}$, ion/electron mass $m_{i/e}$, elementary charge e , and electron density N_e . It can be seen that the Joule heating rate is affected by thermospheric (neutral wind $\vec{U}_N$ and density $n_n \propto \nu_{in}$) and ionospheric (electron density N_e) parameters.

To distinguish and evaluate the respective impacts of geomagnetic forcing with the MAGE model and the high-resolution model configuration, we analyze and compare four WACCM-X runs: We performed two MAGE-driven runs leveraging high (HR) and coarse-resolution (CR) WACCM-X, and two (CR) runs driven by the empirical Heelis and Weimer convection patterns. The following research questions will be addressed in this paper:

1. How does the Joule heating in MAGE-coupled runs differ from empirical forcing in terms of magnitude and distribution?
2. What are the respective contributions of particle precipitation and convection potential forcing to these changes in Joule heating?

3. Do the changes of thermospheric circulation in high-resolution runs affect the Pedersen conductivity and Joule heating?
4. How much does the increased resolution of meso-scale ionospheric structures affect the local Joule heating rate?
5. What are the secondary effects, for example, on the O/N₂ ratio, of the different Joule heating rates?

It should be noted that the main focus is on inter-model comparisons. To give a general overview, an initial comparison of the model results to SSUSI and SuperDARN measurements is shown. A thorough validation would require a statistically significant number of model results and better measurement coverage than is available for the August 2005 storm and will be conducted in future work.

The investigated model runs will be introduced in Section 2. The obtained results are presented in Section 3. In Section 4, the results will be discussed, and a brief comparison to available measurements will be shown. Section 5 will give a summary and the main conclusions. An overview of possible future work can be found in Section 6.

2. Model Description

2.1. WACCM-X

The Whole Atmosphere Community Climate Model with thermosphere/ionosphere extension (WACCM-X) is the atmospheric part of the NCAR Community Earth System Model (H.-L. Liu et al., 2018). While the standard model configuration is based on a finite volume dynamical core, a new configuration with a spectral elements (SE) core (Lauritzen et al., 2018) has been developed, which allows for an increased horizontal resolution. All investigated model runs were generated in the SE-WACCM-X configuration. The high-resolution (HR) MAGE-coupled run was conducted in the SE-WACCM-X NE120/L273 configuration (120 elements on each cubed sphere face; 273 pressure levels), resulting in a horizontal resolution of ~25 km and a vertical resolution of 0.1 scale heights. The model results are saved on a $0.25^\circ \times 0.25^\circ$ grid. For reference, a second MAGE-coupled, a Heelis-driven, and a Weimer-driven model run in the SE-WACCM-X NE30/L130 configuration, resulting in a coarse-resolution (CR) of ~100 km (saved on a $1^\circ \times 1^\circ$ grid) and 0.25 scale heights, are analyzed. More detailed information about the SE-WACCM-X configurations can be found in H. L. Liu, Lauritzen, Vitt, and Goldhaber (2024) and references therein.

2.2. Geomagnetic Forcing

Empirical models provide the default geomagnetic input into T-I models, most commonly Heelis (Heelis et al., 1982) and Weimer (Weimer, 1995, 2005). The Heelis model is a parameterization based on the K_p index. The Weimer model is based on the solar wind density and speed, as well as the B_y and B_z components of the interplanetary magnetic field. Particle precipitation is in both cases described by the parameterization from Roble and Ridley (1987). This formulation assumes the position and size of the auroral oval as given by the respective convection model and gives the particle precipitation energy flux distribution based on the K_p index.

The Grid Agnostic MHD for Extended Research Applications (GAMERA) is an MHD simulation tool applicable to planetary magnetospheres, including Earth's. It originates from the Lyon-Fedder-Mobarry code (Lyon et al., 2004). GAMERA explicitly solves the MHD equations as described in B. Zhang et al. (2019). For the MAGE model run in Pham et al. (2022), GAMERA was coupled to the Rice Convection Model (Toffoletto et al., 2003) and the re-developed magnetosphere-ionosphere coupler/solver (REMIX, Merkin & Lyon, 2010). The results of this MAGE run are used in this study to drive the SE-WACCM-X model. The GAMERA output used to drive the SE-WACCM-X runs has a horizontal resolution of 0.5° . GAMERA models the precipitation of monoenergetic and diffuse electrons according to B. Zhang et al. (2015) and overwrites the standard particle precipitation formulation of WACCM-X.

2.3. Validation Measurements

Though the focus of this paper is to evaluate the model Joule heating with respect to recent model developments, an initial comparison to available measurements shall be given. We will evaluate horizontal patterns of Pedersen conductivity with measurements from the SSUSI instrument aboard the DMSP F16 satellite, which allows

inferring the maximum E region electron density (Knight et al., 2018). Model electric field patterns will be compared to SuperDARN maps (Greenwald et al., 1995) of the polar plasma potential.

3. Results

3.1. Geomagnetic Forcing

On 24 August 2005, a severe geomagnetic storm occurred. As shown in Figure 1a, the Kp index reached a maximum of 9— and the auroral electrojet index AE went up to ~ 2200 nT at 10:00 UT.

Figure 1b shows 1-hourly instantaneous values of the total modeled Joule heating power integrated over the northern hemisphere at 90–300 km altitude by multiplying the geometric volume of each model grid point with the local Joule heating rate. The Joule heating peaks in both MAGE-coupled runs are approximately 1,600–1,750 GW, comparable to the results in Pham et al. (2022). The Weimer-driven WACCM-X Joule heating rates are similar to the MAGE-coupled runs, which are lower than the Weimer-driven TIE-GCM heating rates in Pham et al. (2022) (~ 3000 GW). This difference between WACCM-X and TIE-GCM might be caused by the Joule heating scaling factor of 1.5 applied in TIE-GCM (Codrescu et al., 1995; Günzkofer et al., 2024). Also, the formulation of the ion drag (TIE-GCM applies a scalar drag coefficient, WACCM-X a tensor) is different in both models, which might cause additional deviations. The Heelis-driven run shows a lower peak Joule heating rate of about 700 GW.

The total energy input from 08:00–24:00 UT in the two MAGE-coupled runs (HR: $3 \cdot 10^{16}$ J; CR: $3.7 \cdot 10^{16}$ J) is 71.7%–121.7% larger compared to the two empirically driven runs ($\sim 1.7 \cdot 10^{16}$ J). It should be noted that both empirical model runs give a similar Joule heating energy integrated over the investigated periods (starting at 8 UT to avoid influences from the model spin-up), though the peak Joule heating powers are very different.

Mapping the model Joule heating rates to altitude-adjusted corrected geomagnetic coordinates (AACGM, Shepherd, 2014) and integrating the local Joule heating over all longitudes and altitudes allows studying how different geomagnetic forcing models affect the distribution of heating power with geomagnetic latitude. The maximum Joule heating power in the MAGE-coupled and the Heelis-driven runs during the storm peak is at $\sim 66^\circ$ N geomagnetic latitude (Figure 1c). The Weimer-driven run gives the maximum Joule heating power at lower geomagnetic latitude ($\sim 60^\circ$ N). During the recovery phase, the maximum Joule heating is further north by 1° – 2° in the empirically driven runs, and 9° – 10° in the MAGE-coupled runs (Figure 1d). The International Geomagnetic Reference Field (Alken et al., 2021) for the year 2005 is assumed.

Equation 1 shows that the Joule heating rate is determined by the Pedersen conductivity σ_p and the dynamo electric field $\vec{E} + \vec{U}_N \times \vec{B}$. The dynamo electric field can be expressed as $(\vec{U}_N - \vec{U}_I) \times \vec{B}$, with $\vec{U}_I$ being the ion velocity (this expression can also be applied in the E region since, in the model, no altitude-dependent drag force is applied on the ions). Figure 2 shows the common logarithm of q_J , σ_p , and the squared ion velocity in the neutral atmosphere reference system $(\vec{U}_N - \vec{U}_I)^2$ at 10:00 UT for the three coarse-resolution WACCM-X runs at the altitude of maximum Joule heating (~ 120 km). All quantities are mapped to altitude-adjusted corrected geomagnetic coordinates (AACGM, Shepherd, 2014) and we leverage the *M_Map* software package (Pawłowicz, 2020) for plotting.

Though all three runs in Figure 2 are conducted at the same resolution, the parameters of the MAGE-driven run show significantly more meso-scale variability. This was also observed by Pham et al. (2022, Figure 2), comparing MAGE-coupled and Weimer-driven TIE-GCM results, and is presumably because GAMERA specifically solves monoenergetic and diffuse electron precipitation (B. Zhang et al., 2015). The Pedersen conductivity patterns in the Heelis- and Weimer-driven runs (Figures 2e and 2h) are similar in shape and nearly identical at high latitudes, but the auroral oval extends further south in the Weimer-driven run. The similarity is expected since the standard formulation from Roble and Ridley (1987) is applied in both these runs, which assumes the size and shape of the auroral oval as given by the respective convection model. However, the two empirical convection models result in different $(\vec{U}_N - \vec{U}_I)^2$ patterns (Figures 2f and 2i). The higher Joule heating in the MAGE-coupled model runs appears to be the result of a higher $(\vec{U}_N - \vec{U}_I)^2$ term (Figure 2c), that is, stronger electric fields. The empirically driven model runs show intuitive convection maps with (at least) two distinct minima on the magnetic dawn and dusk sides. The MAGE-coupled runs show an unexpectedly strong

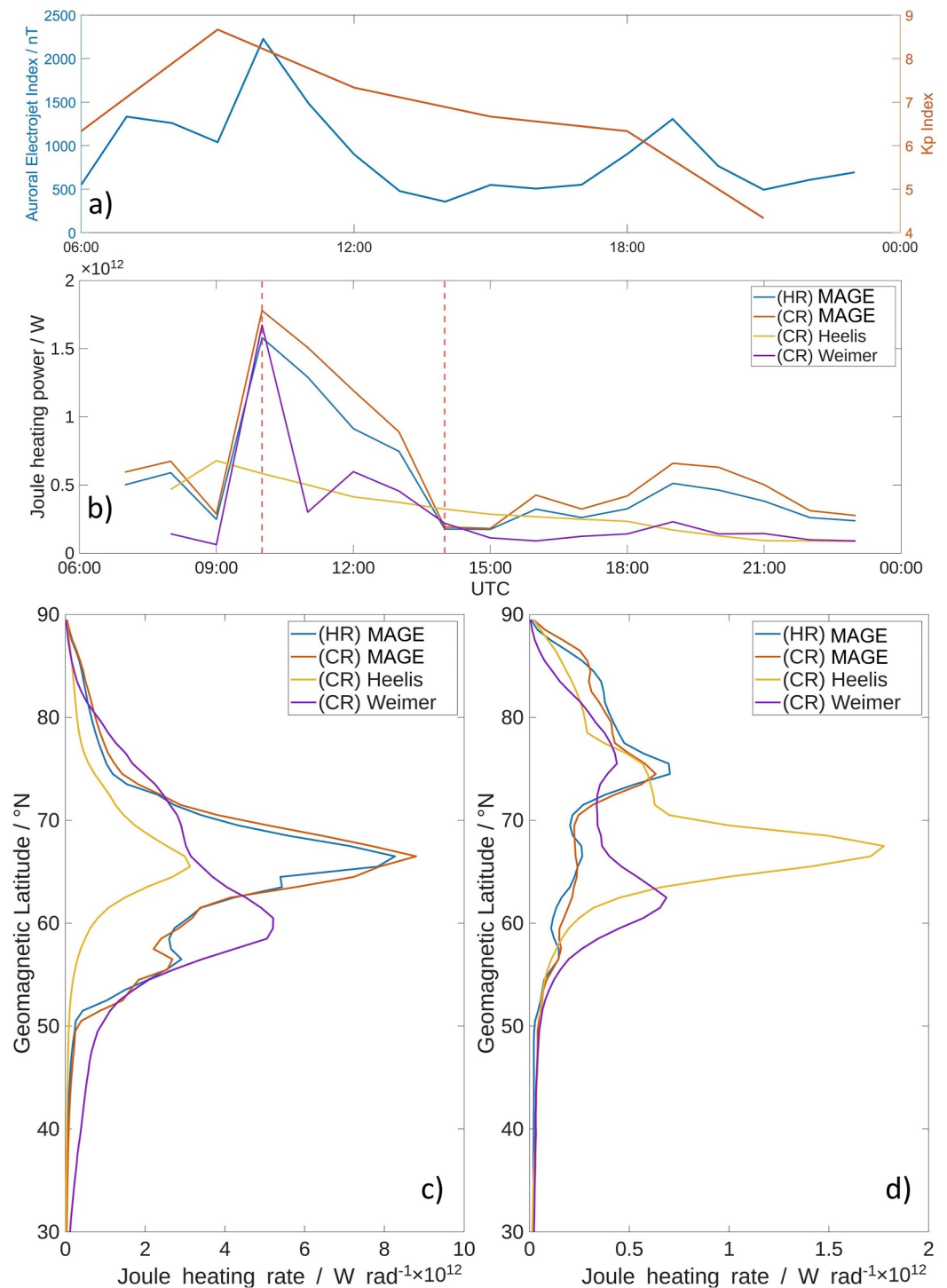


Figure 1. (a) Auroral electrojet and Kp indices for 24 August 2005. (b) Total Joule heating power integrated over the northern hemisphere. Distribution of Joule heating with geomagnetic latitude at (c) 10:00 UT (storm peak) and (d) 14:00 UT (recovery phase).

meso-scale variability of the plasma convection. A thorough validation of MAGE-driven conductivity and convection patterns is necessary, and in Section 4, we will give a brief comparison to SSUSI and SuperDARN maps.

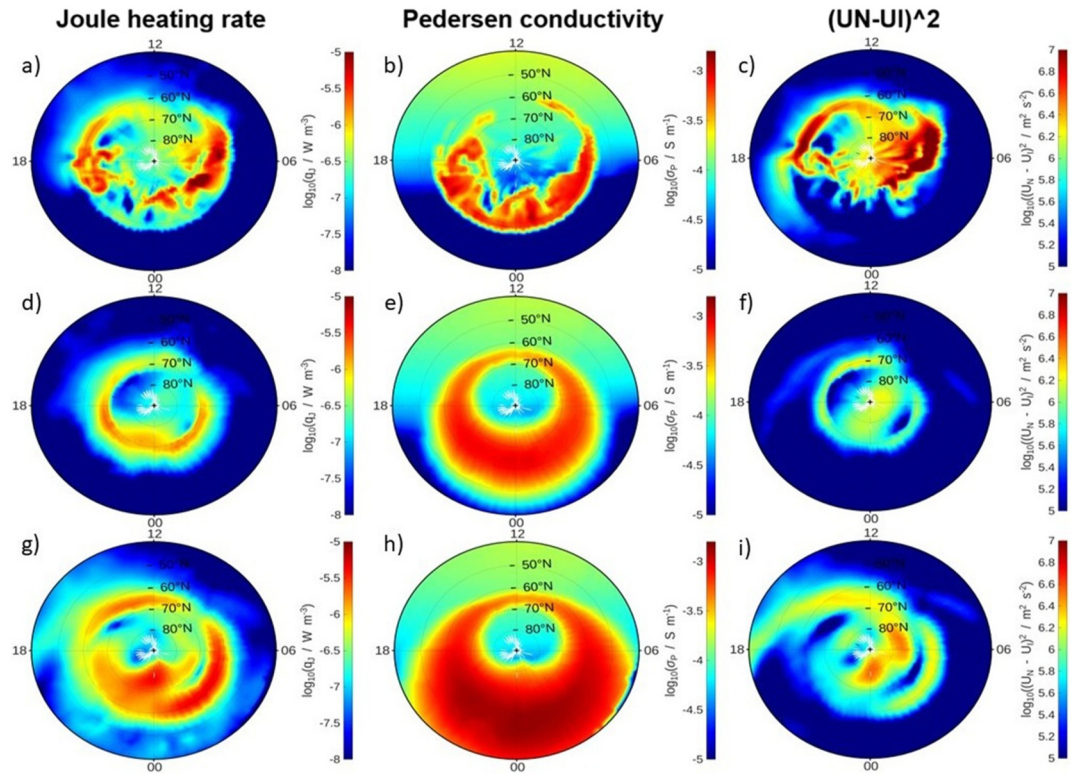


Figure 2. Common logarithm of Joule heating rate q_J (a, d, g), Pedersen conductivity σ_P (b, e, h), and squared ion velocity in the neutral atmosphere reference system $(U_N - U_I)^2$ (c, f, i). Shown are the MAGE-coupled (CR) SE-WACCM-X run (a, b, c), and the Heelis- (d, e, f) and Weimer-driven (g, h, i) SD-WACCM-X runs. All quantities are shown at 10:00 UT at 120 km altitude.

3.2. Model Resolution

In Figure 1, it can be seen that both MAGE-coupled runs exhibit similar total Joule heating powers and distributions with geomagnetic latitude. Integrated from 07:00 to 24:00 UT, the (CR) run shows a 20.8% higher Joule heating energy input than the (HR) run. During the two storm peaks at 10:00–11:00 UT and 19:00–20:00 UT, the (CR) Joule heating energy input is up to 30% larger than in the (HR) run. However, during storm recovery at about 14:00 UT, the Joule heating is approximately equal in both runs. For comparing (HR) and (CR) model results, 6-min instantaneous model outputs are analyzed, and only (HR) results at (CR) grid locations are considered.

Figure 3 shows the ratios of the horizontally integrated Joule heating rate, Pedersen conductivity, squared ion velocity, squared neutral velocity, electron density, and neutral density between the (HR) and (CR) MAGE-coupled runs in the (sub-)polar region ($>50^\circ\text{N}$). We notice a sharp band at about 100–120 km altitude from about 10:00 to 17:00 UT (after the storm peak), where the (HR) run gives larger Pedersen conductivity and Joule heating values. Simultaneously, it shows a lower Pedersen conductivity above about 170 km from about 13:00 to 17:00 UT compared to the (CR) run. Something similar, though less pronounced, can be observed following the second smaller storm peak around 19:00 UT. It can be seen from Figure 3f that both these changes are caused by the lower neutral gas density at 100–120 km altitude and above about 170 km in the (HR) run. The correlation of collision frequency, and hence neutral density, and Pedersen conductivity can be explained using Equation 2:

The ion-neutral collision frequency undergoes a transition from $\nu_{in} \gg \omega_i$ below about 120 km altitude to $\nu_{in} \ll \omega_i$ above ($\nu_{en} \ll \omega_e$ at all investigated altitudes). Simplifying Equation 2 for these regimes, we find that

$$\sigma_P \propto \begin{cases} \nu_{in}, & \text{if } \nu_{in} \ll \omega_i \\ \nu_{in}^{-1}, & \text{if } \nu_{in} \gg \omega_i \end{cases} \quad (3)$$

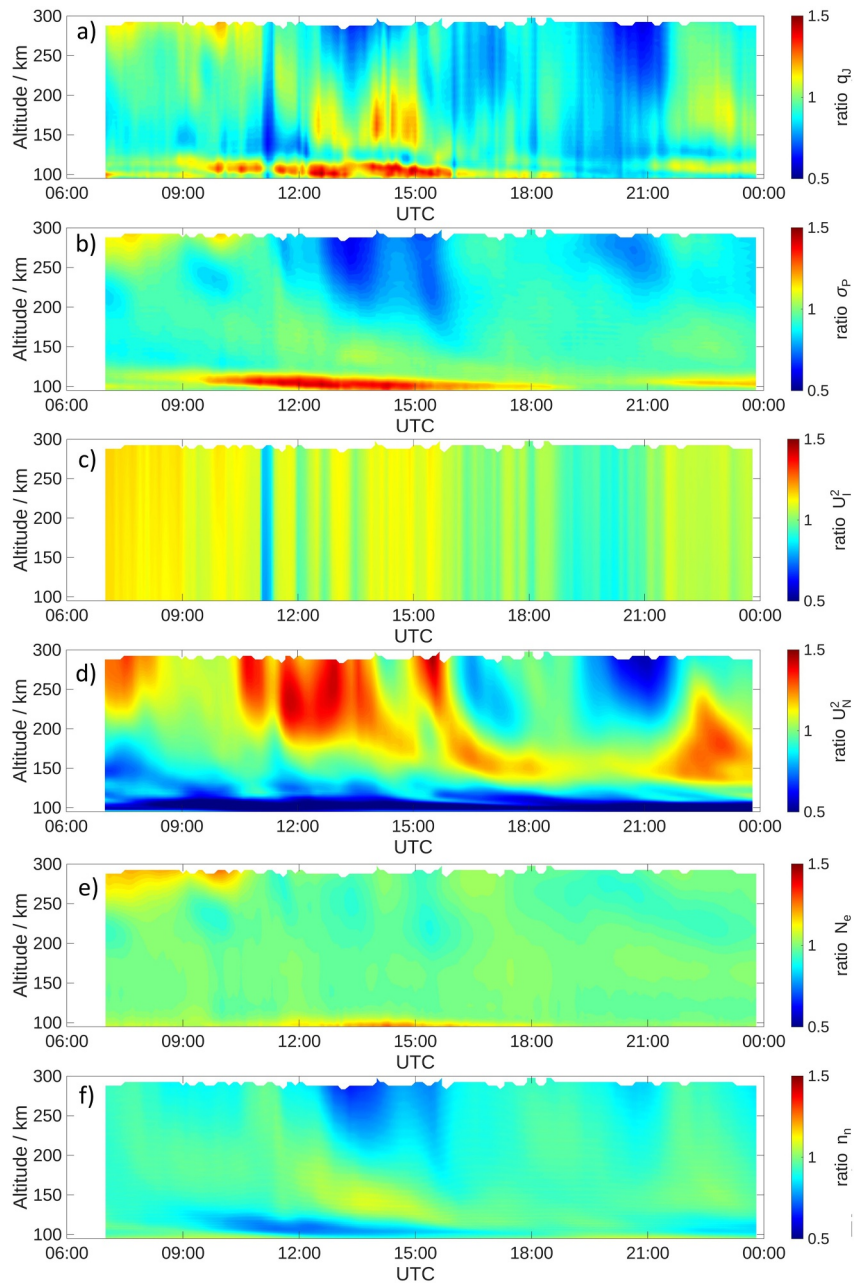


Figure 3. (HR)-to-(CR) ratios of (a) Joule heating rate q_J , (b) Pedersen conductivity σ_P , (c) squared ion velocity U_I^2 , (d) squared neutral wind U_N^2 , (e) electron density N_e , and (f) neutral density n_n . All quantities have been horizontally integrated at latitudes $>50^\circ\text{N}$.

Since $\nu_{in} \propto n_n$, the neutral density has an altitude-dependent effect on the Pedersen conductivity, as seen in Figure 3. While there seem to be large-scale variations in the neutral density caused by the increased model resolution, the electron density appears to be nearly unaffected on a global scale (Figure 3e).

Figure 3c shows that the ion velocity is also affected by the model resolution, though less strongly than the Pedersen conductivity. However, it clearly has a significant contribution to the 20.8% lower Joule heating in the (HR) run, especially due to lower ion velocities at all altitudes at around 11:00 UT and 19:00–21:00 UT. The model resolution effect on the neutral wind is stronger (Figure 3d), but the ion velocities are considerably larger

than the neutral winds and are therefore dominant for the $(U_N - U_I)^2$ -term. It appears, though, as if the changes in neutral wind and density caused by the increased model resolution are correlated.

Due to the complex coupling of ionospheric electrodynamics and thermospheric circulation, the obtained results are not trivial to interpret. Figure 3c shows the (HR)-to-(CR) ratio of squared ion velocity, indicating that the ionospheric electrodynamics are only slightly different between the two MAGE-driven model runs. On the other hand, the squared neutral velocity in Figure 3d shows that the thermospheric dynamics are significantly affected by the high-resolution model configuration. However, thermospheric dynamics are influenced by both ionospheric electrodynamics and model resolution, and, in turn, significantly affect Joule heating (see Equation 3). Additionally, the thermospheric impact of Joule heating, the neutral particle heating, is also affected by the thermospheric density. This will be discussed in Section 4.

Figure 4 shows the (HR)-to-(CR) ratios of σ_P , N_e , and n_n at 110 km altitude at 14:00 UT and the respective absolute parameters at the same time and altitude in the MAGE-coupled (HR) run. Figures 4b and 4d underline that the horizontal variability of Pedersen conductivity is mainly determined by the electron density. However, the (HR)-to-(CR) ratio of the Pedersen conductivity in Figure 4a is a superposition of the N_e and n_n ratios in Figures 4c and 4e. The area of higher σ_P agrees well with the area of lower n_n , confirming the $\sigma_P \propto n_n^{-1}$ relation derived in Equation 3 for these altitudes.

The resolution of meso-scale electron density features causes significant local inter-model-variability of Pedersen conductivity as shown in Figures 4a and 4c. The auroral oval can be seen slightly north of 60°N on the night and dawn side (180° - 60°E). Figure 4c shows that the maximum electron density in the center of the oval is larger in the (HR) run, while it is lower at the edges. This is more pronounced at certain locations, for example, 60°E, presumably caused by auroral arcs at these locations.

Figure 5 shows q_J , $(U_N - U_I)^2$, σ_P , U_I^2 , and N_e in the (CR) MAGE-driven model run at 120 km (approximately the altitude of maximum Joule heating) during storm peak (10 UT). Additionally, the absolute differences of all quantities between high- and coarse-resolution runs are shown. It can be seen in Figure 5a, that the Joule heating rate differs locally between the two runs, but positive and negative biases appear to be roughly equal. This agrees with the horizontally integrated Joule heating rate ratio in Figure 3, which showed a higher (HR) Joule heating rate below the maximum altitude of about 120 km and a lower (HR) Joule heating rate above. Electric fields appear to be generally larger in the (HR) run compared to the (CR) run (Figures 5b and 5d). As already seen for storm recovery conditions (Figure 4), Pedersen conductivity and electron density are reduced in the (HR) run at the edge of the auroral oval due to the sharper gradients (Figures 5c and 5e). At 120 km altitude, there is no global-scale reduction of neutral density (Figure 3f) and consequently the global-scale increase of σ_P that is shown in Figure 4a is not found here.

The high-resolution model configuration results in stronger electric fields from the same GAMERA forcing, but also appears to significantly alter the thermospheric response to Joule heating, in turn reducing Pedersen conductivity and Joule heating on a global scale, reinforcing the picture of a highly complex ionosphere-thermosphere-magnetosphere coupling.

4. Discussion

4.1. MAGE-Coupling Effects

We found that MAGE-coupled and Weimer-driven WACCM-X runs show significantly higher peak Joule heating (up to ~1750 GW) compared to Heelis-driven model runs (up to ~700 GW). Integrated over the investigated 16-hr period, both empirically driven runs show lower Joule heating energy input than MAGE-coupled runs. Empirical parameterizations are limited for high geomagnetic activity, due to the limited availability of measurements under such conditions (Weimer, 2005). Studies comparing incoherent scatter radar (ISR) measurements and TIE-GCM runs indeed found a considerable underestimation of modeled Joule heating rates for Weimer-driven model runs (Baloukdis et al., 2023; Günzkofer et al., 2024). Whether the MAGE-coupled runs correct the underestimation of Joule heating rates by empirical models or overestimate the Joule heating themselves, for example, due to insufficient saturation of the electric potential for storm conditions (Weimer, 2005), cannot be conclusively determined, as there are no high-latitude ISR measurements available for 24 August 2005. As the convection pattern given by the MAGE-coupled runs (Figure 2c) is missing an electric pole on the

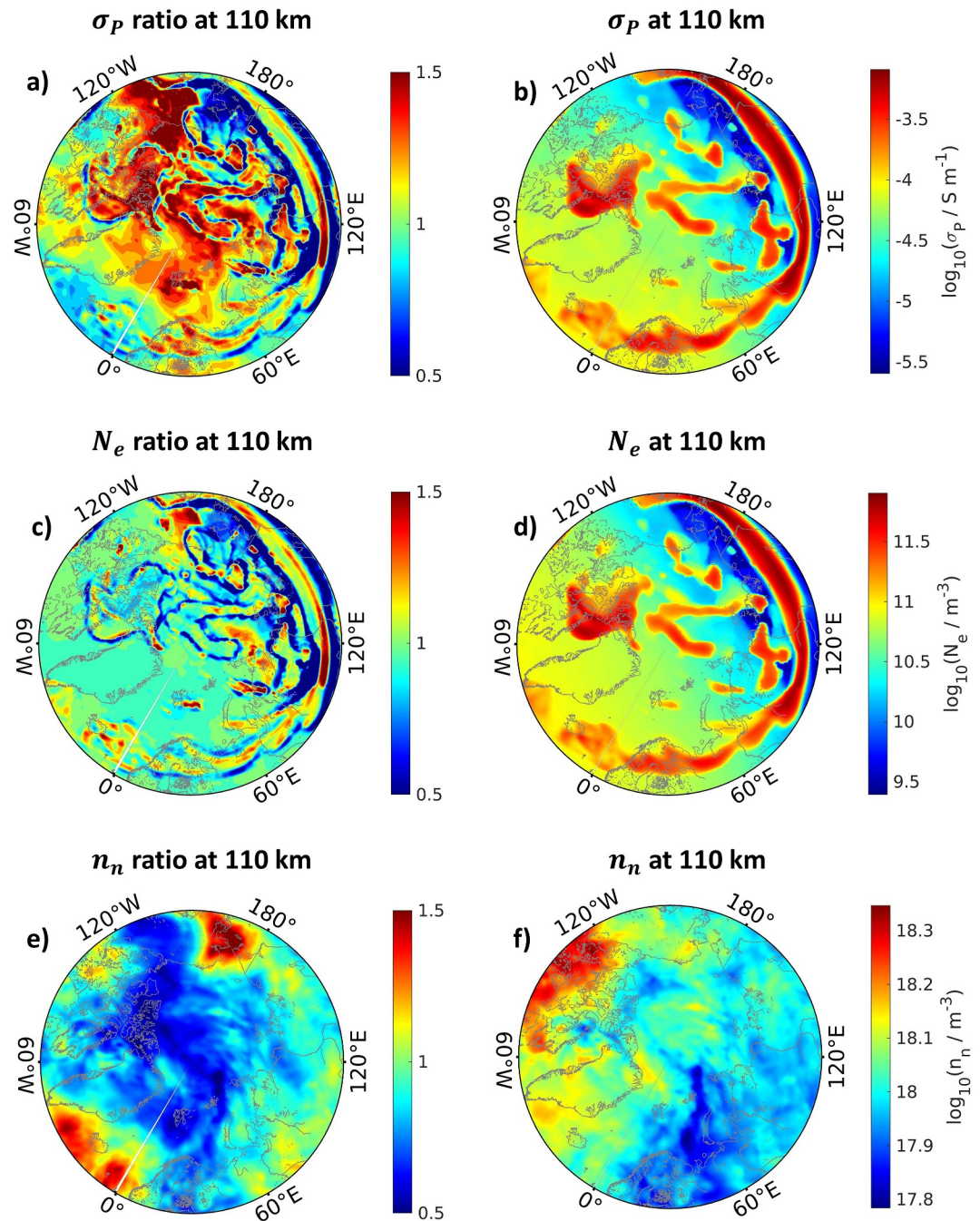


Figure 4. (HR)-to-(CR) ratios and (HR) absolute values (common logarithms) of (a), (b) Pedersen conductivity σ_P , (c), (d) electron density N_e , and (e), (f) neutral density n_n in the polar and auroral region at 110 km altitude at 14:00 UT.

magnetic dawn side, a thorough validation of MAGE-coupled WACCM-X runs is required first. Additionally, the variability of the 3-hourly mean AE for this particular storm is considerably higher than the statistical average (Rostoker, 1991), making a comparison to statistical Joule heating relations difficult.

Modeling studies specifically targeting storm conditions indeed found total Joule heating powers >1000 GW (Fedrizzi et al., 2012; Smith et al., 2023; X. X. Zhang et al., 2005). The data assimilative convection model AMIE has also been shown to result in higher Joule heating rates compared to empirical forcing (Lu et al., 2016; Smith et al., 2023; X. X. Zhang et al., 2005).

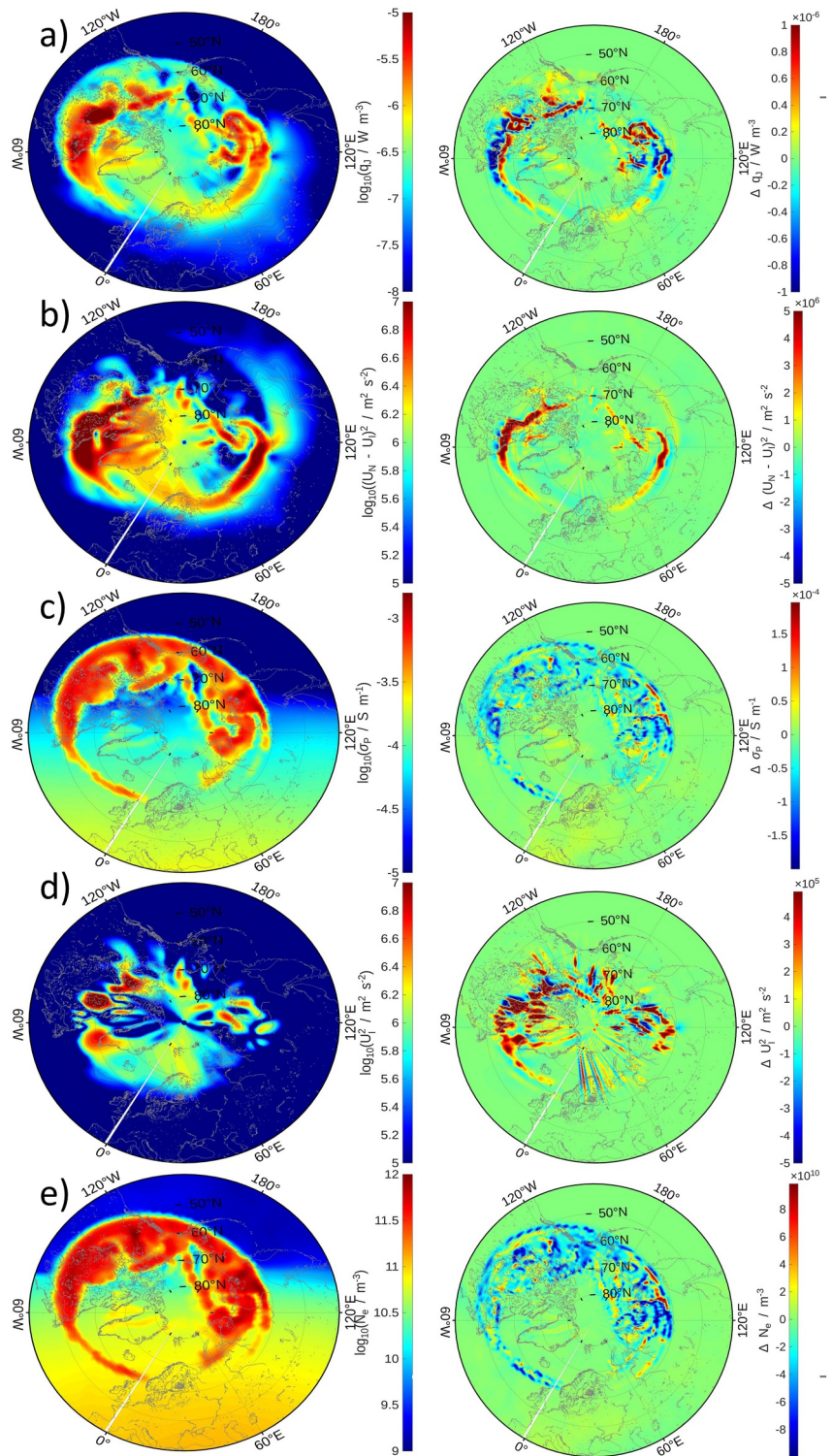


Figure 5. Comparison of (CR) state variables (left column) and (HR)-to-(CR) absolute difference (right column) during storm peak (10 UT) at 120 km altitude: (a) Joule heating rate q_J , (b) squared ion velocity in neutral reference frame $(U_N - U_I)^2$, (c) Pedersen conductivity σ_P , (d) squared ion velocity U_I^2 , and (e) electron density N_e .

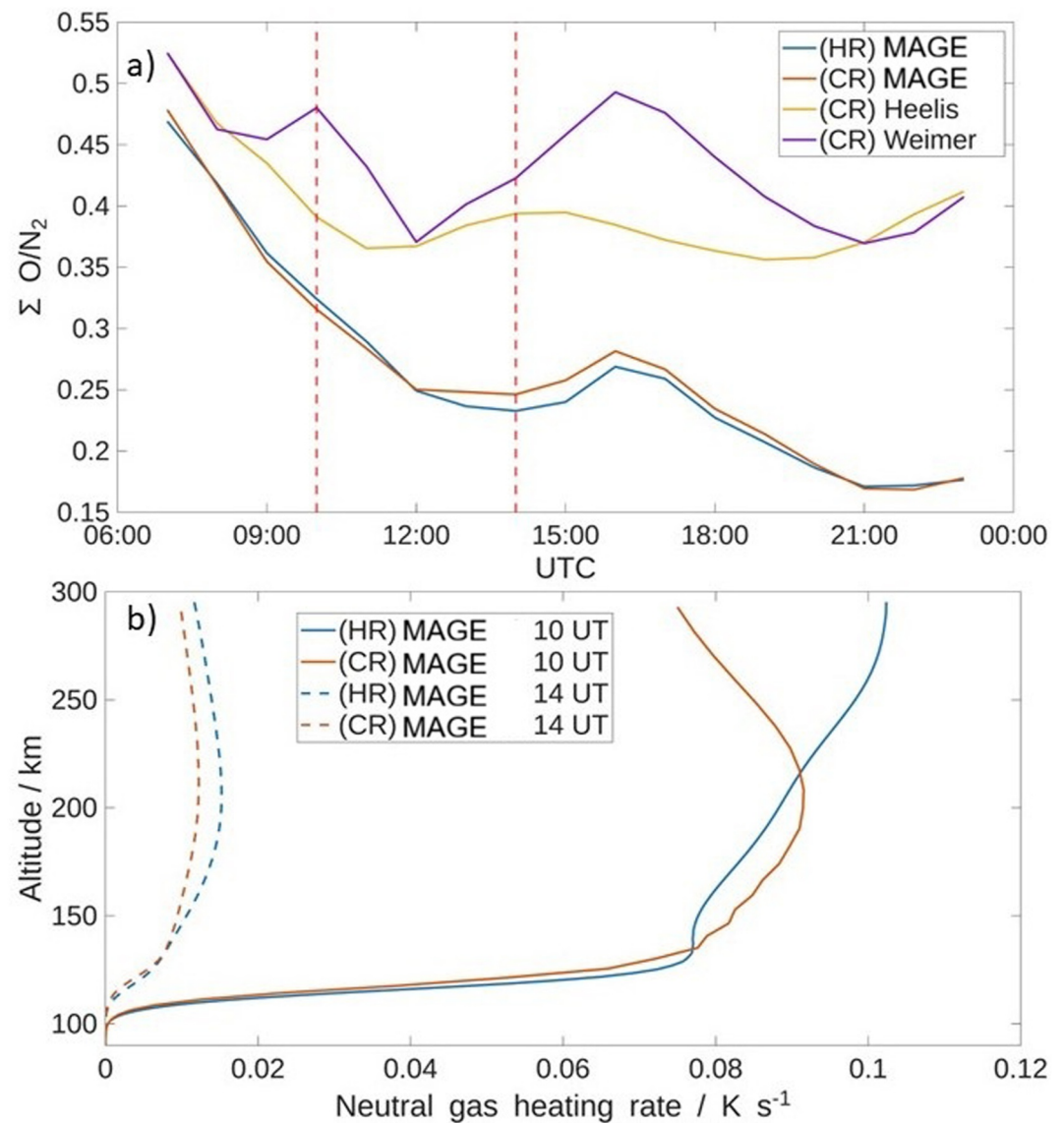


Figure 6. (a) Column integrated O/N_2 ratios in all four investigated WACCM-X runs averaged at latitudes $>50^\circ N$. (b) Mean neutral gas heating rates of (HR) and (CR) SE-WACCM-X at 10:00 UT and 14:00 UT at latitudes $>50^\circ N$.

The higher Joule heating in MAGE-coupled runs has important consequences for the thermospheric composition. During geomagnetic storms, the heating in the lower thermosphere due to particle precipitation and Joule heating causes an upwelling of the atmosphere, thereby decreasing the ratio of atomic oxygen to molecular nitrogen O/N_2 (e.g., Stephan et al., 2008; Y. Zhang et al., 2014). Figure 6a shows O/N_2 integrated following the Strickland convention (Strickland et al., 1995) and averaged at latitudes $>50^\circ N$ ($\Sigma O/N_2$).

As expected, the storm peak at 10:00 UT (09:00 UT in the Heelis-driven run) reduces $\Sigma O/N_2$ in all four model runs due to the upwelling of molecular atmospheric constituents. This decrease of $\Sigma O/N_2$ is stronger in the MAGE-coupled runs due to the stronger, persistent Joule heating. Since WACCM-X generally overestimates $\Sigma O/N_2$ compared to satellite measurements (G. Liu et al., 2023), MAGE-coupling of the high-latitude regions presumably improves the modeled thermospheric composition. H. L. Liu, Lauritzen, and Vitt (2024) reported that an increased model resolution also improves the model $\Sigma O/N_2$. Here, we find that the resolution impact is minor in comparison to the geomagnetic forcing impact.

4.2. High-Resolution Effects

The accumulated difference of Joule heating energy input of 20.8% between the (HR) and (CR) MAGE-coupled runs is minor compared to the 71.7%–121.7% difference compared to empirical forcing runs. The 20.8% lower Joule heating in the (HR) run compared to the (CR) run contradicts previous findings, where increased measurement and model resolutions resulted in higher Joule heating rates (Cosgrove et al., 2011; Günzkofer, Liu, Pham, et al., 2025, Günzkofer, Liu, Liu, et al., 2025). However, previous studies mainly considered the model resolution effect due to meso-scale electric field variability (Codrescu et al., 1995, 2000; Deng & Ridley, 2007). Figure 5 showed that also here, the (HR) run leads to stronger electric fields. However, the Pedersen conductivity integrated over the northern hemisphere from 07:00 – 24:00 UT is 20.7% smaller in the (HR) run compared to the (CR) run (not shown in Figures), nearly identical to the integrated Joule heating energy input. The lower Joule heating and Pedersen conductivity in the (HR) run compared to the (CR) run are, hence, mainly caused by a large-scale reduction of neutral density and, consequently, in the F region, Pedersen conductivity, not by changes in electric field variability. Differences between the two runs in electron density occur on meso-scales due to the auroral oval (auroral arcs) and, according to the two MAGE-coupled runs, E region plasma patches within the cusp region that can be seen in Figures 4b and 4d. The electron density is lower at the edges of these meso-scale structures in the (HR) run (Figure 4c), indicating that they are “blurred” in the (CR) run. Since the GAMERA driving is given on a 0.5° grid, the (CR) model run cannot resolve the meso-scale structures provided by GAMERA, as well as the (HR) run. The origin of E region plasma patches (polar plasma patches usually refer to F-region features) is unclear. Direct particle precipitation from the solar wind is known to cause ionization in the cusp region, though extremely high flux rates are required to cause the high electron densities in the E region produced by the MAGE-coupled runs (Fujiwara et al., 2007; Ogawa et al., 2008). This remains to be verified. While these meso-scale structures can cause local differences in Joule heating up to 50%, they cause no global or large-scale net difference between the two runs.

The origin of the different thermospheric densities in (HR) and (CR) configurations is not trivial. While it has been previously shown that the thermospheric circulation is affected by model resolution (H. L. Liu, Lauritzen, & Vitt, 2024; H. L. Liu, 2025), Joule heating also affects the thermosphere dynamics, and the complex coupling of the thermosphere-ionosphere makes it difficult to distinguish both effects. The thermospheric impact of Joule heating, the neutral gas heating rate dT/dt is related to the Joule heating rate q_J by

$$\frac{dT}{dt} = \frac{2 \cdot q_J}{k_B \sum_i f_i \cdot n_{n,i}}. \quad (4)$$

In Equation 4, which is derived from the thermal energy of ideal gases, $n_{n,i}$ and f_i are the neutral particle densities and the thermodynamic degrees of freedom of the i th particle species (we consider O, O₂, and N₂). In Figure 6b, the horizontally integrated neutral gas heating rate at >50°N of both MAGE-coupled SE-WACCM-X runs is shown for 10:00 UT and 14:00 UT. Notably, dT/dt is larger in the high-resolution run than in the coarse-resolution run during storm recovery and at high and low altitudes, even during the storm peak. Therefore, though the Joule heating power is slightly lower in the (HR) run compared to the (CR) run, the thermospheric impact of Joule heating can be stronger in the (HR) run, explaining the slightly lower O/N₂ ratios in Figure 6a. To complicate things even more, the lower, more realistic (H. L. Liu, Lauritzen, & Vitt, 2024), O/N₂ ratio found when using the (HR) model configuration leads to less realistic TEC values, presumably due to a numerically dissipative O⁺ transport scheme.

4.3. Initial Validation of MAGE-Coupled Runs

As mentioned before, this paper provides an inter-model assessment of Joule heating effects due to novel model developments. While a thorough validation of these model developments will be required before an actual “improvement” can be certified, this will require a computationally expensive extension of the modeled events. Nevertheless, we want to provide an initial assessment of the MAGE-coupled model runs with available measurements.

Figure 7 shows comparisons of the (HR) MAGE-coupled model run with DMSP F16 SSUSI and SuperDARN measurements. SSUSI far ultraviolet measurements allow inferring the peak E region electron density (Knight et al., 2018), which can be directly compared to the model output. Figures 7a and 7b show that the MAGE-coupled

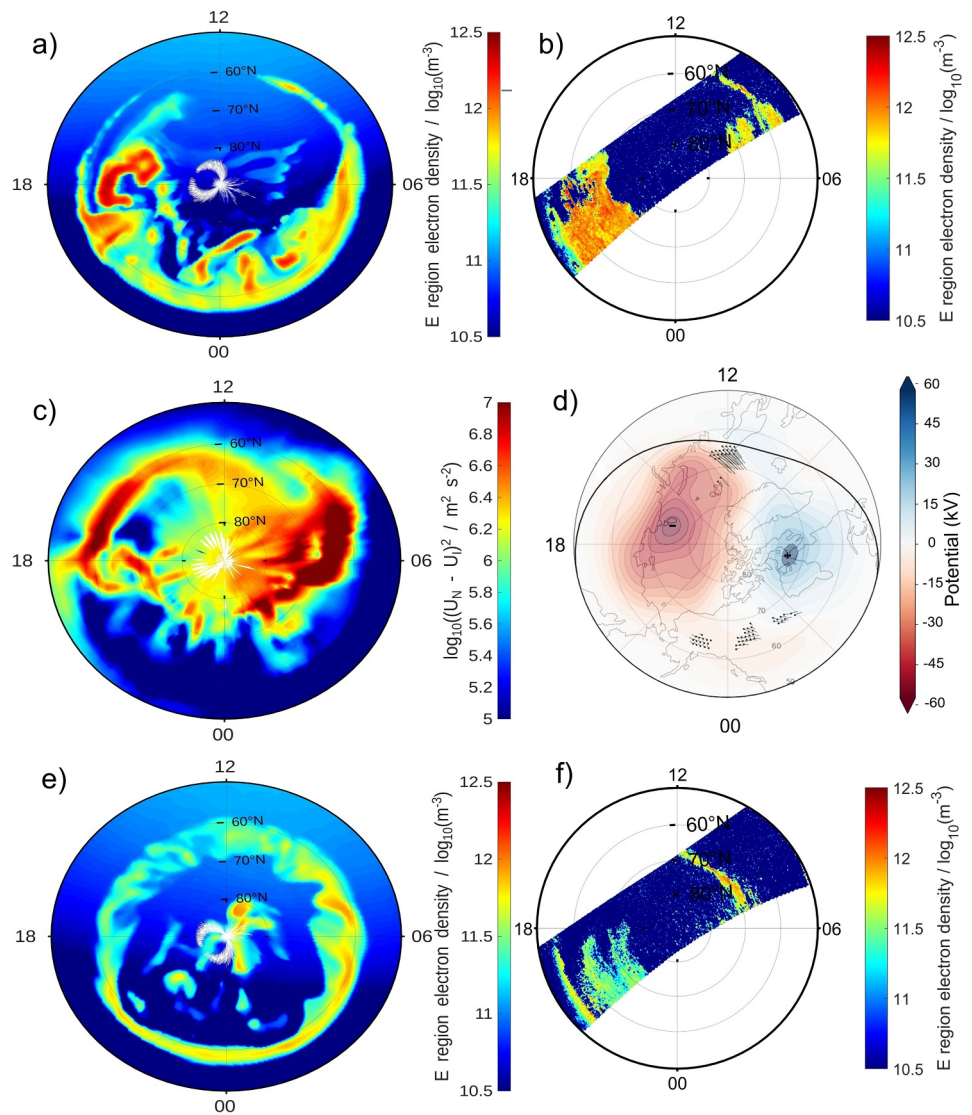


Figure 7. Comparison of MAGE-coupled model results with measurements. E region peak density given by the model at (a) 10:00 UT and (e) 14:00 UT, and the DMSF F16 SSUSI measurements during those times in (b) and (f). (c) Model convection pattern at 10:00 UT and (d) SuperDARN convection map at the same time.

model represents the position and broadness of the auroral oval well. However, not all meso-scale features are accurately represented (e.g., increased ionization at latitudes above 70° geomagnetic north at around 9 MLT), which underscores the need for a thorough validation study. During storm recovery (Figures 7e and 7f), the differences between the model and measurement become more obvious, as the geomagnetic position of the auroral oval in the MLT morning sector does not match. Additionally, the E region cusp plasma patches predicted by the model are not supported by the measurements. In Figures 7c and 7d, a map from the SuperDARN convection map archive (Greenwald et al., 1995) is compared to the $(U_N - U_I)^2$ pattern given by the MAGE-coupled model. While the position of the potential pole on the MLT dusk side and the arc of strong convection at 60°N geomagnetic latitude from 12 to 18 MLT match well in model and measurements, certain discrepancies can be noted. The SuperDARN radar network gives a very high cross-polar plasma potential of about 120 kV, but the model ion velocities reaching locally up to 3,000 ms⁻¹ seem unreasonably high. However, due to the limited number of SuperDARN radars operated at the time, only further validation with more recent events will allow an assessment of the convection velocities given by MAGE-coupled model runs.

5. Summary and Conclusions

We investigated four WACCM-X runs of the severe geomagnetic storm on 24 August 2005. Two of these runs were coupled to the MHD magnetosphere model GAMERA, using the MAGE geospace model; in the other two runs, the high-latitude electrodynamics were obtained from the empirical Heelis and Weimer models. One MAGE-coupled run was conducted in the Ne120/L273 (high-resolution) configuration, resulting in approximately 25 km horizontal and 0.1 scale heights vertical resolution. The other MAGE-coupled run was conducted in the Ne30/L130 (coarse-resolution) configuration, resulting in approximately 100 km horizontal and 0.25 scale heights vertical resolution. Both empirically driven runs were conducted in the Ne30/L130 (CR) configuration. As highlighted several times in this paper, the complex two-way coupling of thermospheric dynamics and ionospheric electrodynamics via Joule heating and the large number of feedback effects make it difficult to obtain definitive conclusions. In answer to the addressed research questions from Section 1, we can say:

1. The total Joule heating energy input in the northern hemisphere is 71.7%–121.7% higher in both MAGE-coupled runs compared to the empirically driven runs. At the storm peak, the maximum Joule heating in the MAGE-coupled and Heelis-driven runs is at higher geomagnetic latitudes ($\sim 66^\circ\text{N}$) than in the Weimer-driven run ($\sim 60^\circ\text{N}$).
2. The MAGE-coupled model runs showed stronger electric fields compared to the two empirically driven runs, which caused the aforementioned higher Joule heating rates. The Pedersen conductivity showed a similar range of values in all four model runs, but the MAGE-coupled run exhibited a more complex horizontal distribution of Pedersen conductivity due to the GAMERA particle precipitation solution.
3. The (HR) MAGE-coupled model run showed about 20.8% lower Joule heating rates integrated over the investigated time compared to the (CR) MAGE-coupled run. While the electric fields are locally larger in the (HR) run, a global-scale lower neutral particle density caused an altitude-dependent impact of model resolution on Pedersen conductivity and Joule heating reaching up to 50%. Therefore, while the Joule heating rates are lower in the (HR) run, the neutral gas heating is actually larger compared to the (CR) model run. This complex coupling makes it difficult to clearly identify the physical effect of the high-resolution model configuration.
4. The increased resolution of meso-scale ionospheric structures leads to sharper electron density gradients and local differences of Pedersen conductivity up to 50%. This especially affects the region of the auroral oval, where large Joule heating is expected and impacted by these local deviations. The occurrence of E region plasma patches within the cusp region, as given by the two MAGE-coupled runs, remains unclear, and no conclusion should be drawn at the present stage.
5. One of the main secondary effects of Joule heating is the reduction of thermospheric O/N_2 ratio. The higher Joule heating in MAGE-coupled runs significantly reduces the thermospheric O/N_2 ratio compared to the empirically driven runs. The two MAGE-coupled runs show slightly different O/N_2 ratios after 12 UT. Notably, the lower O/N_2 ratio in the (HR) run agrees with the higher neutral gas heating compared to the (CR) run, despite the Joule heating rates being lower.

The reliability of the ionization and convection patterns over the polar region given by the MAGE-coupled model runs was assessed by comparison to DMSP F16 SSUSI and SuperDARN measurements. While certain features agree well in model and measurement results, a statistical validation based on more than a single event is required before the MAGE-coupled model can be called a significant improvement over empirically driven setups.

6. Outlook

The combination of physical magnetosphere forcing in a high-resolution thermosphere-ionosphere model promises to improve model capabilities for both global- and meso-scale processes. However, due to the computational demand of such model runs, statistical data is not yet available. One issue is that for the geomagnetic storm on 24 August 2005, there are few observations to evaluate the model results. Crowley et al. (2010) and Pham et al. (2022) showed neutral density measurements with the CHAMP and GRACE satellites. Electric field measurements are available from DMSP satellites as shown by Wilder et al. (2012). However, satellite measurements for a specific event are limited to the passes of the orbits over the region of interest, occurring approximately every 100 min for the mentioned satellites. To evaluate the global-scale impact of coupling the high-latitude electrodynamics to GAMERA, data assimilated electric fields, for example, from AMIE (Richmond & Kamide, 1988) or AMGeO (Matsuo, 2020), are most promising. Crowley et al. (2010) and

Wilder et al. (2012) analyzed AMIE results for the 24 August 2005 geomagnetic storm but noted shortcomings due to limited data availability. Since then, the data assimilation capabilities have been expanded vastly; hence, performing a high-resolution MAGE-coupled WACCM-X run for a more recent event would allow for a better evaluation. Meso-scale variations of electron density and Joule heating caused by the high-resolution configuration could be evaluated with ISR measurements. However, on 24 August 2005, none of the EISCAT ISRs was operated, and the Sondrestrom ISR was only operated after 21:00 UT. The ISRs at Poker Flat and Resolute Bay were not yet operational. Resources should be allocated toward high-resolution, MAGE-coupled model runs for events that were covered by ISR measurements.

Inclusion in Global Research Statement

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Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

The data shown in this manuscript and the software required to reproduce the figures can be obtained from Günzkofer, Liu, Pham, et al. (2025) and Günzkofer, Liu, Liu, et al. (2025). All data and software are available under the Creative Commons Attribution 4.0 International license. SuperDARN data is available, for example, from the Canadian Federal Research Data Repository (<https://www.frdr-dfdr.ca/repo/collection/superdarn?order=DESC&sort=1>) and convection maps can be found in the Convection Map Archive (<https://superdarn.ca/convection-maps>). SSUSI data is available from <https://cdaweb.gsfc.nasa.gov/pub/data/dmsp/dmspf16/ssusi/data/e draurora>. In case of further questions about the data or the analysis software, please contact the corresponding author.

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