Self-consistent modeling of electron precipitation and responses in the ionosphere: application to low-altitude energization during substorms

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Key Points:

• Advanced global modeling capability allows investigation of the impact of transient magnetospheric dynamics on the ionosphere

• Model captures high-energy tail produced by energetic electron precipitation, which creates a sub-layer in the D region characterized by enhanced Pedersen conductivity

• The sub-layer arises intermittently, correlated with recurrent substorm injections and has global impact due to eastward migration

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Abstract

We report a new modeling capability that self-consistently couples physics-based magnetospheric electron precipitation with its impact on the ionosphere, representing a significant improvement over previous models, in which the ionosphere is either treated as a 2D spherical boundary of the magnetosphere, or is driven by empirical precipitation models that are incapable of capturing small-scale, transient variations. The model enables us to study the impact of substorm-associated, spectrum-resolved electron precipitation on the ionosphere. We find that following each substorm injection, a high-energy tail (10<E<100 keV) is produced in the precipitation spectra. An ionospheric sub-layer intermittently arises at unusually low altitude (~85km), characterized by enhanced Pedersen conductivity. This transient layer propagates eastward due to the drift of source electrons, causing global effects within the ionosphere. This study thus provided insights on the global-scale current closure during substorms and demonstrated the model’s capability of revealing complex cross-scale interactions within the strongly coupled system.

1 Plain Language Summary

Understanding the variability within the near-Earth magnetosphere-ionosphere-thermosphere system is not only a scientific goal but also a critical need for reliable nowcasting and forecasting of hazardous space weather. The system is fully coupled in a variety of ways that challenge our current modeling and observational capabilities. In order to unify the ionospheric and magnetospheric dynamics and their interactions in models, we report a latest modeling effort that self-consistently couples the magnetospheric particle precipitation to its impact on the ionosphere. This model significantly advances the consistency of the models, providing the opportunity to study the 3D ionospheric variability and the transient magnetospheric drivers. With this new tool, we find that earthward particle injections in the magnetosphere result in energetic electron precipitation with 10<E<100 keV, which cause intense ionization and a transient sub-layer with enhanced electric conductivity at unusually low altitudes near 85 km. Such an additional layer at low altitude implies the complexity of the ionosphere and can impose severe disruptions on radio communications/navigations that heavily rely on ionospheric properties. Although often reported as a short-lived phenomenon, the layer actually develops in a global manner which may change the traditional pattern of current closure within the geospace system. Our new model demonstrates the improved capability of revealing the complex variability and cross-scale interactions within the near-Earth environment.
2 Introduction

Transient structures in the ionosphere, including sudden enhancement of ionization in the low-altitude D region [e.g., Rodger et al., 2012; Cresswell-Moorcock et al., 2013], add complexity to the ionosphere electrodynamics, and have important implications to terrestrial atmosphere dynamics, including ozone loss [e.g., Seppälä et al., 2015]. They may also impose severe threats to normal operation of radio communications and navigations [e.g., Kelley and Heelis, 1989]. Understanding the causes and their dynamics is thus of practical importance. Those low-altitude structures can be attributed to solar proton events between 1 and 100 MeV in energy [e.g., Reagan and Watt, 1976; Clilverd et al., 2005], or energetic electron precipitation from the magnetosphere [e.g., Beharrell et al., 2015; McGranaghan et al., 2015a; Sivadas et al., 2017; Oyama et al., 2017]. There have been extensive reports that the energetic electrons in the ring current/radiation belts and plasma sheet can precipitate into the ionosphere through various mechanisms [e.g., Jordanova et al., 2008; Newell et al., 2009; Fu et al., 2011; Li et al., 2013, 2017; Su et al., 2017]. Identifying the location of the sources in the magnetosphere and the acceleration mechanisms to produce high-energy precipitating electrons are among the important unsolved topics in the magnetosphere-ionosphere (MI) coupled system. In order to understand the low-altitude structural variations and the magnetospheric drivers, it is natural to investigate simultaneous and magnetically conjugate measurements in both ionosphere and magnetosphere. For example, Sivadas et al. [2017] analyzed an intense transient energetic ionization layer in the D region (< 70 km) after substorm onset. With simultaneous measurements from ground-based incoherent scatter radar and in-situ THEMIS spacecraft, they identified > 100 keV loss cone electrons accelerated from the distant plasma sheet as the source for the low-altitude ionization in the ionosphere. Oyama et al. [2017] also reported intense ionization of the low altitude ionosphere due to energetic electron precipitation in auroral patches, and attributed this to resonant interactions of electrons with low-band chorus waves in the magnetosphere.

However with sparse in-situ measurements or limitation of instruments, it is challenging to coordinate multi-point observations in both magnetosphere and ionosphere at the time and locations of interest. It is also difficult to determine the spatial and temporal evolution of the low-altitude structure across finite monitors. Therefore, a self-consistent modeling of the MI system is required to investigate the global-scale causes and effects in the MI system. However, to date, most ionosphere models coupled with
thermospheric dynamics, such as TIEGCM [Roble et al., 1988; Richmond et al., 1992], CTIM [Fuller-Rowell and Rees, 1980; Rees and Fuller-Rowell, 1988], and GITM [Ridley et al., 2006], are driven by auroral precipitation obtained from empirical precipitation models [e.g. Spiro et al., 1982; Hardy et al., 1987; Newell et al., 2009]. The statistical nature of these precipitation models precludes specification of small-scale, transient variations in both space and time. Furthermore, these empirical models are generally limited to energies below 50 keV and rely on the assumption of a Maxwellian distribution, while in-situ spectral measurements indicate frequent departure from the Maxwellian distribution [McIntosh and Anderson, 2014; McGranaghan et al., 2016a] and often exhibit a high-energy tail in the precipitation [Frahm et al., 1997]. As a result, an accurate representation of the precipitation spectrum at the top of the ionosphere is missing in many ionosphere-thermosphere models. Even when the ionosphere is driven by first-principle magnetospheric models that provide the particle precipitation [e.g. Raeder et al., 2001; Raeder et al., 2016; Zhang et al., 2015; Chen et al., 2015; Connor et al., 2016], the precipitation itself is still crudely estimated without having a physical energy spectrum. In view of this, Yu et al. [2016] developed a new physics-based electron precipitation module within a ring current model due to wave-particle interactions, and significantly improved the loss cone precipitation to drive the ionosphere-thermosphere model. On the other hand, in many magnetospheric models, the ionosphere is stilled treated as a 2D spherical sheet around 110 km, which is regarded as the lower boundary of the magnetosphere. Such a simplification may impose inaccuracies in representing the ionospheric electrodynamics while neglecting the self-consistent 3D magnetosphere-ionosphere-thermosphere interactions [Amm et al., 2008; McGranaghan et al., 2016b].

In this paper, we report on a new effort to develop a self-consistent modeling capability for the MI system. This model, for the first time, unifies physics-based precipitation driven by wave-associated pitch angle scattering in the inner magnetosphere [Yu et al., 2016; Jordanova et al., 2016] with first-principle electron transport and impact in the 3D ionosphere [Solomon, 2017], providing an extended coverage of the near-Earth MI system. This self-consistent model allows us to investigate the effects of substorm-associated, spectrum-resolved precipitation on the 3D ionospheric dynamics. It is found that energetic electrons (10<E<100 keV) scattered by whistler-mode waves in the midnight-to-dawn sector form a high-energy tail in the precipitation flux spectra and cause intense ionization extended down to the low-altitude D region, resulting in an ionospheric sub-layer characterized by enhanced Pedersen conductivity. This
layer structure appears intermittently, well correlated with recurrent substorm injections, and has a global impact due to the eastward drift of source electrons in the magnetosphere. This study may shed lights on how the energy flows from the magnetosphere to the ionosphere, and on the large-scale current closure within the geospace system.

3 Methodology

The new model couples two first-principle codes: The RAM-SCBE model [Jordanova et al., 2006, 2010; Yu et al., 2017] representing the ring current dynamics driven by self-consistently calculated electric and magnetic fields, and the GLOW model [Solomon, 2001; Bailey et al., 2002] that solves two-stream electron transport below 600 km and the impact on the upper atmosphere.

3.1 RAM-SCBE model

The ring current-atmosphere interactions model (RAM) [Jordanova et al., 2006] solves the bounce-averaged Fokker-Planck equation for three ring current ion species (H, He, O) and electrons on the magnetic equator within geosynchronous altitude (6.6 Re) for all magnetic local times (MLTs), pitch angle from 0 to 90°, and kinetic energy from ~0.15 to 400 keV. It has been coupled to a 3D magnetic field equilibrium code [Zaharia et al., 2006] and a 2D ionospheric potential solver [Yu et al., 2017], resulting in self-consistency (SC) between the plasma and both magnetic (B) and electric (E) fields, thus named as RAM-SCBE [Yu et al., 2017]. This ring current model is unique primarily because the particle distribution functions are pitch angle resolved, which is particularly important in plasma wave excitation and subsequent wave-particle diffusion processes.

The source plasma to the ring current is provided at the outer boundary of the model (i.e., 6.6 Re), where ion and electron differential fluxes are obtained from geosynchronous observations (e.g., LANL-GEO MPA and SOPA data) and the total ion flux is decoupled into different ion species according to Young et al. [1982] statistical formula on their respective ratios. The ring current ions can be lost via charge exchange and Coulomb collisions. The ring current electrons are lost due to resonant wave-particle scattering process and collisions with the dense atmosphere with a time scale of a quarter bounce period [Jordanova et al., 2008].
To incorporate the wave-particle scattering process for electrons, we apply pitch angle diffusion coefficients \(D_{\alpha \alpha E}\) derived from statistical wave properties [Glauert and Horne, 2005; Horne et al., 2013; Glauert et al., 2014]. Two kinds of waves are considered: whistler-mode chorus waves outside the plasmapause and whistler-mode hiss waves inside the plasmapause. Both can effectively diffuse electrons with energy from a few to hundreds of keV into the loss cone (details regarding the implementation of wave-induced scattering in the model can be found in Yu et al. [2016] and Jordanova et al. [2016]). This study includes only pitch angle scattering by plasma waves (no local acceleration). The loss cone corresponds to an altitude of 600 km.

Previously, the total precipitating energy flux is used to compute auroral conductance via empirical formalisms, such as the Robinson relations [Robinson et al., 1987]. This empirical approach, commonly used across the modeling community for conductance specification [e.g., Fok et al., 2001; Chen et al., 2015; Raeder et al., 2001; Zhang et al., 2015; Yu et al., 2016, 2017], however ignores the ionization and emission processes in the upper atmosphere and impedes the understanding of time-varying transient responses in the field-aligned direction in the ionosphere. Therefore, to study the integrated effect of the auroral conductance and account for the physics and chemistry responsible for the variations in the vertical direction of the ionosphere, we rely on the GLOW model, a two-stream electron transport code described below, to receive the energy from the magnetosphere and resolve the altitude profiles of ionospheric properties.

### 3.2 GLobal airglOW (GLOW) model

The GLobal airglOW (GLOW) model solves the two-stream Boltzmann electron transport equations, in which electrons move upwards or downwards along magnetic field lines between 70 and 600 km. It also accounts for chemical processes within the ionosphere-thermosphere system and the optical emissions of neutrals and ions. Two major ionization processes considered in the model: the photoionization due to solar radiation flux, and the electron impact by incident precipitating electrons and secondary photoelectrons generated in the photoionization. The neutral composition and temperature are obtained from NRLMSISE00 [Picone et al., 2002]. The model determines altitude profiles of emission rates, ionization rates, electron density, and conductivity [McGranaghan et al., 2015b]. Recently, the GLOW
model [Solomon, 2017] has been improved to be incorporated into global general circulation models, hence making it possible to couple GLOW with the global ring current model, as reported in this paper.

### 3.3 Coupling Interface

We first feed the GLOW model with differential auroral electron precipitation flux $f_E$ obtained from the RAM-SCBE model. The precipitation flux $f_E$ is determined in the equator within the loss cone corresponding to an altitude of 600 km, the upper boundary of the GLOW model. The flux at 600 km is isotropic.

The GLOW model then takes the downward precipitation flux within its designated energy range (i.e., 0.05 - 170 keV) as the input, and computes the vertical profiles of ionization rate, electron density, and Hall and Pedersen conductivities. Note that the low energy bound of the GLOW model is lower than the low energy bound in the ring current model (i.e., 0.15 keV). We therefore only consider the precipitation within the overlapping energy range (i.e., 0.15-170 keV). The altitude-resolved conductivity is then integrated over height to yield the conductance for solving the convective electric field, to be used in RAM-SCBE for the ring current particle transport.

The coupling between the ring current model and the GLOW model upgrades the conductance calculator from the empirical Robinson relations to a first-principle calculation, and advances the self-consistency in the ionosphere electrodynamic solution. Therefore, the GLOW model is not only used as a conductance calculator for the circulation system, providing the feedback effects to the magnetosphere, but also allows for the study of self-consistent responses in the ionosphere due to fast magnetospheric dynamics.

We note that more sophisticated ionosphere-thermosphere models may be more appropriate for studying the entire upper atmosphere dynamics, but as a first attempt to self-consistently couple the ionosphere with the magnetospheric precipitation without any assumption or limit on its energy spectrum, our current coupling capability offers a significant tool to examine the transient and structural variations in the ionosphere. Incorporating more comprehensive ionosphere-thermosphere dynamics will be considered in future studies.
3.4 Event Description

With the new model, we simulate a magnetic storm event that occurred on August 31, 2005. The storm started at 12 UT when IMF $B_z$ turned southward (Figure S1). Several substantial substorm injections occurred in the storm main phase with the AE index frequently exceeding 1000 nT. Three sharp increases of the AE index took place approximately at 15:50, 18:00, and 21:00 UT, indicating strong injection events. Observations from LANL satellites showed flux injections at these times on the nightside. These fluxes are used as the outer boundary conditions for the model (see Figure S1 or Figure 3 in Yu et al. [2017]).

4 Simulation Results

The electrons injected from the plasmasheet drift around the Earth, providing not only the source population for exciting plasma waves, such as whistler-mode waves, but also the local population to be scattered into the upper atmosphere as a result of wave-particle interactions. Note that no acceleration mechanisms are included in the model from the magnetosphere to the ionosphere. The precipitation flux spectrum remains the same along magnetic field lines. Figure 1 illustrates the evolution of precipitation flux spectra at magnetic latitude of 60° and MLT = 6. The precipitation flux between 3-40 keV is initially intensified around 13:30 UT, followed by an enhancement of lower energy flux at 14:00 UT. (Note that although the quiet-time flux before 12:00 UT displays a tail around 40 keV, it is much smaller compared to storm time. This weak high-energy tail may be attributed to the weak scattering processes within the plasmasphere where hiss waves are able to interact with tens of keV electrons. Nevertheless, such precipitation contributes only mildly to the ionization at low altitudes, as will be shown in Figure 2.) After 14:00 UT, while the low-energy (<6 keV) precipitation remains persistently high, a high-energy tail above 10 keV recurrently arises with its peak centered around 10-20 keV and the tail extending to 100 keV. The occurrence of these high-energy tails in the precipitation spectra is well correlated with plasmasheet injections at the geosynchronous altitude (see Figure S1), with a time lag varying from 0.5 to one hour. It is worth noting that the presence of the high-energy tail during injections notably hardens the spectra, suggesting that the typical assumption of a single Maxwellian distribution is invalid in regions associated with substorm-driven precipitation.

Once the loss cone electrons arrive at the top of the ionosphere, they transport downward and create ionization and emission in the ionosphere. Figure 2 shows the storm-time evolution of height-dependent
ionospheric electron density, ionization rate, and Pedersen and Hall conductivities at the same location (MLT = 6; MLat = 60°). The plotted ionization and associated conductivities are the result of only incident electron precipitation as shown in Figure 1 and the contribution from solar radiation flux is not included. The electron density and ionization rate are significantly intensified in the storm time, and show quasi-periodic enhancements. The location of peak electron density exhibits a sudden lift from 85 km to about 100 km after the storm initiation. The low-altitude D region atmosphere at 80 km frequently experiences large ionization with \( N_e \) reaching \( 10^5 \ cm^{-3} \). The Pedersen conductivity mainly peaks around 115 km in the storm main phase, elevated from quiet time. The conductivity is also remarkably large around 85 km during the storm, hence forming a two-layer profile in altitude. Unlike the upper layer that lasts throughout the course of storm, the lower layer disappears from time to time, each persisting for less than one hour. On the other hand, the profile of Hall conductivity constantly shows a single layer in the storm time with its maximum primarily locating around 95 km. The above deep penetration of ionization in the D region and the emergence of a sub-layer with large Pedersen conductivity are well correlated in time with the high-energy tails in the precipitation spectra, indicating a direct causal relationship between the plasmasheet injections and transport, energetic electrons precipitation (10<E<100 keV), and the formation of a sub-layer.

To understand the spatial distribution of the sub-layer, we show in Figure 3 global patterns of precipitation number flux being dumped to the ionosphere at different energies (E=4.5, 50, 80 keV) and the resultant electron density and Pedersen conductivity at different altitudes (z=120, 100, 85 km) at 15:00 UT. Due to the boundary limit of the ring current model, high-latitude polar cap region with open magnetic field lines is not resolved. The auroral zone is partially covered during the storm main phase as the open/closed magnetic field boundary expands equatorward. The black dots in Figure 3 (a) denote the plasmapause boundary mapped from the magnetic equator, chosen at locations where cold plasma density drops below 50 \( cm^{-3} \). The keV electron precipitation (4.5 keV) occurs at nearly all local times except in the noon-to-dusk sector. On the nightside, the electrons are mostly precipitated from outside the plasmapause due to chorus wave scattering. In the dawn-to-noon sector, electrons are precipitated from across the plasmapause boundary, therefore both hiss and chorus waves participate in the scattering process. Such a global distribution of keV electron precipitation demonstrates a generally consistent pattern as in the electron density (Figure 3 (b)) and Pedersen conductivity (Figure 3 (c)) at 120 km and 100 km. The higher
energy (e.g., 50, 80 keV) electron precipitation takes place mainly in the dawn sector and predominantly near or inside the plasmapause. Such a high energy incident precipitation augments the original ionization caused by the keV electrons, so that the electron density and Pedersen conductivity at 100 km are more intensified in the dawn sector than on the nightside. At 100 km, while the global distribution of Pedersen conductivity is similar to that at 120 km, the magnitude is globally reduced due to increased ion collision frequency at lower atmosphere. At 85 km, the conductivity continues to decrease except in the dawn sector where tens of keV electrons are able to penetrate deep and thus the conductivity is enhanced again, indicating a sub-layer there. Consistent with the pattern of high-energy precipitation flux, the spatial extent of the sub-layer is approximately in 3<MLT<9 above 55° at this time. It may be extended poleward even more if wave-particle interactions at outer magnetospheric region were accounted for and if the model boundary were not limited at 6.6 \( R_e \).

As shown above, substorm-associated energetic electron precipitation produces intermittent enhancement of ionization and high-conductivity sub-layer at low altitude near 85 km at MLT = 6, and such a high-conductivity structure appears transient and lasts less than one hour, consistent with observations in Sivadas et al. [2017]. The low-altitude layer also spans widely in MLT in the dawn sector, as shown in Figure 3. It may be expected to see the sub-layer to migrate equatorward as the plasmapause or inner plasmasheet boundary shifts towards the Earth and the aurora expands, and that is indeed found in the simulation. In fact, we also find that the structure dynamically moves eastward. This is because when the freshly injected electrons move closer to the Earth from nightside and drift around, they gain energies, develop temperature anisotropy, and excite whistler-mode waves near the plasmapause. Energetic electrons (>10 keV) can interact with whistler-mode waves and then are scattered down to the ionosphere. Therefore, along the drift path of the injected electrons in the magnetosphere, energetic electrons are persistently precipitated so long as the sources exist. Figure 4 shows the energy spectra of precipitation flux at selected MLTs with one hour apart in time. As the storm starts and considerable plasma sources are populated into the inner magnetosphere at 14:00 UT, the ionosphere in the post-midnight-to-dawn sector (0<MLT<6) receives intense precipitation flux with a high-energy tail (2<E<60 keV). Later on, the high-energy tail grows up at MLT = 8 and 9 (the upward arrow in (b)) while it starts to drop firstly at MLT = 0 (the downward arrow in (b) at 15:00 UT) and then at MLT = 3 (see at 15:00 UT and 16:00 UT). This is because the injected electron population passes through the early morning local times and arrives at later local times. At 17:00
UT, due to a fresh injection, ionosphere at MLT = 4 and 6 again experiences energetic precipitation with E > 70 keV (upward arrow in (d)). At 18:00 UT, the spectrum at MLT = 9 shows largest high-energy flux while spectra at other earlier MLTs mostly fall into a quasi-Maxwellian shape with decreased magnitude at higher energies. At the same time, the spectra at MLT = 0 and 3 find themselves harder around 40 keV, indicating a new injection from nightside (see upward arrow in (e)). As expected, the high-energy tail shows up in later MLTs at 19:00 UT (see upward arrow in (f)). In such, the ionosphere in the dawn sector repeatedly undergoes intensified ionization and accordingly forms a sub-layer firstly in the post-midnight sector and then in the dawn and noon sectors. In other words, the two-layer conductivity profile develops in a global manner from the nightside to the dayside. With such a low-altitude conductivity channel spread widely across the dawn sector in the auroral zone and traveling eastward during substorms, the current closure in the MI system may be even more complicated than expected.

5 Summary

We reported a self-consistent modeling capability of the MI coupling, by providing the auroral electron precipitation from the ring current dynamics to the electron transport code in the ionosphere. The ring current model RAM-SCBE, which solves the loss mechanisms of keV to hundreds of keV electrons due to wave particle interactions, produces physics-based spectra of precipitation flux at the ionospheric altitude. The incident spectrum-resolved precipitation further drives the electron transport within the ionosphere in the GLOW model. The resultant altitude-dependent profile of conductivity in turn is used to specify the auroral conductance for solving the electric potential needed for the ring current particle transport. This new approach significantly advances the self-consistency of current circulation models.

The new model thus allows for the investigation of transient variations in the ionosphere driven by fast magnetospheric dynamics. In particular, as the model is capable of capturing high-energy tail produced by energetic electron precipitation during substorm injections, we examine the corresponding effects in the ionosphere. The results are summarized as follows.

1. Following each substorm injection, the precipitation spectrum at auroral latitudes in the post-midnight-to-noon sector shows a high-energy tail, produced by energetic electron precipitation (10 < E < 100 keV) that are scattered by whistler-mode waves near the plasmapause boundary. The
precipitation energy spectrum is hardened by the tail and hence deviates from the commonly assumed single Maxwellian distribution.

2. Owing to the high-energy tail, the low-altitude D region ionosphere experiences intensified ionization, leading to a sub-layer with enhanced Pedersen conductivity peaked around \( \sim 85 \) km. The sub-layer in the D region arises successively, in strong correlation with recurrent substorm injections.

3. The sub-layer, although often reported as a transient structure from observations, actually develops globally when it propagates eastward towards the dayside. Such development follows the drift direction of the injected electrons from the tail plasmasheet. Therefore, the low-altitude layer of large Pedersen conductivity is a global phenomena. This may shed lights on the large-scale current closure in the MI system during substorms.

Through studying the responses in the ionosphere due to fast magnetospheric drivers, we demonstrate that the newly advanced model is capable of revealing the complex cross-scale interactions within the strongly coupled MI system. Future studies will continue to improve the modeling capability by incorporating more realistic physics. It is worth noting that the ionospheric conductivity calculated in the present study overlooks the effects of horizontal gradients and transport in the ionosphere, as well as the contribution from auroral proton precipitation. Investigating how these factors would influence the strength, location, and development of the low-altitude layer is among our future plans.

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Figure 1. The time evolution of precipitating electron flux spectra at MLT = 6 and magnetic latitude of 60° during the storm event occurred on August 31, 2005.
Figure 2. The time evolution of height-dependent (a) electron density, (b) ionization rate, (c) Pedersen conductivity, and (d) Hall conductivity at MLT = 6 and magnetic latitude of 60°.
Figure 3. Row (a): precipitating number flux at different energies (E=4.5, 50, 80 keV). Row (b): ionospheric electron density at different altitudes (z=120, 100, 85 km). Row (c): Pedersen conductivity at different altitudes (z=120, 100, 85 km). Each panel shows ionosphere polar region above 50°. The black dots in the top row represent the plasmapause mapped down to the ionosphere altitude. All the patterns are obtained from the simulation results at 15:00 UT. The ionospheric surface is resolved with 2° in longitude and 1° in latitude.
Figure 4. The precipitating electron flux spectra at different MLTs denoted by color lines. Each panel represents different times during the storm. The upward arrow marks the rise of high-energy tail, while the downward arrow marks the drop of the high-energy tail.
Supporting Information for
“Self-consistent modeling of electron precipitation and responses in the ionosphere: application to low-altitude energization during substorms”

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Contents

1. Figure S1

Figure S1

The Solar wind/interplanetary magnetic field and geomagnetic indices on August 31, 2005. The bottom panel shows the electron differential flux input to the model at midnight, observed from LANL-GEO satellites. The vertical dashed lines mark three sharp increases in the AE/AL index and the enhancement in the high-energy electron flux at the boundary.

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