Penetrating electric field during the Nov 3-4, 2021 Geomagnetic Storm

Qian Wu[1], Wenbin Wang[1], Dong Lin[1], Chaosong Huang[2], and Yongliang Zhang[3]

[1]High Altitude Observatory, National Center for Atmospheric Research, Boulder, CO, USA

[2]Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, USA

[3]Applied Physics Laboratory, Johns Hopkins University, Laurel, MD, USA

Abstract

We simulated the Nov 3-4, 2021 geomagnetic storm event penetrating electric field using the Multiscale Atmosphere-Geospace Environment (MAGE) model and compared with the NASA ICON observation. The ICON observation showed sudden enhancement of the vertical ion drift when the penetrating electric field arrived at the equatorial region. The MAGE model simulated vertical ion drifts have the similarly fast enhancement that shown in the ICON data at the same UT time and satellite location. Hence, ICON ion drift data was able to verify MAGE simulation, which couples the magnetospheric model was able to simulate the penetrating electric field very well.

Introduction

Penetrating electric field is a fast magnetospheric effect (~ minutes) on the mid- and low-latitudes (Kikuchi et al. 2008; Lu et al.,2012; Kelley et al., 2003; Fejer et al., 2007; Huang et al., 2005; 2019a; 2019b; W. Wang et al., 2008). Understanding penetrating electric field is important because it can bring significant changes to the low-latitude ionosphere. However, simulating the penetrating electric field is not easy because of lack of a fast-varying high latitude driver for ionosphere thermosphere models (e.g., Lu et al., 2012; Wu et al., 2022). Recent advance in coupling magnetosphere and ionosphere model has made it possible to simulate penetrating electric field (e.g., Wu et al. 2022; Shi et al., 2022). Multiscale Atmosphere-Geospace Environment (MAGE) directly couples the magnetosphere to the ionosphere and thermosphere and gives more dynamic high latitude inputs to the ionosphere and thermosphere general circulation model Thermosphere Ionosphere Electrodynamic General Circulation Model (TIEGCM) (Pham et al., 2022; Lin et al., 2021; 2022).

While Wu et al. (2022) were able to use MAGE to simulate the penetrating electric field, they were not able to verify the simulation with observations. The NASA Ionospheric Connection Explorer (ICON) mission ion drift observations used by Wu et al. (2022) were not at a favorable location to observe the penetrating electric field.

Given the importance of understanding the penetrating electric field, we selected a recent storm event (Nov 3-4, 2021) for a further study with MAGE simulations in conjunction with ICON observations. The main reason for selecting this event is the availability of the ICON IVM data on the nightside to capture the arrival of the penetrating electric field near the equator. Figure 1 shows the interplanetary magnetic field (IMF) parameters for the Nov 3-4, 2021 event. The disturbed solar wind arrived at 2020 UT on Nov 3, 2020, with enhancements in both solar wind speed and density. The IMF B_y changed to positive. The negative IMF B_z arrived about 10 minute later. The disturbance lasted until Nov 4, 1300 UT. The focus of this study will be on the first hour when the disturbance arrived (highlighted by light green color). We will select 6 intervals between 20 and 21 UT on Nov 3 for detailed analysis. The expanded IMF parameters are plotted in Figure 2 with the selected times highlighted.

The first three intervals represent the quiet times prior to the arrival of the storm. The latter three are for disturbed times. By comparing the before and after intervals we will examine how the penetrating electric field affected the equatorial ionosphere in the simulation and observed by ICON. The paper is organized as follows. A brief model description will be provided and followed by short introduction on the ICON IVM instrument. Then the simulations results at high latitudes and equatorial region will be presented in along with the simultaneous observation from ICON. The results will be discussed and summarized.

MAGE Model and ICON Ion Velocity Meter Instrument

MAGE model is a new framework for magnetosphere and ionosphere coupled model (Pham et al., 2022, Lin et al., 2019; 2021; 2022). It connects the magnetosphere model Grid Agnostic MHD (Magnetohydrodynamics) with Extended Research Applications (GAMERA, Zhang et al., 2019) with (TIEGCM, Richmond et al., 1992) while incorporate Ring Current Model (RCM, Toffoletto et al., 2003). The GAMERA and TIEGCM are connected by RE-developed Magnetosphere-Ionosphere Coupler/Solver (REMIX) (Merkin and Lyon, 2010). Unlike the traditional TIEGCM run with empirical high latitude convection models, GAMERA offers more dynamic features from the magnetosphere. The MAGE provides high latitude input every 5 seconds. MAGE model was driven by CDAWeb OMNI database 1-minute resolution data. The TIEGCM model was set with 1.25 deg resolution in latitude and longitude and 0.25 vertical scale height with 5 second step size matching the GAMERA input. The data were saved at 1-minute intervals.

ICON is a NASA mission for equatorial ionospheric coupling study (Immel et al., 2018). It carries an Ion Velocity Meter (IVM, Heelis et al. 2017). The IVM instrument measures ion drift in 1 second resolution. In this analysis, the ExB meridional ion drift is used, which at the magnetic equator is vertically upward.

Simulation and Observation Results

Figure 3 shows the high latitude potential maps for the six intervals around the time of geomagnetic storm arrival. The first three panels show a low cross polar cap potentials (CPCP) during the quiet time (< 40 kV). The latter three have very high CPCP (over 100 kV) indicating the arrival disturbed solar wind. In the lower left panel, CPCP at 20:30 UT became much higher although the IMF Bz remained nearly zero. The large CPCP was attributed to the large positive By and elevated solar wind speed and density. Similarly, the large CPCP at 20:41 UT in the lower middle panel was caused by the combined effects of elevated solar wind speed and density, large positive By, and weakly negative Bz. CPCP at 20:51 UT in the lower right panel was further enhanced when the IMF became strongly southward. The dusk and dawn convection cell sizes are consistent with positive IMF B_y condition. The high CPCP brings penetrating electric field to the equatorial region as shown in Figure 4. The equatorial dawn-dusk potentials are 4.5, 6.0, 6.0 kV for the three quiet times. During the disturbed times the equatorial dawn-dusk potential are 15.0, 13.5, and 15.0 kV, respectively. The dawn to dusk potential is defined by drop from the high potential point on the dawnside (+/- 40 minutes in local time or 10 deg in longitude) to the low point on the duskside (+/- 40 minutes or 10 deg in longitude). All these values are listed in Table 1. These are similar to Wu et al. (2022) analysis results showing the dawn-dusk potential is about 8-20% of the CPCP. The electric field is eastward on the dayside and westward on the nightside.

Table 1. CPCP and Equatorial Dawn/Dusk Potential

Time (UT)	2000	2011	2021	2030	2041	2051
CPCP (kV)	30.7	23.3	37.6	123	167	188
Dawn/Dusk Potential Drop (kV)	4.5	6.0	6.0	15	13.5	15

The daytime equatorial vertical ion drifts for the six cases are plotted in Figure 5. The vertical ion drifts at the magnetic equator are upward due to mostly eastward electric field. During the quiet time (the first three cases), the upward ion drifts are relatively small. Once the disturbance arrived (latter three cases), the upward ion drifts are greatly enhanced in response to the increase of the eastward electric field from the dawn-dusk potential. The ICON ExB meridional ion drift (vertical at the magnetic equator, in cyan and magenta colors) along with the sampled MAGE simulations at the ICON orbit (black line) are also plotted. The magenta color represents the data taken at the time of each subplot and data track starts at 20 UT. During the disturbed time, ICON moved into the dusk sector, and the ICON data are shown below.

Following the ICON satellite moving eastward, the dusk side of the ion drifts from MAGE and ICON are shown in Figure 6. The first three images show 20:26, 20:30, and 20:36 UT. At 20:26 UT, ICON sampled a strong increase in the ExB meridional ion drift corresponding to the enhancement at the magnetic equator simulated by MAGE. While the daytime vertical ion drifts were all enhanced, as the ICON moved into dusk, the ICON observed drift decreased due to local time variation of the ion drift, which is shown similarly by the MAGE simulation at the ICON orbit and the magnetic equator.

Figure 7 is for the nighttime ion drifts. The MAGE simulated ion drift showed great enhancement of the downward drift after 20:26 UT (arrival time of the disturbed IMF conditions). The nighttime ion drifts are downward due to the westward electric field from the dawn-dusk potential. The ICON satellite arrived at the nightside only from 20:51 UT, which are mostly downward.

The thermospheric zonal winds from the nightside are plotted in Figure 8. From the quiet time to disturbed time, the zonal wind did not change much. Hence, the fast vertical ion drift variation at 20:26 UT shown earlier cannot be due to neutral wind dynamo driven. Given the significant ion drift change due to penetrating electric field, we also examined the Joule heating rate near the equator (Figure 9). Because in general the ion drift is much smaller near equator than in the polar region, the Joule heating in low latitude is much smaller. Figure 9 shows that there is slight enhancement of the Joule heating after the disturbance arrived at 20:41 and 20:51 UT near 21 LT. Figure 9 shows the Joule heating from the polar cap to the equator. The scale is set to emphasize the changes near the equator. During the last two intervals, small enhancement of the joule heating near 20 LT are seen (~ 27000 erg/g/s). That is the region closest to the larger eastward zonal wind. Penetrating electric field associated Joule heating in the equatorial region has not been explored in the past and should be investigated in the future.

While the penetrating electric field is uniform on dayside and nightside, near dusk the penetrating electric field changes sign and is complicated. We examine in detail how the penetrating electric is seen by ICON in the potential map as shown in Figure 10. The ICON satellite passed the dusk side from 20:26 UT to 20:41 UT as shown in the top row of potential map (magenta color hexagon). The electric field directions are also plotted as yellow arrows. For the first three case, the observation and MAGE simulation are mostly consistent. In the first case at 20:26 UT, the penetrating electric field just arrived, and ICON captured the dayside eastward electric field resulting in upward ion drift seen by the ICON IVM in the lower row marked by magenta color vectors. As ICON moved eastward further into dusk at 20:31 UT, it entered the extension of the dusk convection cell, and the electric field became poleward reducing the vertical ion drift to zero. At 20:36 UT, ICON exited the dusk convection cell and felt slightly westward electric field leading to downward ion drift. The MAGE simulation and ICON observations are in a good agreement.

As ICON moved further east, ICON felt the eastward electric field in the MAGE model again probably enhanced by the penetrating electric field leading the upward ion drift in the MAGE simulated results. The ICON IVM data, on the other hand, show mostly downward ion drift suggesting westward electric field. There are many possibilities as to how the discrepancy came about. It could be the dusk convection cell is too small in the model. Had the dusk convection cell become larger and ICON stayed within the dusk convection the ICON could see less eastward electric field and subsequently less upward ion drift. Since we do not have the measurement of the morphology of the electric potential, it is hard to judge how realistic the MAGE simulated potential map is.

Discussions

The MAGE model is capable of simulating fast varying penetrating electric field (Wu et al., 2022). The difficulty is to find ICON observations to verify the simulation. In this case, the MAGE was able to show the penetrating electric field and more importantly, the ICON was at the right location to capture the penetrating electric field arrival as well. ICON satellite was at dayside close to dusk. It probably would be able to see larger variation if ICON were located near the noon.

The equatorial dawn-dusk electric potential is also about 14% of the CPCP similar to the MAGE simulation in the earlier study by Wu et al. (2022). In addition, we examine the Joule heating in the equatorial region shortly after the onset of the penetrating electric field, small enhancement near 20 LT was seen in the simulation. Having Joule heating associated with the penetrating electric is understandable due to the changing of ion drift associate with the electric field. The model simulation shows only a small increase compared with the high latitudes. The impact of the Joule heating probably will be small as well.

We further explored the ExB meridional ion drift near the dusk and follow the ICON from dayside into the nightside as shown in Figure 10. The ICON caught the penetrating electric before dusk at 20:26UT. Then, ICON traveled into the extension of the dusk and saw poleward electric field and near zero vertical ion drift. Afterward, ICON captured briefly a westward electric field and observed small downward ion drift in both the MAGE simulation and observation 20:36UT.

Keep in mind that we have only one case in the paper. We are continuing the search for good cases where the ICON and other equatorial ion drift data are available. MAGE model needs more comparisons with observations for further improvements.

Summary

The MAGE model is able to simulate the penetrating electric field during the Nov 3-4, 2021 geomagnetic storm event. Moreover, the NASA ICON mission IVM instrument was on the dayside when the penetrating electric field arrived near the equator and was able to capture the penetrating electric field as well. We performed one-to-one comparison of the MAGE simulated ion drifts sampled at the ICON satellite locations with the ICON IVM ion drift data. The ICON observed penetrating electric field enhancement is on the same order of magnitude as the MAGE simulations. Hence, the MAGE simulation of penetrating electric field is demonstrated by the ICON observation in this event.

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Figure Captions

Figure 1 IMF Bz, By, solar wind speed, density, and interplanetary electric field during Nov3-4, 2021 geomagnetic storm. The highlighted interval includes the arrival of the solar wind disturbance and is selected for analysis of penetrating electric field.

Figure 2. Same parameters as in Figure 1, but for the interval highlighted in that figure. The six highlighted intervals are selected for close inspection with MAGE simulations. The first three

represent quiet time prior to the arrival the solar wind disturbance. The latter three are for disturbed time after arrival of the disturbed solar wind, when the penetrating electric field occurs.

Figure 3. MAGE simulated high latitude electric potential map (> 50 N) during the six selected intervals highlighted in Figure 2. The IMF Bz conditions and cross polar cap potential (CPCP) are provided. Noon is at the top of each of the subplots and midnight is at the bottom. Dusk is on the left and dawn is on the right. The potential color map range from -200 kV to 80 kV.

Figure 4. MAGE simulated electric potential extending to the equator.

Figure 5. Dayside equatorial vertical ion drift (black vectors), ICON observed ExB meridional ion drift (lime and magenta vectors along the ICON orbital track). Magenta color vectors represent ICON data taken at the same time of the global picture of the MAGE simulation. ICON sampled ExB meridional ion drift from the MAGE simulation (black line following the ICON orbital track). Because eastward electric field on the dayside, the vertical ion drift is mostly downward. The horizontal scale vector is for 20 m/s at the lower part of the each subplots. The color map scale is in 1/cm3 and top panels from 0 to 2 and bottom 0 to 1.8.

Figure 6. Duskside MAGE simulation of vertical ion drift and ICON observation and ICON sampled MAGE simulation along the ICON orbital track. All these plots are for disturbed time. The first image is the time of penetrating electric field arrived as seen by ICON and simulated by the MAGE. Because ICON was moving from dayside the nightside, in the lower row, the center point of the plot was shifted eastward to have better view of ICON observation and MAGE simulated PRE.

Figure 7. Nightside the vertical ion drift and ICON observation in same format as Figure 5. Because nightside electric field is mostly westward, the equatorial ion drift is downward. Enhancement of the downward ion drift is the results of penetrating electric field in the latter three intervals.

Figure 8. Zonal wind during the 6 selected interval highlighted in Figure 2. There is no significant changes before and after the arrival of the disturbed solar wind at 20:26 UT.

Figure 9. Joule heating rate during the 6 intervals highlighted in Figure 2, with emphasis to show the low latitude region. Enhancements near 20 LT are shown in two intervals after the arrival of the disturbed solar wind.

Figure 10. Duskside ICON samples of vertical ion drifts relative to the electric field potential. ICON is marked as magenta color hexagons in the upper plots. The lower plots are the same format as Figure 6.