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

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We simulated the Nov 4, 2021 geomagnetic storm event penetrating electric field using the Multiscale Atmosphere-Geospace Environment (MAGE) and compared with the NASA ICON observation. The ICON observation showed enhancement of the vertical ion drift when the penetrating electric field arrived at the equatorial region. The simulated vertical ion drifts are consistent with ICON observation. Hence, we are able to verify the MAGE simulation with ICON observation. On the dusk side, the MAGE simulation showed strong pre-reversal enhancement (PRE), whereas the ICON observation did not display any sign of the PRE. The MAGE simulation did show that PRE amplitude decreases as altitude increase. Because the ICON orbital height is above the model upper boundary, it could be a factor for the discrepancy. Instrumental issue cannot be ruled out at this moment. GOLD UV image at the same time exhibits multiple plasma bubbles, which seem to suggest the existence of the PRE.

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Abstract

We simulated the Nov 4, 2021 geomagnetic storm event penetrating electric field using the Multiscale Atmosphere-Geospace Environment (MAGE) and compared with the NASA ICON observation. The ICON observation showed enhancement of the vertical ion drift when the penetrating electric field arrived at the equatorial region. The simulated vertical ion drifts are consistent with ICON observation. Hence, we are able to verify the MAGE simulation with ICON observation. On the dusk side, the MAGE simulation showed strong prereversal enhancement (PRE), whereas the ICON observation did not display any sign of the PRE. The MAGE simulation did show that PRE amplitude decreases as altitude increase. Because the ICON orbital height is above the model upper boundary, it could be a factor for the discrepancy. Instrumental issue cannot be ruled out at this moment. GOLD UV image at the same time exhibits multiple plasma bubbles, which seem to suggest the existence of the PRE.

Introduction

Penetrating electric field is a fast magnetospheric effect 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 input 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. Additionally, the simulation showed pre-reversal enhancement (PRE) whereas the observation from the ICON mission did not. The discrepancy was not explored further.

Given the importance of understanding the penetrating electric field, we selected a recent storm event (Nov 3, 2021) for a further study with MAGE simulations in conjunction with ICON observations. Figure 1 shows the 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 impacted 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 provide 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 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. As the ICON moved from dusk into the night from 20:41, 20:45, and 20:51 UT, the MAGE simulated drift along the ICON track showed clear pre-reversal enhancement (PRE) and so do the MAGE simulation at the magnetic equator. At the same time, ICON drift data themselves showed no sign of PRE. The ICON observed ion drift turned downward (20:41 UT) earlier than the simulation showed (20:51 UT).

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.

Because MAGE simulation showed strong PRE, which can lead to Rayleigh-Taylor instability and plasma bubble. The GOLD UV image data are examined for plasma bubbles and shown in Figure 10. Multiple bubbles are seen in the GOLD UV image and some reached midlatitudes (~ 30 MLAT) indicating very high apex height. The presence of plasma bubble seems to support the existence of PRE.

One of the issues of the MAGE simulation and ICON comparison is the altitude difference. The MAGE simulation shown in the paper is from 240 km altitude, whereas the ICON is ~ 575 km orbital height close the MAGE upper boundary. In the MAGE simulation, the PRE is smaller at higher altitudes so it can be a factor.

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 11. 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. Up to this point 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. It should be noted that the ICON IVM have consistently shown large downward ion drift at the local time when PRE in the MAGE simulation is present. Further verification with other observations such as ground incoherent scatter radars are needed in future studies.

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.

The discrepancy related to the PRE between the simulation and observation is still unresolved, although we explored some possibilities. Existence of the multiple plasma bubbles and some very strong in the GOLD image seem to suggest strong upward ion drift. During quiet time, the MAGE simulation shows decrease of the PRE amplitude as altitude increases. Noting that ICON is at a higher altitude, furthermore ICON is not at the magnetic equator, so the apex height is even higher. It is possible ICON is unlikely to encounter strong PRE because of its altitude. On the other hand, MAGE seems to show PRE frequently, whereas the ICON tends to show large downward ion drift near dusk. Further study is needed.

We further explored the ExB meridional ion drift near the dusk and follow the ICON from dayside into the nightside as shown in Figure 11. 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. When the simulated PRE was reached by the ICON, it saw a simulated eastward electric field and upward ion drift at 20:41 UT. The ICON data however shows strong downward ion drift at that time.

As to what is the source of the discrepancy between MAGE simulation and ICON observation of PRE, beyond the high orbital height of the ICON, there are many possibilities. For example, the MAGE simulated potential map has a minimum potential point around 20 LT, which could be at an earlier local time in reality. That would lead to ICON detect westward electric field at 20:41 UT and downward ion drift in real world. We have not been able to find report of PRE in ICON data. Given the mission is relatively new, it may take more time for the ICON to observe PRE. The bottom line is whether PRE is expected or not in this case. The GOLD UV image observation of multiple bubble seems to give a strong hint for strong PRE, which is directly linked to the Rayleigh-Taylor instability and plasma bubbles. The PRE discrepancy between the simulation and observation is a very important issue for space weather study. We will need to find more ICON passes near the magnetic equator near the dusk. Near magnetic equator can reduce the apex height of the ICON samples, which may lead to strong PRE.

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. The observed penetrating electric field is on the same order of magnitude as the MAGE simulations. Hence, the MAGE simulation of penetrating electric field is confirmed by the ICON observation. The MAGE again show PRE, whereas the ICON IVM did not show PRE. We examined altitude difference and other possible source. Unfortunately, it is still unresolved.

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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.

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.

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. GOLD UV image of plasma bubbles. Cyan circle are the locations of the plasma bubble at the magnetic equator. Orange and yellow circles are locations of northern and southern equatorial ionosphere anomalies. Magnet longitudinal grid are in 2 degrees. Magnetic equatorial and 20 N and 20S magnetic latitudes are also plotted. Some plasma bubbles reached to about 30 magnetic latitudes indicating bubble reaching very high apex height.

Figure 11. 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.