Ionospheric electric field variations during a geomagnetic storm simulated by a coupled magnetosphere ionosphere thermosphere (CMIT) model

Wenbin Wang, 1,2 Jiuhou Lei, 1 Alan G. Burns, 1 Michael Wiltberger, 1 Arthur D. Richmond, 1 Stanley C. Solomon, 1 Timothy L. Killeen, 1 Elsayed R. Talaat, 3 and David N. Anderson 4

Received 26 June 2008; accepted 25 August 2008; published 25 September 2008.

[1] A coupled magnetosphere ionosphere thermosphere (CMIT 2.0) model has been developed. It is capable of self-consistently calculating global ionospheric electric fields that include the imposed magnetospheric convection field, neutral wind dynamo and penetration electric fields. The CMIT 2.0 simulated ionospheric F region ion vertical drift velocities at the magnetic equator were compared with those measured by ground-based instruments during the April 2–5, 2004, storm. CMIT 2.0 captured the temporal variations seen in the measurements during both the quiet and active periods. These temporal variations corresponded mainly to the variations in the high latitude electric fields driven by changes in solar wind conditions. CMIT 2.0, however, overestimated the magnitudes of the variations of the vertical drifts. In addition, CMIT 2.0 simulated the observed pre-reversal enhancement well. This enhancement was driven mostly by the neutral wind dynamo. Citation: Wang, W., J. Lei, A. G. Burns, M. Wiltberger, A. D. Richmond, S. C. Solomon, T. L. Killeen, E. R. Talaat, and D. N. Anderson (2008), Ionospheric electric field variations during a geomagnetic storm simulated by a coupled magnetosphere ionosphere thermosphere (CMIT) model, Geophys. Res. Lett., 35, L18105, doi:10.1029/2008GL035155.

1. Introduction

[2] The ionospheric electric field has two primary sources: the neutral wind dynamo and the convection electric field mapped from the magnetosphere. The electric field of magnetospheric origin is normally confined to high latitudes and low latitudes [e.g., Vasylkivnas, 1972]. However, because of the slow reaction of these region 2 currents to changes in solar wind/interplanetary magnetic field (IMF) conditions, the region 2 currents can not effectively provide the necessary shield when there is a rapid change in these conditions, so the electric field in the polar cap can penetrate into middle and low latitudes [e.g., Kelley et al., 1979; Huang et al., 2005]. This penetration of electric field during changing solar wind/IMF conditions was first suggested by Nishida [1968]. The penetration electric field has since been studied extensively using various ground and space-based observations [e.g., Kelley et al., 1979; Huang et al., 2005]. The neutral wind dynamo is significantly enhanced during geomagnetic storms, producing the so-called disturbance dynamo [Blanc and Richmond, 1980]. The mechanism for the disturbance dynamo is that the enhanced energy and momentum inputs during storms greatly change the global neutral winds, which, in turn, cause major changes in the dynamo electric fields.

[3] Penetration electric fields can have a significant impact on ionospheric electron densities [Lei et al., 2008]. However, the study of the global ionospheric electric field has mostly involved correlation analysis or using global thermosphere/ionosphere models driven by empirical or specified high latitude convection patterns [e.g., Richmond et al., 2003], and thus lacks a self-consistent description of the global electric field.

[4] In this paper, we present global ionospheric electric fields simulated by the coupled magnetosphere ionosphere thermosphere (CMIT 2.0) model during the April 2–5, 2004, storm. This model can self-consistently calculate global ionospheric electric fields of magnetospheric origin, the neutral wind dynamo, the disturbance dynamo and penetration electric fields. We will describe CMIT 2.0 briefly in Section 2, and compare the modeled electric fields with those observed by several ground-based instruments in Section 3. Discussion and conclusions of the results will be given in Section 4.

2. The CMIT 2.0 Model

[5] CMIT 2.0 couples the Lyon Fedder Mobarry (LFM) global magnetosphere MHD code [Lyon et al., 2004] with the Thermosphere Ionospheric Electrodynamics General Circulation Model (TIEGCM) [Richmond et al., 1992]. These two codes are coupled by exchanging parameters across their interfaces through a magnetosphere-ionosphere (M-I) coupler module. A detailed description of the coupling procedure can be found in work by Wiltberger et al. [2004].

[6] In CMIT 2.0, the ionospheric electric fields are obtained in two steps. First, high latitude electric fields are solved in the M-I coupler using self-consistently calculated ionospheric conductivity and magnetospheric field-aligned currents. Then, ionospheric electric fields in middle and low latitudes are calculated using high latitude electric fields as time-dependent boundary conditions at 60° mag-...
natic latitude for the dynamo solver in the TIEGCM. Thus, the impact of high latitude electric fields on low and middle latitudes fields (penetration electric fields) is also included. CMIT 2.0 is thus able to simulate self-consistently global ionospheric electric fields that include high latitude electric fields driven by solar wind/IMF conditions, neutral wind dynamo fields, and penetration electric fields. This new capability can better describe the dynamical and electrodynamical responses of the magnetosphere, ionosphere and thermosphere, as a system, to variations of the solar wind/IMF conditions.

3. Results

[7] The top panel in Figure 1 gives the IMF B_z (nT) and Kp during the April 2–5, 2004 geomagnetic storm event (top panel). The bottom three panels are the CMIT simulated cross polar cap potential (kV), hemispheric power of auroral precipitation (GW) and Joule heating (GW).

[8] A geomagnetic storm occurred on day 94. During this day, unlike in the quiet-time case, large temporal variations in the vertical drifts occurred. The day-time vertical drifts were also significantly larger than those under quiet conditions. The radar was not operating after 1700 UT (~1200 LT). We plot also the E × B drifts inferred from the ground-based magnetometer observations and those determined from the F_2-region bottomside height changes from the Jicamarca digisonde using the Anderson et al. [2002] and Bittencourt and Abdu [1981] techniques. It appears that modeled vertical drifts were about a factor of two larger than those obtained from magnetometer observations between 1530 and 1800 UT, but were much closer to them between 1900

Figure 1. IMF B_z (nT) and Kp during the April 2–5, 2004 geomagnetic storm event (top panel). The bottom three panels are the CMIT simulated cross polar cap potential (kV), hemispheric power of auroral precipitation (GW) and Joule heating (GW).

Figure 2. (a) Ion vertical drift velocities (m/s) at the F_2 peak measured by the Jicamarca radar (blue crosses), inferred from ground-based magnetometer (light green line) data and determined from the F_2 peak bottomside height changes from the Jicamarca digisonde (light blue line), and simulated by the CMIT model (red line) for the April 2–5, 2004 geomagnetic storm event. Also shown in the plot is the IMF B_z component (nT, green line). (b) Ion vertical drift velocities (m/s) caused by the neutral wind dynamo (dynamo only, green line), and those from the stand-alone TIEGCM (red line).
to 2200 UT. The modeled drifts were again much larger than the drifts inferred from digisonde observations between 2200 and 2400 UT. Nevertheless, the model captured the early morning peak around 1300 UT and closely followed the observed temporal variations.

[10] During nighttime on Day 94, from 0100 to 1300 UT, the observed drifts showed significantly different temporal variations from those in the quiet-time case. Upward drifts were seen between 0130 and 0230 UT, and also briefly around 0330 UT, whereas, in quiet time, the observed nighttime drifts were all downward. The modeled drifts traced the temporal variations of the observed drifts very well, with both the upward and downward drift peaks occurring at roughly the same times. The model, however, overestimated the magnitude of the drifts substantially in some time periods, most noticeably around 0300 and 0900 UT.

[11] CMIT 2.0 thus captured most of the temporal variations seen in the observations during both the active and quiet periods. The question to be addressed is then: what caused these temporal variations? We plot $B_z$ again in Figure 2a. The peaks and temporal variations of the observed and simulated drifts were consistent with those seen in $B_z$. There were some time shifts in the temporal variations between the observed drifts, modeled drifts and $B_z$. These time shifts were caused mainly by the fact that CMIT 2.0 uses a constant solar wind speed (averaged solar wind speed during the event) to calculate the propagation time from the L1 point to the magnetopause. This may introduce tens-of-minutes differences between the calculated and the actual solar wind arrival times. Nevertheless, it appeared that those rapid changes seen in the vertical drifts were related to the changes in the imposed electric fields at high latitudes, which corresponded to variations in the IMF and solar wind conditions.

[12] To elucidate how the IMF driven magnetospheric electric field affects low latitude electrodynamics, we plot the simulated eastward electric fields at the Jicamarca longitude in Figure 3. Figure 3a shows the total electric field obtained from CMIT 2.0 driven by the solar wind/IMF data and Figure 3b gives the neutral wind dynamo field obtained by post-processing the model outputs. The post-processing is a rerun of the model for one time step from the actual model outputs with high latitude electric fields being set to zero. Thus the electric fields obtained from the post-processing are only the neutral wind dynamo fields. It should be noted that this manner of obtaining the wind-dynamo component uses the same ionospheric electron densities and conductivities as for the full CMIT run, and thus avoids the complication of nonlinear coupling between the wind-dynamo and penetration electric fields through conductivity modifications, as discussed by Maruyama et al. [2005]. The difference between Figures 3a and 3b is thus the penetration electric fields from high latitudes. In addition, the differences between day 93 and day 94 of the dynamo fields in Figure 3b were caused by the disturbance dynamo produced by the storm.

[13] The lines in Figure 3 give the geographic latitude of the Jicamarca radar. At night, dynamo fields varied smoothly with time during both the quiet and storm periods. Thus the rapid variations seen in both the simulated and observed drifts were caused by the temporal variations of the imposed magnetospheric electric fields. During daytime, low latitude electric fields were mostly of dynamo origin during quiet conditions, but large penetration electric fields occurred during the storm, which also caused more variations in the low latitude electric fields. The pre-reversal enhancement at about 2400 UT resulted from the neutral wind dynamo effect. Comparing dynamo fields on day 93 with those on day 94, it is clear that larger dynamo electric fields occurred during storm than during quiet time at night; these were disturbance dynamo and were significant in middle and low latitudes.

[14] Figure 2b shows CMIT vertical drifts caused only by the neutral wind dynamo and the total vertical drifts calculated by the stand-alone TIEGCM driven by $K_p$, as well as measured vertical drifts. The dynamo drifts simulated by CMIT and the total vertical drifts calculated by the stand-alone TIEGCM were very smooth compared to the observed ones, and with the CMIT simulated total vertical drifts that include both neutral wind dynamo and penetration electric fields shown in Figure 2a. The stand-alone model also significantly underestimated the vertical drifts that were associated with the pre-reversal enhancement. However, the drift caused by the neutral-wind dynamo was almost the same as the observed drifts for the pre-reversal enhancement in the CMIT 2.0 dynamo-only case.
In addition, the dynamo-only vertical drifts from CMIT 2.0 did not have most of the shorter-duration variations seen in the observed vertical drifts at night on the quiet day, indicating that these temporal variations were the result of penetration electric fields. The stand-alone run followed the general trend of the observations, but was off significantly in both the magnitude and temporal variations. Comparing dynamo induced drifts on day 93 with those on day 94, we can see that the disturbance dynamo enhanced vertical drifts in the nighttime, but significantly suppressed the daytime dynamo. The daytime dynamo field was downward after 1700 UT, instead of upward. The penetration electric field was large enough to compensate for this and made the overall vertical drifts upward.

4. Discussion and Conclusions

[15] Figure 3 shows that there were continual penetrations of electric fields over long periods of time. For instance, from 0100 to 0800 UT on day 94, the penetration time was about 7 hours. These penetration times are much longer than those predicted by the classic shielding theory for steady state conditions [Senior and Blanc, 1984]. Our simulations are consistent with previous studies that long lasting penetration of electric fields can occur when there are temporal variations in $B_z$ and thus in polar cap electric fields. Under these conditions the magnetosphere is dynamical and the region 2 currents cannot respond fast enough, allowing penetration of the electric fields to occur [Richmond et al., 2003; Huang et al., 2005]. It is also interesting to note that an earthward penetration electric field occurred around about 0200 UT on day 94; this penetration electric field was in the opposite direction to that of the neutral wind dynamo and caused the observed upward vertical drifts.

[16] On day 93, when geomagnetic activity was low, the magnitudes of the simulated vertical drifts were very close to the observed ones. Figure 2b illustrates that neutral wind dynamo alone could not account for the observed downward vertical drift at night. Figure 3 shows that there was a significant westward penetration electric field that helped to produce the overall observed downward plasma drifts. This is understandable since, as illustrated in Figures 1 and 2, $B_z$ was oscillating between southward and northward; thus penetration of the electric field was expected. However, $B_z$ was northward during daytime. Thus, there were larger penetration electric fields at night than during the day. By including the effect of high latitude electric fields CMIT 2.0 was able to reproduce the observed vertical drifts. The fact that there was still significant penetration of the electric field under relatively very quiet conditions ($K_p \leq 1$, Figure 1) is potentially very important in interpreting observational results. Hourly averaged indices such as $K_p$ and $Ap$ may not be good parameters to use to study electric-field-related ionospheric changes. Time-varying solar wind/IMF conditions need to be applied to understand these changes.

[17] CMIT 2.0 overestimated the magnitude of the penetration electric fields, and hence the vertical drifts. This is probably caused by two factors: an overestimation of the high latitude electric field and the weak region 2 currents that are calculated in the magnetospheric MHD code [Merkin et al., 2007]. We are currently working on coupling the Rice Convection Model (RCM) with CMIT 2.0 [Toffoletto et al., 2004]. The RCM gives a better description of the ring current, and thus can better calculate the region 2 currents and shielding effects. The overestimation of the high latitude electric field also results in the overestimation of Joule heating and global neutral wind circulation, and in turn, the disturbance dynamo effect. This is evident around 0800 UT on day 94, when the model overestimated the combined effects of the neutral wind dynamo and the penetration electric field (Figures 2 and 3).

[18] The weak region 2 currents in CMIT 2.0 also prevent us from studying the overshielding effect during the northward turning of $B_z$ [Kelley et al., 1979]. The upward turning of the vertical drift around 0800 UT on day 94 was caused by the disturbance dynamo. A large eastward dynamo field occurred in response to the enhanced neutral winds. This eastward dynamo field was offset by the westward penetration electric field at night, thus the drift was downward. However, at about 0800 UT the strength of southward $B_z$ decreased and it briefly turned northward. This reduced the strength of the penetration electric field and, eventually, the net electric field became eastward, resulting in an upward drift. As discussed earlier, since $B_z$ changed constantly with time, the shielding by region 2 currents was not well established, and overshielding effect was probably weak. Nevertheless, we expect that the coupling of CMIT 2.0 with the RCM will make it possible to fully understand the relative importance of overshielding effects and the disturbance dynamo to the ionospheric electric field when $B_z$ turns northward.

[19] In summary, CMIT 2.0 is capable of self-consistently studying the ionospheric electric field, including the neutral wind dynamo and penetration electric fields. In this paper, we applied CMIT 2.0 to simulate the ionospheric electric fields and compared the upward drift produced by these fields with the vertical drifts observed at the magnetic equator during a geomagnetic storm. CMIT 2.0 was able to capture the temporal variations seen in the measurements. However, it overestimated the magnitudes of these changes. This overestimation was most likely related to the overestimation of the penetration electric field by the model. These temporal variations were caused by variations in the imposed high latitude electric fields, which were, in turn, driven by changes in solar wind/IMF conditions. CMIT 2.0 also simulated the observed pre-reversal enhancements well which is mostly caused by the neutral-wind dynamo. In addition, high latitude electric fields were also seen to penetrate to lower latitudes during nighttime in the quiet period. The upward drifts around 0800 UT on day 94 were caused by the neutral wind dynamo when IMF $B_z$ had a northward excursion, so penetration electric fields were absent at the time.

[20] Acknowledgments. This material is supported in part by the National Science Foundation Cooperative Agreements through Cornell University.

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D. N. Anderson, Space Weather Prediction Center, NOAA, 325 Broadway, Boulder, CO 80303, USA.

A. G. Burns, T. L. Killeen, J. Lei, A. D. Richmond, S. C. Solomon, W. Wang, and M. Wiltberger, High Altitude Observatory, National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307, USA. (wbwang@ucar.edu)

E. R. Talaat, Applied Physics Laboratory, Johns Hopkins University, 11100 Johns Hopkins Road, Laurel, MD 20723-6099, USA.