The observation and simulation of ionospheric response to CIR-induced geomagnetic activity on 4 April, 2005

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ABSTRACT

The ionospheric response to CIR-induced geomagnetic activity on 4 April, 2005 was analyzed both from ground GPS-TEC, in-situ electron density measurement and simulations from the National Center for Atmospheric Research Thermosphere - Ionosphere - Electrodynamics General Circulation Model (TIE-GCM). The result showed the ionospheric positive response can be observed from high to low latitude. The positive effect at low latitude continued for more than 4 days, whereas at middle to high latitudes the disturbance lasted only for 1-2 days. The model results showed the penetration electric field was responsible for the positive response during the initial and main phase of the geomagnetic storm. The long-duration positive during the recovery time at low latitude was found to be related to the thermospheric composition (O/N2) changes during the storm.

1. INTRODUCTION

The investigation and modeling of ionospheric response to geomagnetic activity is very important to satisfy the needs of estimating ionosphere effects on HF radio wave propagation, GNSS navigation and satellite communication. Although the research on ionospheric storm has a long history, it is still very difficult to predict ionospheric response to a geomagnetic storm as many physical processes still unknown. In recent years, researchers pay much attention on ionospheric response to recurrent geomagnetic activity which is induced by interplantary corotating interaction regions (CIRs). The CIR is produced when high-speed solar wind streams originating from solar coronal holes interact with slow-speed solar winds. The periodic magnetic activity driven by CIR also produced periodic ionospheric disturbances (e.g. Lei et al., 2008; Crowley et al., 2008; Pedatella et al., 2010; Tulasi Ram et al., 2010; Wang et al., 2011). For example, Lei et al. [2008] showed that 7 and 9 day periodic oscillations exist in total electron content (TEC), associated with the periodic variations in the solar wind and geomagnetic activity.

Besides the periodic analysis, further studies on the characteristic and commonality of ionospheric response to CIR event induced geomagnetic activity is also important because it will give the possibility for forecasting the disturbance during recurrent geomagnetic activity [Wang et al., 2011; Burns et al., 2012; Solomon et al., 2012; Liu et al., 2012a; Verkhoglyadova et al., 2013; Chen et al., 2015]. Burns et al. [2012] compared ionospheric peak electron density with the result from the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM) for three CIR events during the WHI in 2008. They showed the CIR events can have significant effects on the ionosphere and thermosphere for several days after the CIR has ended, and attributed this long-lasting effect to the continued forcing by Alfven wave-driven changes in the interplanetary magnetic field (IMF) and the continuation of high solar wind speed. Solomon et al. [2012] showed the comparison of neutral composition (neutral density and NO cooling rate) and ionospheric peak density with the results simulated from the TIE-GCM running under different solar wind and IMF conditions. They confirmed north-south component (Bz) of IMF was most important for the response of thermosphere and ionosphere parameters to CIR events. Verkhoglyadova et al. [2013] showed that the daily averaged vertical TEC in middle to low latitudes increased by 60% on average during HSS/CIR events in 2008 and 2009. Chen et al.[2015] presented an epoch analysis of global ionosphere responses to recurrent geomagnetic activity during 79 CIR events from 2004 to 2009. They showed the TEC positive disturbance at low latitudes sometimes could last for 2–4 days during the recovery time, whereas at middle to high latitudes the disturbance lasted only for 1 day in most cases.

Although CIR-induced geomagnetic activity was weak to moderate, the above studies suggested the ionospheric response could be strong and last long time. In this paper, we describe comparisons between the ground-based GPS-TEC observations, in-situ electron density measurements and the results from TIE-GCM for the CIR event occurred on 4 April, 2005, and try to explain how the ionospheric response changes with latitude and time. The data sets used in this work are described in section 2. A detailed presentation of the results is given in section 3, and conclusions are presented in the final section.

2. DATA AND MODEL

2.1 IONOSPHERIC DATA SETS

The ground-based GPS TEC data were obtained from the Madrigal Database at the Massachusetts Institute of Technology Haystack Observatory (http://www.openmadrigal.org).The detailed algorithms and processing procedure for the TEC estimation from the global GPS data were described in Rideout and Coster [2006]. The electron density data were obtained from the CHAMP Planar Langmuir Probe (PLP) observations, which are available from the Information Systems and Data Center operated by Geo Forschungs Zentrum (GFZ) Potsdam (http://isdc.gfz-potsdam.de). The CHAMP satellite was in an almost circular, near-polar orbit at approximately 400 km altitude and 87° inclination.

2.2 MODEL DESCRIPTION

The NCAR Thermosphere–Ionosphere–Electrodynamics General Circulation model (TIE-GCM) (Roble et al.,1988; Richmond et al., 1992) was used to perform the model simulation. The TIE-GCM is a comprehensive, first-principles, three-dimensional, non-linear representation of the coupled thermosphere and ionosphere system that includes a self-consistent solution of the low-latitude electric field. The model solves the Eulerian continuity, momentum, and energy equations for neutral and ion species at each time step. It uses pressure surfaces as the vertical coordinate and extends in altitude from approximately 97km to 600km. The normal resolution of the model is 5°in latitude and longitude, and 0.5 scale height in altitude. The time step is 120 s.

3. RESULTS

3.1 SOLAR WIND AND IMF CONDITIONS

Figure1 shows the solar wind density, speed, the north-south component (Bz) of the interplanetary magnetic field (IMF), Dst and AE indicies on 1–8 April 2005. The IMF Bz and solar wind speed were measured by the ACE satellite. The CIR event started at about 01:00UT on 3 April 2005, referenced from the criteria of Jian et al.[2006]. The IMF Bz began to oscillate after the CIR occurred, whereas the the main phase of geomagnetic storm driven by the CIR event started at about 21:00UT on 4 April, over

40 hours later than the CIR start time. The minimum value of IMF Bz was about -10 nT on 5 April. Bz continued to be southward for about 10 h before it oscillated between southward and northward directions during 5-8 April. Solar wind speed reached 700 km/s on 5 April. This CIR event induced a major geomagnetic storm (Kp = 7, minimum of Dst=-85nT). The AE showed there is continuous deposit of energy from magnetosphere to ionosphere during the recovery time of the geomagnetic storm.

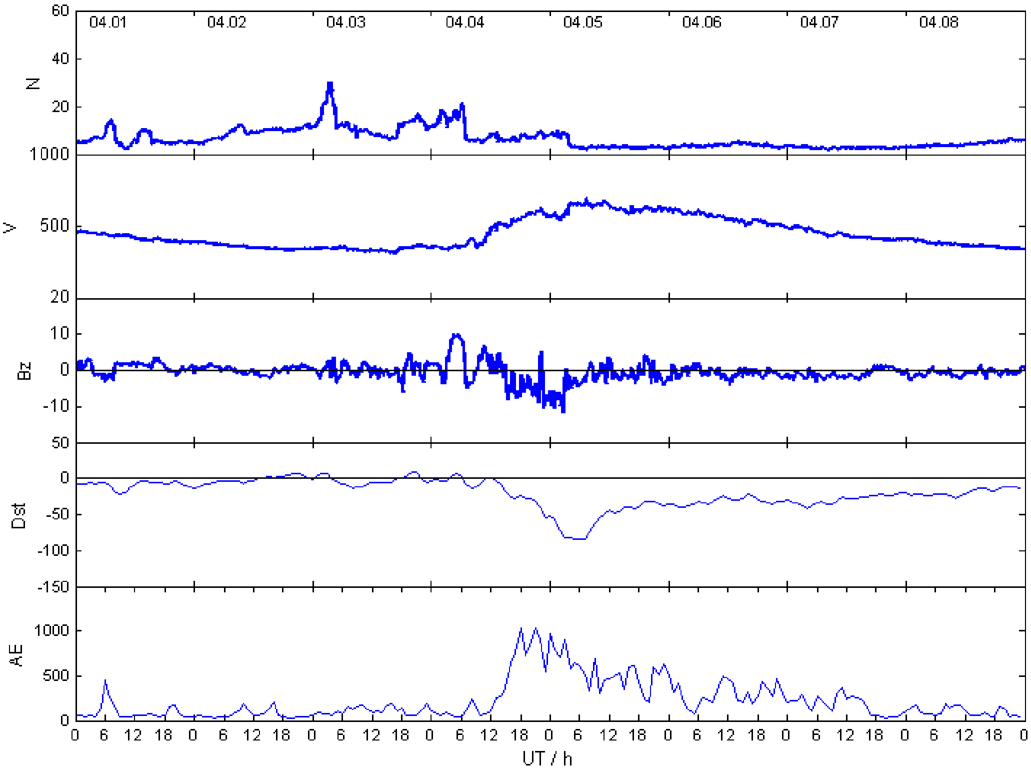

Figure 1. The solar wind, IMF Bz, Dst and AE on 1-8 April, 2005

3.2 THE ELECTRON DENSITY FROM OBSERVAION AND MODEL SIMULATION

Figure 2 gives the CHAMP PLP electron density (Ne), Dst, and Bz variations during the CIR event of April 2005. The temporal resolution of the measured electron densities was 15 s. Because CHAMP had a high inclination, near-polar orbit (87°), the observations were made at almost a constant local time during the event. The electron densities in Figure 2 were obtained by averaging over a 2 h window; thus, the effects of UT and longitudinal variations were probably mixed.

The electron densities showed a strong positive storm effect from high to low latitudes in the main phase of the geomagnetic storm. The positive storm effect at low latitudes lasted for more than 4 days. A decreased Ne region was seen in the middle to high latitudes on 5 April. On 6–8 April, CHAMP-observed electron densities continued to be enhanced. There was a weak north-south asymmetry with higher electron densities in the Northern Hemisphere.

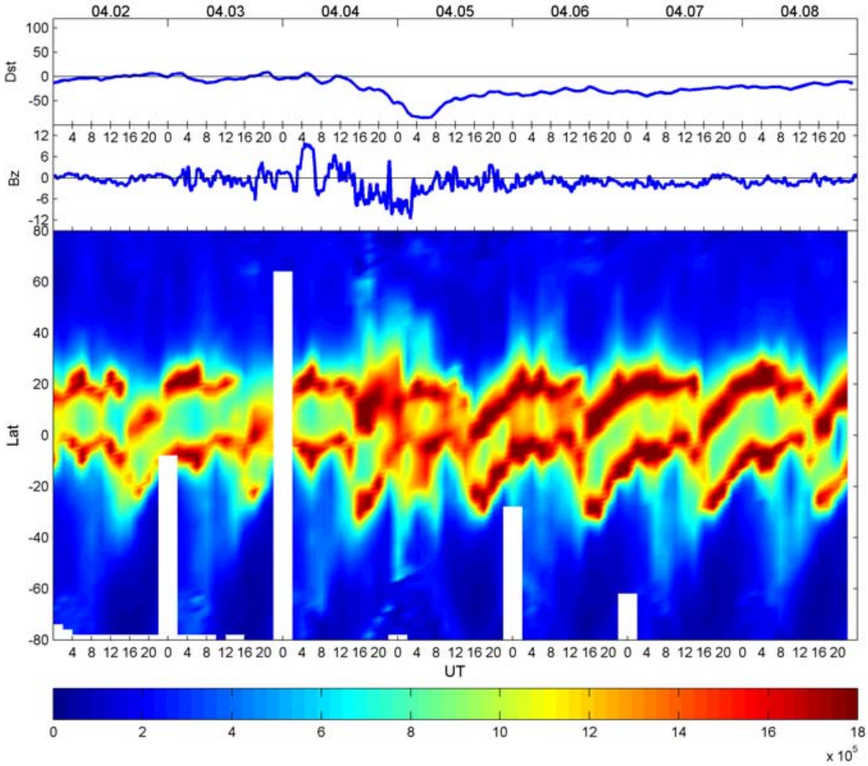

Figure 2. CHAMP zonal mean Ne variations during 2–8 April 2005. The local time of observations were fixed at 13:00 LT.

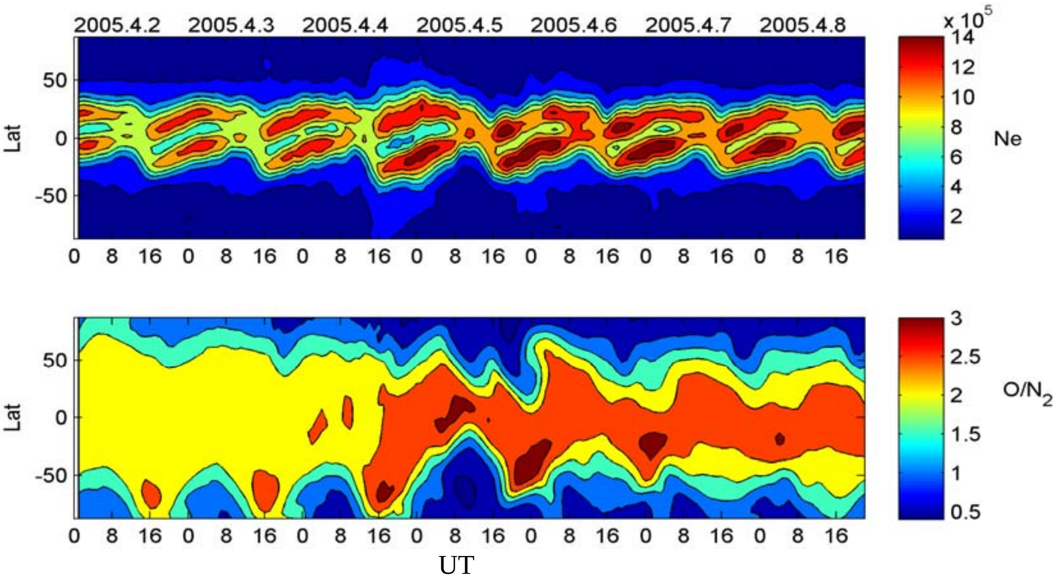

Figure 3. The Ne, O/N2 and Vertical drift output from TIE-GCM at LT=13:00 (The average height of Ne is about 380km.)

Figure 3 shows model outputs of TIE-GCM using the Weimer model. The average height of the electron density is about 380km, similar to that of CHAMP satellite orbit. The model result also showed a positive effect and subsequent negative response at middle to high latitude region. The Ne had a positive effect from middle to low latitude. The positive effect at low latitude lasted for more than 4 days. The model simulation is very consistent with the observation showed in Figure 2. The variation of O/N2 ratio indicated the decrease of O/N2 ratio at high latitude move to lower latitude after the main phase on 5 April. The decrease of O/N2 can lead to stronger molecular recombination and a decrease in ionospheric electron densities. Thus, the negative storm was produced at high latitude. At middle to low latitude, there are significant enhancement of O/N2 ratio, which is responsible for the long-duration positive effect.

3.3 GLOBAL TEC FROM OBSERVATION AND SIMULATION

Figure 4 gives global TEC difference from ground GPS observation and TIE-GCM simulation at 6:00UT and 18:00UT on April 5. In this paper, the TEC on April 1 was selected as a reference background level of TEC. At 6:00UT, the GPS-TEC showed a daytime positive effect from high to low latitude on 5 April. During the night time, the positive response was observed at low latitude region. The model simulation was good at performing the dayside TEC enhancement, but not very well for the nighttime positive effect at low latitude. At 18:00UT, the daytime positive only occurred at middle to low latitude region, and the model result is very consistent with the observation.

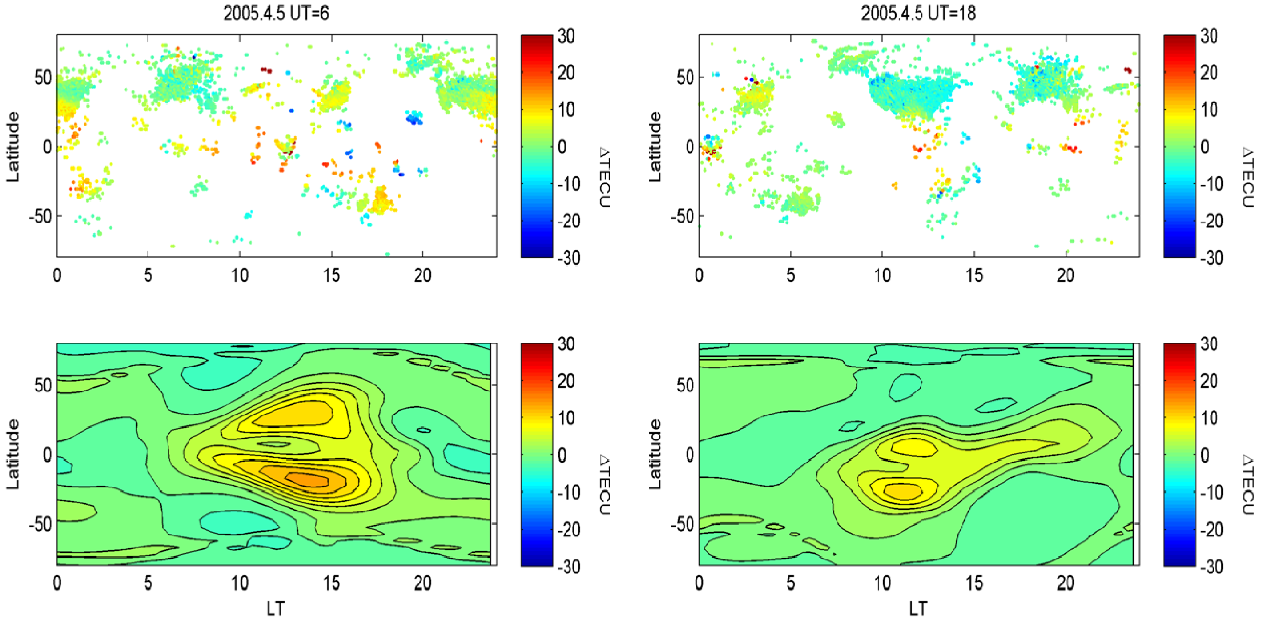

Figure 4. TEC from GPS observation (upper) and TIE-GCM simulation (bottom) on April 5 fixed at 6:00UT (left) and 18:00UT(right).

The comparison of TEC observations and model simulations for several single points of American sector during the CIR event are showed in Figures 5-7. The TEC difference, O/N2 ratio difference and vertical ion drift from TIE-GCM are also showed in the figures. At high latitude in American sector (Figure 5), the model output underestimates the TEC, which is reasonable because the upper boundary of integral electron density is about 600km. GPS-TEC includes the electron density from ground to about 36000km where GPS satellite located. The TEC from observation and model result showed similar variation trend with an increase during 4 – 5 April, followed by a negative effect lasted from April 6 to April 8. The agreement between observation and model suggests the physical process producing the ionospheric disturbance in the model is reasonable and can be used to explain the ionospheric variation during the CIR events. The vertical drift increased on April 4 to 5 suggests penetration electric field may be responsible for the positive response. During the recovery time, the decrease of O/N2 is responsible for the negative response following the positive effect.

At middle latitude (Figure 6), the difference between observation and model result is similar to that in high latitude. The model can also well simulate the storm-time ionospheric TEC. The positive effect is relative to the enhancement of vertical drift.

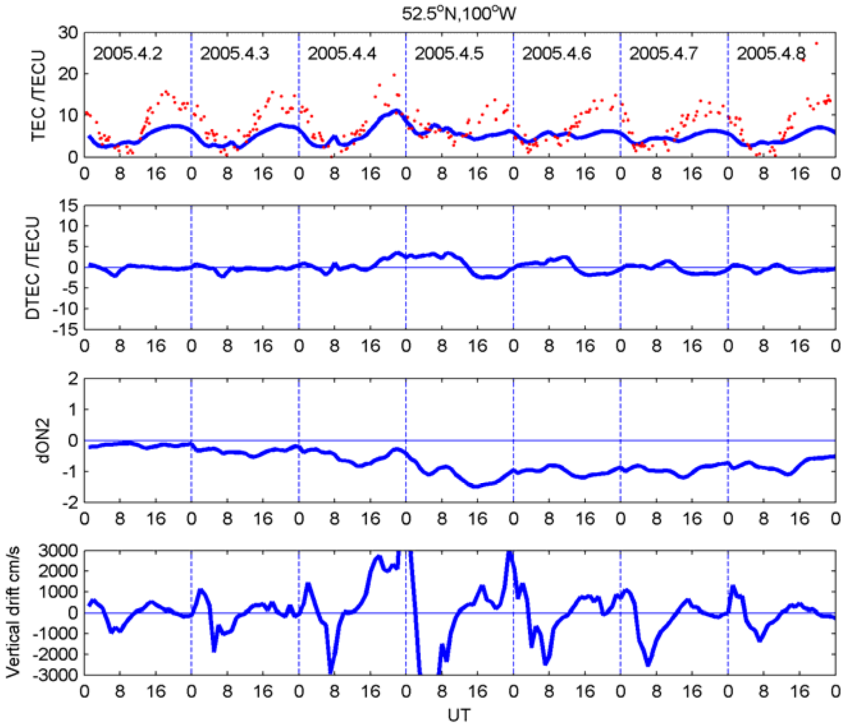

Figure 5. The observation of GPS-TEC (red point), compared with the results from TIE-GCM run with the Weimer convection pattern.

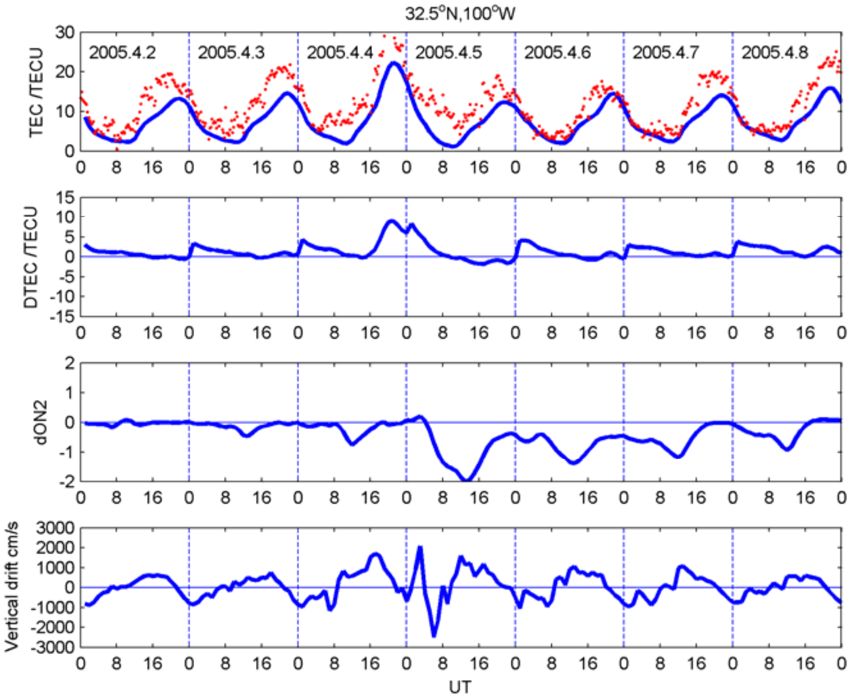

Figure 6. Same as figure 5 but at middle latitude

At low latitude in American sector (Figure 7), the output of TIEGCM showed a positive response at low latitude. The positive lasted for 4 days, similar to the result of electron density in 3.2. On April 4-

5, the vertical drift showed an enhancement, and the O/N2 ratio increased as well. This suggests the neutral composition and penetration electric field jointly responsible for the positive effect during the main phase of the CIR-driven geomagnetic storm.

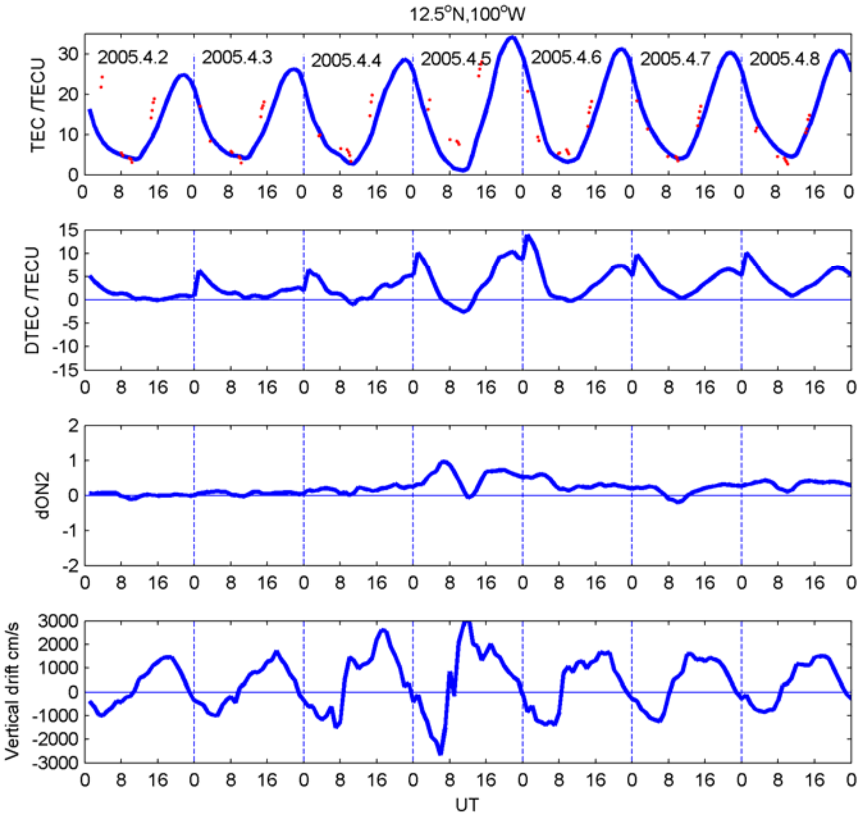

Figure 7. Same as figure 5 but at low latitude

4. CONCLUSIONS

In this paper we have compared CHAMP electron density and ground-based GPS TEC observations with the results from TIE-GCM during the CIR event on April 4, 2005. Our main conclusions are as follows:

1. Ionosphere TEC and electron density has a positive response from high to low latitude. At high latitude, after the positive response, there is a negative effect continued for several days. At low latitude, the positive effect can last for more than 4 days.
2. The results from TIE-GCM were consistent with the observations and good to simulate the storm-time positive and negative effect.
3. The model output indicated the penetration electric field was responsible for the positive response at middle to high latitude. At low latitude region, penetration electric field and thermospheric composition (O/N2) changes jointly responsible for the positive response during the initial and main phase of the geomagnetic storm. The long-duration positive during the recovery time at low latitude was found to be related to O/N2 changes during the storm.

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