Ionospheric response to CIR-induced recurrent geomagnetic activity during the declining phase of solar cycle 23

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Abstract This paper presents an epoch analysis of global ionosphere responses to recurrent geomagnetic activity during 79 corotating interaction region (CIR) events from 2004 to 2009. The data used were GPS total electron content (TEC) data from the Madrigal Database at the Massachusetts Institute of Technology Haystack Observatory and the electron density (Ne) data obtained from CHAllenging Minisatellite Payload (CHAMP) observations. The results show that global ionospheric responses to CIR events have some common features. In high and middle latitudes, the total electron content (TEC) showed a significant positive response (increased electron densities) in the first epoch day. A negative TEC response occurred at high latitudes starting during local daytime and 10–18 h later for the CIR onset during local nighttime. Case studies indicate that the TEC and Ne positive response had a strong dependence on the southward component (Bz) of the interplanetary magnetic field and solar wind speed. This suggests that penetration electric fields that were associated with changes in solar winds might play a significant role in the positive ionospheric response to storms. During the recovery time of the CIR-produced geomagnetic activity, the TEC positive disturbance at low latitudes sometimes could last for 2–4 days, whereas at middle to high latitudes the disturbance lasted only for 1 day in most cases. A comparison of the ionospheric responses between the American, European and Asian sectors shows that the ionosphere response in the North American sector was stronger than that in the other two regions. The response of fF2 to the CIR events in middle to high latitudes showed a negative response for 2–3 days after the first epoch day. This is different from the response of TEC, which was mostly positive during the same period of time.

1. Introduction

During the declining phase of a solar cycle, coronal holes become another dominant solar phenomenon causing geomagnetic activity besides coronal mass ejections (CMEs). High-speed solar wind streams originating from solar coronal holes interact with slow-speed solar winds, producing corotating interaction regions (CIRs). These CIRs occur periodically and result in recurrent geomagnetic activity, which perturbs the ionosphere and thermosphere on a global scale as a result of energy and momentum deposition. Periodic perturbations in the upper atmosphere of 3, 7, 9, and 13.5 day periodicities have been observed during the declining phase of solar cycle 23 [e.g., Lei et al., 2008a, 2008b, 2008c; Thayer et al., 2008; Crowley et al., 2008; Pedatella et al., 2010; Tulasi Ram et al., 2010; Qian et al., 2010; Liu et al., 2010; Wang et al., 2011]. Lei et al. [2008a] showed a close connection between periodic oscillations of thermospheric mass density and reoccurring solar coronal holes over several solar rotations. Their subsequent studies indicated that 7 and 9 day periodic oscillations also exist in global mean ionospheric total electron content (TEC) and are associated with the periodic variations in the solar wind and geomagnetic activity [Lei et al., 2008b].

The dependence of the ionospheric response to the CIR-driven geomagnetic activity on altitude, local time, and latitude has also been investigated using different observations. Tulasi Ram et al. [2010] showed dayside 9 day oscillations of ionospheric electron densities from the observations of Constellation Observing System
for Meteorology, Ionosphere, and Climate (COSMIC) correlated these oscillations with the changes in the Kp index. They suggested that daytime electron density response to recurrent geomagnetic activity strongly depends on altitude. Pedatella et al. [2010] revealed the local time dependence of the 9-day periodicity of TEC and electron density at altitudes of 350–370 km from the CHAllenging Minisatellite Payload (CHAMP) satellite data. They showed that nighttime 9-day TEC oscillations occur mainly at high latitudes. On the other hand, the largest daytime TEC oscillations occur at middle latitudes. Liu et al. [2010] showed that the peaks of the 9-day periodic oscillations in the topside ion densities (~840 km) are mainly located at high (50°N–60°N) and low (15°N–35°N) latitudes, depending on local time and day of the year. Wang et al. [2011] investigated the day-to-day variability of ionospheric peak density (NmF2) from ground ionosonde data around the Whole Heliosphere Interval (WHI) in 2008 and found that the dominant periodicities in ionospheric daily variations are different at different latitudes.

There have been a large number of studies on the ionospheric responses to geomagnetic storms. In one of the earliest studies of ionospheric storms, Matsushita [1959] analyzed ionospheric NmF2 response to 51 strong (Ap > 50) and 58 weak (Ap < 50) storms using ionosonde data from 1946 to 1955. He showed that, on average, the ionosphere had a short positive response after the storm onset, followed by a prolonged negative response at high and middle latitudes, whereas at low latitudes the storm response was mostly positive. Afterward, many case and statistical studies were made to describe the morphology and mechanism of ionospheric storms in different seasons, latitudes, and local times. Most of the studies, however, were focused on strong to severe storm events [e.g., Prölss, 1980, 1993; Fuller-Rowell et al., 1994; Mendillo, 1971, Mendillo and Narvaez, 2010; Wang et al., 2010; Zhao et al., 2007, 2012; Lu et al., 2012]. Recently, researchers began to pay more attention to ionosphere variations associated with weak to moderate geomagnetic activity driven by coronal hole high-speed streams (HSS/CIR) [Wang et al., 2011; Burns et al., 2012; Solomon et al., 2012; Liu et al., 2012a; Verkhoglyadova et al., 2013] when more ionospheric data became available and HSS/CIR-associated geomagnetic activity occurred periodically and frequently during the declining phase of the last solar cycle. Burns et al. [2012] compared ionospheric peak electron density from COSMIC observations, neutral density from CHAMP, and NO cooling rate from the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite with the results from the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM) for three CIR events during the WHI in 2008. They showed that the ionosphere effect of CIR events can last for several days and attributed this long-lasting effect to the continued forcing by Alfvén wave-driven changes in the interplanetary magnetic field (IMF) and the continuation of high solar wind speed. Solomon et al. [2012] compared the neutral composition (neutral density and NO cooling rate) and ionospheric peak density with the simulation results from the TIE-GCM running under different solar wind and IMF conditions. They indicated that the north-south component (Bz) of IMF has the most significant effect on the response of thermosphere and ionosphere parameters to CIR events. Verkhoglyadova et al. [2013] studied the variability of ionospheric TEC during 2008–2009 and showed that the daily averaged vertical TEC in middle to low latitudes increased by 60% on average during HSS/CIR events.

CIR-driven geomagnetic storms can have significant effect on the thermosphere-ionosphere (T-I) system. A CME storm is often more intense and has stronger magnetospheric convection electric fields than a CIR storm does [Denton et al., 2006]. However, a CIR storm usually lasts much longer and continuously deposits energy and momentum into the T-I system [Tsurutani and Gonzalez, 1987]. The total amount of energy deposited into the T-I system of long-duration, less-intense CIR storms can thus be roughly the same as or even higher than that of a moderate CME storm over the entire period of the storm [Turner et al., 2009; Emery et al., 2009; Verkhoglyadova et al., 2011]. Chen et al. [2012] recently compared thermospheric density and CHAMP satellite orbit changes caused by CIR storms with those resulting from CME storms. They found that the total perturbations to thermospheric densities and CHAMP satellite orbit decay rates during CIR storms are usually larger than those during CME storms since the total perturbations are the accumulated effect of the total energy deposited into the T-I system that is determined by both the strength and the duration of the storms.

A full understanding of the behavior of the T-I system during HSS/CIR events is thus of significant importance for developing improved forecasting capabilities of the response of this system to changes in geophysical conditions. In particular, a better knowledge of the commonality of the ionospheric response to CIR-induced geomagnetic activity and its difference from that of CME-driven events can be of great value in furthering our
understanding of the behavior of the T-I system under the influence of individual or a combination of several external forcings. Liu et al. [2012b] did an epoch study of thermospheric mass density and $\Sigma O/N_2$ responses to CIR events and showed that these responses have solar cycle and seasonal dependences. However, there are still many open questions that need to be addressed. For instance, is the ionosphere response to recurrent CIRs similar? Are there any latitudinal, longitudinal, and local time differences in this response? There have been so far very few statistical investigations on the ionosphere variations during CIR events. In this paper, we will use ground-based GPS TEC measurements and electron densities from the CHAMP satellite to investigate the ionosphere response to CIR events during 2004–2009 and to illustrate the common features of this response and their causes by expanding the Burns et al. [2012] and Solomon et al. [2012] case studies to statistical epoch studies of tens of CIR events. The data sets used in this work are described in section 2. A detailed presentation of the results is given in section 3. Discussion of the results will be provided in section 4, and conclusions are presented in the final section.

2. Data Sets

The ground-based GPS TEC data and in situ electron density measurements from 2004 to 2009 were used to analyze global ionosphere variations during CIR events. The 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 GeoForschungsZentrum (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.

Ionosonde $f_{\text{F}}$, measurements were also used in our study. The data were from the US National Geophysical Data Center Web site (http://spidr.ngdc.noaa.gov/spidr/). Solar wind and interplanetary magnetic field parameters were obtained from the NASA’s Space Physics Data Facility OMNIWeb interface with a 5 min resolution. Geomagnetic activity indices $Kp$ and $Dst$ were obtained from the World Data Center in Japan. Thermospheric $O/N_2$ from the Global Ultraviolet Imager (GUVI) instrument onboard the TIMED satellite (http://guvi.jhuapl.edu/) was used to investigate thermospheric composition changes and their effects on the ionosphere during CIR events.

The CIR events studied in this work were selected from the CIR list of Jian et al. [2006] that was based on the Wind and ACE data during 1995–2004. The list was later updated to include CIRs up to 2009 (http://www.srl.caltech.edu/ACE/ASC/DATA/level3/index.html). There were a total of 202 CIR events during 2004–2009. However, not all of the CIR events were used in our study. There were many CIR events with solar wind and IMF conditions that were associated with or contaminated by the earlier CIR or CME event(s). This makes the ionospheric response very complicated and hard to isolate the physical processes that result in the response. Thus, we only used the CIR events with continuously quiet geomagnetic activity conditions ($Dst > -5$ nT) for 2 days before the events occurred. Based on this criterion, we selected 79 CIR events for our statistical study.

The background TEC is needed to get the magnitude of ionospheric disturbances (TEC differences) during the CIR events. It is difficult to determine the most appropriate method for deriving the background TEC. The period of the studied CIR event was always associated with other earlier or following CIR or CME event(s). If we selected a longer period (15 days, 27 days, etc.) of data to obtain the average TEC, the effect of these earlier or following events is most likely to be included. In fact, because we used the median TEC as the background, there was no significant difference when we used different time periods to obtain the average background TEC data. We compared 7 day, 10 day, and 15 day results for several cases. The significant storm time disturbance has little difference for those cases. Therefore, a 7 day running average was used as a baseline for TEC changes in this paper.

3. Results

3.1. Two Case Studies

Figure 1 shows $Dst$, $Kp$, solar wind speed, the north-south component (Bz) of the interplanetary magnetic field (IMF), GPS TEC absolute differences (blue lines), and relative differences (green lines) at different
latitudes of the North American, European, and Asian sectors on 9–16 October 2008. These differences were obtained by subtracting the background TEC, which was determined from the 7 day running median centered on the day of interest. The time resolution was 1 h for Dst, 3 h for the Kp index, 5 min for GPS TEC, and 5 min for the solar wind speed and interplanetary magnetic field, respectively. During this event, the solar wind speed began to increase on 11 October and reached a maximum value of 550 km/s on 12 October. The IMF Bz component started to oscillate with the increase of the solar wind speed, which were the Alfvén waves associated with the high-speed stream (HSS). This Alfvénic oscillation is a typical feature of CIR events [Burns et al., 2012]. The minimum of the southward Bz was \(-10\) nT, occurring on 11 October. The Dst index became negative with the oscillating Bz and reached a minimum of \(-60\) nT on 11 October and then began to recover. On 15 October, there was a small disturbance in the solar wind, with a Bz minimum of \(-5\) nT. Dst in the day also decreased to a minimum of \(-30\) nT and then recovered again. The maximum of Kp was 6 on 11 October. The changes in the Dst and Kp indices suggest that this CIR event induced a minor geomagnetic activity.

The American sector was in the local nighttime when Bz first reached the minimum of \(-10\) nT at 12:00 UT on 11 October. The TEC in the high latitudes (Figure 1a, 60°N) had a positive effect (increased TEC) with an absolute TEC change of about three TEC units (TECU = 10^{16} \text{el m}^{-2}) while the relative TEC change reached more than 150%. In the middle to low latitudes of the American sector (Figures 1d and 1g), TEC had a significant positive response in the daytime on 11 October when Bz was still negative and oscillating after it reached the minimum. The absolute TEC difference was up to 15 TECU with the relative TEC difference of above 100%. Another notable 10 TECU positive disturbance in the low latitudes (Figure 1g) occurred in the daytime when geomagnetic condition was quiet on 9 October. The anomalous TEC enhancements during geomagnetically quiet time have also been reported before [Liu et al., 2008; Zhao et al., 2008], and a full
understanding of the phenomenon is still lacking. Lower atmospheric waves and their coupling with the ionosphere are thought to be related to this anomalous enhancement in ionospheric electron content.

It was in the daytime in the European sector when Bz reached the minimum of $-10$ nT on 11 October. A daytime positive effect in the ionosphere occurred from high to middle latitudes (Figures 1b and 1e), whereas there was only a weak positive TEC disturbance seen in low latitudes (Figure 1h). A subsequent nighttime positive response occurred before the midnight (20:00–24:00 UT) on 11 October in the high latitudes (Figure 1b), near the midnight (22:00–2:00 UT) in the middle latitudes (Figure 1e), and after the midnight (0:00–4:00 UT) in the low latitudes (Figure 1h). The time delay of the TEC response from high to low latitudes was related to the traveling atmospheric disturbances (TAD). The absolute TEC differences were small because the nighttime background TEC was low, but the relative TEC differences were large. On 12 October, there was a weak negative storm effect in high latitudes, but in middle and low latitudes there were no significant ionospheric disturbances. On 14 and 15 October, TEC in high latitudes showed a positive disturbance, which was followed by a weak negative effect. In middle and low latitudes, there was a positive response associated with the southward Bz on 15 October.

In the Asian sector, the local time of the CIR storm onset was 15:00 LT. It was near the sunset time (18:00 LT) when Bz attained the minimum on 11 October. In high latitudes, the TEC experienced a positive response that was associated with the Bz minimum and then a negative response in the recovery period. In middle latitudes, there was only a relatively weak negative response observed. In low latitudes, TEC had a positive response during almost the entire day of 11 October. The significant daytime positive responses also occurred on 13, 15, and 16 October (Figure 1i). The mechanism for the long-duration increase of TEC is still not clear. The long-duration Alfvenic fluctuations in the solar wind may be one of the reasons for the TEC positive disturbance [Burns et al., 2012].

Figure 2 gives the CHAMP PLP electron density (Ne), $Dst$, and Bz variations during the same CIR event of October 2008. 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 vertical red line shows the start time of the
geomagnetic activity. For this case, the CHAMP observations were fixed at 14:00 solar local time. Figure 2
shows a local daytime positive storm effect occurring at middle to low latitudes after UT 08:00 of 11
October. Note that in the Southern Hemisphere, the Ne enhancement expanded to higher latitudes. The
middle- to low-latitude electron density enhancement in the UT afternoon seemed to be correlated to the
southward IMF Bz and its northward turning. The equatorial ionization anomaly north crest moved to
higher latitudes, which suggests that the positive response might be related to the penetration electric
field. In the following 4 days, Ne in the low-latitude region still showed a positive effect compared to that
before the storm.

Figure 3 illustrates CHAMP electron densities at approximately 400 km altitude with geomagnetic latitudes
of 50°N–60°N. The blue lines show the median value of CHAMP electron densities during the 8 days around
the CIR event at a fixed local time of 14:00. The red lines are the IMF Bz values. From Figure 3, we can see
clearly that the electron density enhancement happened in the American and European regions on 11
October. The magnitude of the Ne enhancement was about 2 times the median value of the quiet time. Note
that the positive response had a good correlation with the southward IMF Bz on 11 October.

Figure 4, in the same format as that in Figure 1, shows the variations of geomagnetic activity indices Dst and
Kp, solar wind speed and IMF Bz, and absolute and relative TEC differences in another CIR event occurring on
4 April 2005. Solar wind speed reached 700 km/s on 5 April. The minimum value of IMF Bz was about −10 nT.
Bz continued to be southward for about 10 h before it oscillated between southward and northward
directions. The Kp and Dst values show that this CIR event induced a major geomagnetic storm (Kp = 7).

In the American sector, a large TEC positive response occurred at all latitudes in the local daytime and
nighttime on 4 April when Bz reached a minimum of −10 nT. The daytime absolute TEC enhancement was
~8 TECU at high latitudes and ~15 TECU at middle to low latitudes. The relative TEC difference was 80%
at high latitudes, much larger than the 30% differences at middle to low latitudes. The nighttime TEC
enhancement was small in absolute terms, but high in relative terms, because of the low background TEC
at night. After the positive response on 4 April, there was a negative effect at high and middle latitudes in the
daytime of 5 and 6 April. However, TEC still showed a positive effect at low latitudes that lasted for 2 days. The
maximum of the absolute TEC difference at low latitudes was up to 20 TECU on 6 April, although the relative TEC
difference was only about 50%.
In the European sector, it was in the nighttime when Bz was southward and reached the minimum of $-10$ nT on 4 April. A nighttime positive effect occurred at all latitudes. The relative and absolute TEC differences were greater at low latitudes than at middle to high latitudes. TEC showed a daytime negative response right after the positive effect on 5 April.

In the Asian sector, at high latitudes, TEC showed a nighttime positive response followed by a negative response on 5 April. At middle latitudes, the daytime TEC had an enhancement associated with the southward Bz on 4 and 5 April when Bz was southward or oscillating. The nighttime relative TEC difference was strongly enhanced and reached 80% on 4 and 5 April. At low latitudes, there were no significant positive responses on 4 April when $D_s$ and Bz reached minima. It is notable that TEC had a daytime positive effect on 6 April, with a maximum reaching 25 TECU.

Figure 4 also shows TEC enhancements at low latitudes in the three sectors on 1 and 2 April when there were no obvious geomagnetic disturbances. The enhancement in the American sector reached 30 TECU. The times when these TEC enhancements occurred, however, were not the same. This day-to-day variability under geomagnetically quiet conditions could be related to the coupling between the ionosphere and the lower atmosphere [Liu et al., 2013].

The electron densities from CHAMP PLP observations (Figure 5) at 13:00 LT also had 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. Note that in the UT afternoon of 4 April, the positive storm effect in the Northern Hemisphere was very strong and expanded to much higher latitudes, whereas that in the Southern Hemisphere was relatively weak and was confined to low latitudes. On the other hand, for most of the UTs on 5 April, the positive storm effect was seen in the middle latitudes of the Southern Hemisphere, but the negative storm effect was predominant in the Northern Hemisphere. 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. This asymmetry, nonetheless, was not as strong as that in the first two UT days of the storm. A large electron density enhancement was seen on 4 April at 50°N–60°N geomagnetic latitudes in the North American region at local noon (12:00–14:00 LT, Figure 6). This positive storm response corresponded well to the solar wind condition when IMF Bz was southward. The magnitude of the Ne enhancement was about a factor of 3.
larger than the quiet time electron density in the same region. In other regions, electron densities at local noon on 4 April were not enhanced since IMF Bz was northward. The electron densities in the East Asian region also had a positive response that was associated with the southward Bz at a later UT on 5 April. At other longitudes of the Northern Hemisphere at the same latitude, negative storm effects occurred.

From these two case studies, we can see that there were commonalities in the ionospheric response to CIR storms. For instance, positive storm effects occurred in both cases, and the sector at local daytime when storm started appeared to have a stronger positive response. There are certainly differences in the ionospheric response to each storm. Negative storm effects were more evident in the strong geomagnetic activity event of April 2005 than during the weak one of October 2008. During the declining phase of solar cycle 23, CIR events occurred frequently and periodically. Most of these events were minor ($Kp = 4–6$); thus, they corresponded more to the first storm case. In the next two sections we carry out a statistical analysis of the ionospheric TEC and electron density changes using ground-based GPS observations and satellite in situ measurements during CIR events to investigate the commonality of the ionospheric response to CIR storms, and the dependence of this response on longitude and local time.

3.2. An Epoch Study of 79 CIR Events

According to the selection criteria of CIR events outlined in section 2, we only choose the CIR event with continuously quiet geomagnetic activity conditions ($Dst > -5$ nT) before the CIR events. Finally, 79 events were determined to meet the criteria used in our statistical study. The start time of the CIR events was set as either the time of the abrupt increase of $Dst$ for the geomagnetic storms with an evident storm commencement (SC) or the time when $Dst$ was zero and began to decrease for storms without an evident SC. Here we did not use the change time of stream interface of the solar wind, which was used as the

Figure 5. Same as Figure 2 but for 2–8 April 2005. The local time of observations was 13:00 LT.
beginning time of a CIR event in the list of Jian et al. [2006], because the onset of geomagnetic activity always has a time delay relative to the stream interface.

The vertical red dashed lines in Figures 2 and 5 show the CIR start time determined from the above criteria. Superposed epoch analyses of solar wind, the north-south component of interplanetary magnetic field (Bz), Dst, AE, and ap indices are presented in Figure 7. The vertical red dotted line indicates the epoch zero time (CIR storm start time). The thick red lines are the median values of each parameter. The blue error bars give the standard deviations from the median values. Figure 7 shows that during CIR events the solar wind speed began to increase at the epoch zero time and reached 500 km/s on the second day. The high-speed solar wind continued for about 6 days. In the first epoch day, IMF Bz had a significant southward component with an amplitude of 5 nT. The median value and the standard deviation of Bz then decreased with time and returned to their prestorm values in the second epoch day. The standard deviation after the third epoch day indicated that Bz still had small oscillations between the southward and northward directions. Dst increased at the epoch 0 h; it then decreased toward a minimum value that happened about 12 h after the epoch zero hour. The minimum of the Dst median was about −25 nT with a 1 − σ spread of ~25 nT. The AE index began to increase and reached an averaged maximum of 300 nT on the first day. The median of the ap index (Figure 7) after the CIR onset was about 20 nT. Dst, AE, and ap indices suggest that most of the geomagnetic activity induced by CIRs was minor to moderate. However, AE and ap did not return to their quiet time values for 6 days, indicating that there were continuous energy inputs from the solar wind/magnetosphere to the upper atmosphere and, consequently, the thermosphere and ionosphere system was disturbed for a considerably long period of time (several days), as compared to CME storms that last typically for 1 or 2 days [Tsurutani and Gonzalez, 1987].

Since TEC maps from the Madrigal database are derived from GPS receivers that are located on land, they do not have global coverage. Thus, our analysis focused primarily on several regions where there were sufficient observations. These regions included the high to low latitudes of North America, the low latitudes of South America, the high to middle latitudes of Europe, the middle to low latitudes of Asia, and the Australia and New Zealand region.

First, as an example, we show in Figures 8–10 the TEC differences at three GPS stations in the American sector with the storm starting times near local noon (10:00–14:00 LT). Seven days are shown for each storm. This includes 2 days prior to the CIR storm onset and 5 days after the onset. The red area in each figure indicates that TEC has a positive response relative to the 7 day running median value, whereas the blue area represents a negative perturbation. Figure 8 gives the absolute daytime TEC differences (subtracting from the 7 day
running median) at a geomagnetically high middle-latitude station in the North American sector for 23 CIR events between 2004 and 2009. For most of the CIR events there were a significant positive perturbation (increased TEC) after the CIR started. In some CIR events in 2004 and 2005, the absolute TEC difference reached 10 TECU or even larger. After July of 2008, the absolute TEC changes became very small. However, the relative changes of TEC (not shown) were 30%–50%, more significant than the absolute TEC disturbance. Compared to the positive perturbation, negative perturbations (TEC depletions) were relatively weak but can be seen during the second epoch day in summer days, such as on 28 May 2004, 28 June 2004, and 27 July 2006. The ionospheric loss rates in the summer are larger than those in other seasons [Rishbeth, 1998]. A geomagnetic storm can further increase the loss rates and thus enhance the negative response [Prölss, 1995; Mendillo, 2006]. The slight negative response also occurred for some events with more intense geomagnetic activity, such as the one on 9 November 2006 (minimum Dst was about ~50 nT).

At the middle latitudes of the North American sector (Figure 9), large positive and relatively weak negative TEC responses were also observed. However, the storm time response in this latitudinal region was, in general, stronger, compared to the high middle-latitude case in Figure 8.

Note that at middle latitudes, for most of the storms, ionospheric variations before the storms were usually much smaller than those during the storms. However, this was not the case for low-latitude stations (Figure 10). Positive and large negative TEC perturbations were seen preceding the storms for almost all the CIR events. There was little evidence of geomagnetic activity forcing or changes in solar EUV inputs, so by elimination this was most likely related to the day-to-day variability of the ionosphere that could be the result of the large-scale waves from the lower atmosphere [e.g., Forbes et al., 2000; Rishbeth and Mendillo, 2001; Wang et al., 2011]. Lower atmospheric waves can propagate upward to the lower thermospheric region and tend to affect neutral wind dynamo and ionospheric densities in the low-latitude regions. The magnitude of the day-to-day variability of the ionospheric TEC at low latitudes is comparable to the storm-induced

**Figure 7.** Superposed epoch results of solar wind speed, IMF Bz, Dst, AE, and ap indices for the 79 CIR events.
changes. This day-to-day variability suggests that the TEC at low latitudes is not only determined by the solar wind/IMF conditions and their coupling with the magnetosphere-ionosphere-thermosphere system but is also closely related to the lower atmosphere's variability [Rishbeth, 1975; Liu et al., 2013]. Nevertheless, we do see that low-latitude TEC tended to have positive responses during most of the CIR events. Furthermore, in about one third of the events, the low-latitude ionospheric TEC had a negative response during the daytime of the first storm day, such as in 4 April 2008 and 18 October 2007. On the other hand, no such negative perturbations were seen at middle latitudes (Figures 8 and 9). Thus, those negative perturbations at low latitudes appear to be the continuation of the perturbations that had already occurred in the quiet time, and they were most likely the result of lower atmospheric wave activity.

To determine the common features of the TEC response to CIR events, a superposed epoch study has been carried out in several longitudinal regions. Figure 11 presents a superposed epoch study of the absolute TEC differences during the daytime at high latitudes in the North American (Figures 11a and 11b), European (Figures 11c and 11d), and Australian regions (Figures 11e and 11f), respectively. Figures 11a, 11c, and 11e show the results for CIR events starting during local nighttime (LT = 22–02), whereas Figures 11b, 11d, and 11f show the results for CIRs with the onset at local daytime (LT = 10–14). The red lines indicate the epoch zero time of the CIR events. In each panel, the grey bar is the maximum of TEC absolute differences during the daytime. Here, the period 9:00–17:00 LT was determined as the daytime according to different CIR onset times. For instance, when CIR onset time was between 10 and 11 LT, the ~1–7 epoch hours after epoch hour zero was treated as local daytime. When the CIR started during 11–12 LT, 0–6 epoch hours represented the daytime, etc. When CIR started during 22–23 LT, epoch hours from 11 to 19 h after epoch 0 were the daytime, etc. The median TEC difference between storm days and the 7 day running median was estimated every 30 min. Then the maximum of the median was determined. The blue bars indicate the standard deviations from the median TEC difference. The number of the CIR events starting during the period is also

Figure 8. TEC differences at (70°W, magnetic latitude (MLAT): 52°N) in 23 CIR events. The red vertical line indicates the CIR onset time. The red patch means a positive effect, while the blue area means a negative effect.
shown at the top of each panel. Figure 12 is the result for The TEC percentage difference in the same regions as those in Figure 11. Figures 11 and 12 show that TEC positive responses (1–4 TECU) happened at high latitudes when CIR-induced geomagnetic activity started during local daytime (10:00–14:00 LT). The magnitude of the TEC enhancement in the European sector (about 10%) was smaller than that in the American (about 35%) and Australian regions (about 30%). The time delay of the maximum TEC difference was about 2–6 h from the storm onset or the zero epoch time. The positive response in these high-latitude regions occurred only on the first day of the storm event. In the second epoch day, it appeared that TEC had a negative response, most evidently in the American sector, with TEC percentage difference being −15%. The negative TEC perturbation in the European sector was very small. In the Australian region, no negative effect occurred.

When a CIR started at night, there were also positive effects in the three sectors (Figures 11a, 11c, 11e, 12a, 12c, and 12e). TEC increased in the subsequent daytime, with the maximum of the TEC difference occurring about 10–18 h after the storm onset. The magnitude of the TEC difference in the American and Australian sectors was smaller than that when CIR started at the daytime in the same regions. In the European sector, the TEC perturbation was smaller than that in the other two regions. In the American sector, there was a slight indication of a negative effect from the second to the fourth epoch day. The statistical spread in the first epoch day was large, suggesting significant variability in the ionospheric response regardless of it occurring during the day or the night. Comparing this figure with Figure 8, we can see that the superposed plots smear out the large TEC variations during single CIR events. The magnitude of the TEC perturbation in the epoch analysis may not completely represent the strength of a single event’s perturbation. However, it can reflect the commonality of the ionospheric response to CIR-induced geomagnetic activity.

The TEC absolute and percentage differences at middle latitudes are shown in Figures 13 and 14, respectively. The TEC observations in North America (Figures 13a, 13b, 14a, and 14b), Europe (Figures 13c, 13d, 14c, and 14d), Asia (Figures 13e, 13f, 14e, and 14f), and Australia (Figures 13g, 13h, 14g, and 14h) are plotted to elucidate the longitudinal effects. There were significant TEC positive responses in the four regions regardless of the occurrence time of the CIRs. In the American and Australian regions, the TEC positive response for CIRs starting in the nighttime was smaller than that for CIRs starting in the daytime, whereas in the European sector, TEC enhancements were larger for nighttime CIRs than for daytime CIRs. The statistical spread was also large, indicating significant variability in the ionospheric response to CIRs.
and Asian sectors, the magnitude of the positive effect was very close for the CIRs starting in both the daytime and the nighttime. It is also interesting to note that the positive TEC response also occurred in the daytime of the second epoch day in the American and Asian sectors, although the magnitude was smaller than that in the first epoch day. In the Australian region, there was a positive response in the fourth epoch day, which was not seen in other sectors. There was no noticeable negative response in middle latitudes. The TEC enhancement in the American and Australian sectors (Figures 13a, 13b, 14a, and 14b) was about 4–5 TECU (30%), larger than those in the other sectors for CIRs starting at local daytime and night.

Figures 15 and 16 present the results of the TEC absolute and percentage differences at magnetically low latitudes. Because of the lack of data in Europe, we just show the results from Asia, South America, and North America. There were significant TEC positive responses in these three regions regardless of the CIR onset time. The magnitude of the TEC disturbance was about 1–3 TECU (10%–20%). For the following days, the TEC differences generally showed positive responses and lasted 2–4 days. The statistical spread for the TEC percentage difference (Figure 16) was large after the epoch zero hour, suggesting that TEC had a major response to geomagnetic activity.

The above epoch study suggests that the TEC response to CIR-induced geomagnetic activity is mainly a positive one in the first epoch day in the middle- and high-latitude regions. The negative response is only evident in the high latitudes of the American sector. We have also carried out epoch studies at higher latitudes (geomagnetic latitude: 60°N–70°N) and at another middle-latitude zone (40°N–50°N). These results also indicate a significant daytime enhancement in TEC in the first epoch daytime and a relatively weak negative response in the following epoch day at high latitudes. The positive TEC response with roughly the same magnitude lasts for about 2–4 days after the onset of the storm at magnetically low latitudes. It thus appears that the mechanisms for the ionospheric response may be different between low latitudes and middle to high latitudes.

Figure 10. Same as Figure 8 but for TEC differences at (77°W, MLAT: 12°N).

and Asian sectors, the magnitude of the positive effect was very close for the CIRs starting in both the daytime and the nighttime. It is also interesting to note that the positive TEC response also occurred in the daytime of the second epoch day in the American and Asian sectors, although the magnitude was smaller than that in the first epoch day. In the Australian region, there was a positive response in the fourth epoch day, which was not seen in other sectors. There was no noticeable negative response in middle latitudes. The TEC enhancement in the American and Australian sectors (Figures 13a, 13b, 14a, and 14b) was about 4–5 TECU (30%), larger than those in the other sectors for CIRs starting at local daytime and night.
3.3. A Statistical Analysis of CHAMP Electron Density Changes

CHAMP-observed electron densities were divided into three longitudinal regions (the American sector: 50°W–180°W, the European sector: 30°W–50°E, and the Asian sector: 90°E–180°E). Since the CHAMP satellite orbited the earth every 96 min, there were only two data points at a particular fixed latitude every hour and a half (we will treat this as every 2 h for ease of analysis). The electron density in each longitudinal sector was therefore averaged every 2 h for each magnetic latitude bin of 2°. Figures 17 and 18 show electron density percentage differences between the storm and quiet time in different latitudinal and longitudinal sectors for the daytime (08:00–16:00 LT) and the nighttime (20:00–04:00 LT), respectively. The CHAMP satellite orbited the Earth at almost a constant local time due to its high inclination orbit. We used 7 days of data (centered on the day of interest), with local time differences smaller than 1 h and latitudinal differences smaller than 2°, to calculate the background median value of the electron density.

The x axis in Figure 17 is the percentage change ((storm-quiet)/quiet) of electron densities observed by CHAMP at the three longitudes. The y axis is the occurrence probability for different $\Delta N_e$ bins. Figure 17 shows that the occurrence probability of $\Delta N_e$ centered at 40% (representing $\Delta N_e$ 20%–60%) at high to middle latitudes increases by about a factor of 2 compared to the occurrence probability before the CIR events. The positive response continued for 2–3 days. In addition, the probability of occurrence for $\Delta N_e$ centered at 80% increased obviously after CIR events, especially at middle latitudes (30°N–40°N). At low latitudes (magnetic latitude (MLAT): 10°N–20°N), the day-to-day variability of the electron density was larger than that at middle and high latitudes. However, the occurrence of positive effects was clear, with $N_e$ percentage increased larger than 40%. The positive effect lasted 4 days. Near the magnetic equator (fifth row of Figure 17), the positive effect was significant with $\Delta N_e$ of about 20–60% (centered at 40%) 1–2 days after the CIR events. But there was no Ne enhancement near or larger than 80%. During the nighttime (Figure 18),

Figure 11. Superposed epoch results of absolute TEC differences from middle to high latitudes at different longitudes when geomagnetic disturbance begins at local (a, c, e) nighttime (22:00–2:00 LT) and (b, d, f) daytime (10:00–14:00 LT), respectively. Figures 11a and 11b are for the North American sector, Figures 11c and 11d for the European sector, and Figures 11e and 11f for the Australian sector. The error bars (thick lines) are the standard deviations from the median of TEC differences. The grey bars show the maximum of the daytime TEC difference. The number on the top of each panel indicates the number of CIR events used in the statistical analysis for each longitude region. The vertical thin dot lines indicate the start time of CIR events.
Ne percentage difference was much larger than that in the daytime because of the lower electron density in the nightside ionosphere. A striking feature in Figure 18 was that, at middle to high latitudes (MLAT: 50° N–60° N), the occurrence probability of $\Delta$Ne centered at $-40\%$ increased greatly after the CIR onset day, which means a negative response occurred. This negative storm effect continued for 3 days. In other latitudes, there was no significant negative effect observed. Another noticeable feature during the nighttime was that there was an enhancement for $\Delta$Ne larger than 80% in the magnetic equator region after the CIR onset. The positive effect at the magnetic equator is the result of the combined effect of $E \times B$ drift, ambipolar diffusion, and neutral winds [Lei et al., 2008d]. At night, the enhanced equatorward thermospheric winds can play a dominant role in the electron density enhancement. The neutral wind in the equatorial region is downward, which increases atomic oxygen concentration and decreases the loss rate of plasma in the upper ionosphere [Rishbeth, 1972]. Also, the enhancement of the equatorward wind in the equatorial region can push the ionosphere to higher altitudes and decrease the electron density loss.

The main results of the statistical study of electron density differences are mostly consistent with the TEC statistical results. However, the positive storm effect of Ne from CHAMP could last for 2–3 days at middle and high latitudes, which is not consistent with the result from the TEC superposed epoch study. This may be due to sampling of the electron density above the $F_2$ peak but closer to the peak, as discussed in section 4.1. In addition, the nighttime ionospheric Ne had an obvious negative response in the subauroral region which was not shown in the response of TEC.

4. Discussion

4.1. The Ionosphere Response to CIR Events at Middle to High Latitudes

Although geomagnetic activity induced by CIR events is mostly weak to moderate, it has a significant effect on ionospheric electron densities [e.g., Wang et al., 2011; Burns et al., 2012; Solomon et al., 2012]. In our case
studies and statistical analysis, we also found that TEC and CHAMP electron densities have significant responses to CIR-induced geomagnetic activity.

In an earlier statistical analysis of the ionospheric response to weak storms [Matsushita, 1959], NmF2 appeared to show a short positive response, followed by 2–3 days negative response at high and middle latitudes. The Matsushita study, however, did not separate storms based on their solar wind source; thus, his result was probably a mix of both CME and CIR effects. For the declining phase of solar cycle 23, the previous case studies of the WHI [Burns et al., 2012] indicated that NmF2 had negative responses at high latitudes and positive response at middle to low latitudes. In our epoch studies of the TEC changes during 79 CIR events, the most evident TEC response at middle to high latitudes was a significant positive perturbation in the daytime after a storm occurred. There was a weak negative response in the second day but only in the high latitudes of the American sector. The statistical result of the CHAMP electron densities at about 400 km in Figure 18 suggests that the negative response in electron densities only occurred in the nighttime of the high latitudes and in subauroral regions. The negative responses of ionospheric electron densities to geomagnetic activity are associated mostly with storm time thermosphere composition changes [Prölss et al., 1995]. During geomagnetic storms, the thermosphere expands because of the large Joule heating around the auroral region and, consequently, upwelling of molecular rich air (N2, O2) to higher altitudes at high latitudes. This molecular rich air is then transported toward lower latitudes by the neutral wind circulation which itself is enhanced during the storm. Thus, a decrease of O/N2 occurs in the ionospheric F region, which leads to stronger molecular recombination and a decrease in ionospheric electron densities.

It is fortunate that during the declining phase of solar cycle 23 observations of O/N2 were available from the Global Ultraviolet Imager (GUVI) instrument onboard the TIMED satellite. The inclination of the TIMED satellite is 74.1°. It takes about 2 months to rotate through 12 h local time. Figure 19 shows a superposed epoch

Figure 13. Same as Figure 11 but for TEC absolute difference at middle latitudes; (a, b) for the North American sector, (c, d) for the European sector, (e, f) for the Asian sector, and (g, h) for the Australian sector.
analysis of GUVI O/N₂ during the CIR events studied in this paper. The red vertical lines give the zero epoch time for storm onset. The decrease of O/N₂ ratio was obvious at high and subauroral latitudes in the three longitude sectors. This suggests that at high latitudes an ionosphere chemical process, molecular recombination, played an important role in the response of the ionosphere during CIR-induced, geomagnetically active periods. In the middle- and low-latitude regions, no obvious O/N₂ decrease was observed, suggesting that a chemical process was not a major driver for ionospheric changes during CIR storms in these regions. This is most likely due to the fact that CIR-induced storms are usually weak; thus, daytime O/N₂ decreases are mostly confined to high latitudes. Thus, GUVI O/N₂ observations indicate that, at high latitudes, the F region electron density should decrease. Here we check the ionosonde measurements to examine the variation of ionospheric F₂ layer critical frequency (\(f_{0}F_2\)), which is an expression of NmF₂ in the form of radio wave frequency, during the CIR events. Figure 20 shows an epoch study of the daytime \(f_{0}F_2\) difference from 7 day running median for several ionosonde stations. In the middle- to high-latitude region, \(f_{0}F_2\) did not show obvious changes on the first epoch day, which is very different from the TEC responses (Figure 8) that had a predominantly positive response on the first epoch day. But \(f_{0}F_2\) decreased on the second and third epoch days, indicating a weak negative response of daytime high-latitude ionospheric F region densities to CIR events. This is consistent with the result of Matsushita [1959] but very different from the TEC responses (Figure 8) that were dominantly positive during these events. There was a TEC negative response in the second day but only in the high latitudes of the American sector, which might be reasonable and related to O/N₂ changes. But O/N₂ decreases occurred for at least 4 days in all regions, so the TEC response was evidently not fully consistent with the O/N₂ changes.

A possible explanation for the different behavior of TEC from ionospheric NmF₂ during CIR events is that TEC is electron column densities from the bottom of the ionosphere integrated to the GPS satellites inside the plasmasphere. Thus, TEC is determined not only by NmF₂ but also by the shape of the topside ionosphere.
The statistical analyses of TEC, CHAMP Ne, and \( f_{\text{F2}} \) data suggest that ionospheric electron density profiles at middle to high latitudes during CIR-driven geomagnetic activity periods may have changed in such a way that topside electron densities increase, whereas electron densities at the peak and in the lower ionosphere decrease. The decrease of electron densities in the lower ionosphere and at the peak is caused by the depletion of O/N\(_2\). On the other hand, the enhancement of electron densities in the topside ionosphere is possibly due to the increase of scale height resulting from the enhanced plasma temperatures during the storms [Prölls, 1995; Sojka et al., 2009; Tulasi Ram et al., 2010]. Therefore, TEC shows an increase or no change.

Mendillo and Narvaez [2009] analyzed positive and negative responses of \( f_{\text{F2}} \) to 206 geomagnetic storms at two subauroral stations: Hobart (147.3°E, 42.9°S, MLAT: 54.05°S) and Wallops island (75.5°W, 37.8°N, MLAT: 50.47°N). They showed that the magnitude of the negative response of ionospheric electron densities increases as the strength of the geomagnetic storm increases. This is understandable because the global changes of thermospheric O/N\(_2\) in weak geomagnetic storms are most likely smaller than those in strong geomagnetic storms. CIR-induced geomagnetic storms are predominantly weak to moderate (Figure 7); hence, the negative response in electron densities is usually small and confined to relatively higher latitudes. For the CME-induced storms, the geomagnetic disturbance is often much stronger than that induced by CIR events. Thus, negative TEC responses are frequently observed, as shown in Wang et al. [2010]. Further studies on comparing the similarities and differences between the ionospheric response to CME-induced storms and that to CIR-induced geomagnetic activity will be carried out in the future work.

4.2. Positive Response at Middle to Low Latitudes

The TEC responses are positive in the first epoch day at middle latitudes in Figures 13 and 14. At low latitudes, the positive disturbance occurs in the 1–4 epoch days, as shown in Figures 13–16. Four mechanisms have been proposed to explain the ionospheric positive response [Prölls, 1995, 2006; Mendillo, 2006; Burns et al., 2007; Wang et al., 2010; Verkhoglyadova et al., 2011]: penetration electric fields, equatorward neutral winds, neutral composition changes by large-scale neutral wind circulation, and traveling atmospheric disturbances.
(TADs). These involve changes of ionospheric electron densities by chemical and transport processes. To determine how each of these mechanisms contribute to the observed ionospheric changes, we need to have knowledge of the storm-produced variations of neutral composition, winds, and electric fields that ultimately govern the ionospheric distribution at a particular time. Lei et al. [2008d] analyzed in detail the distribution of the different processes during the initial phase of the December 2006 storm and showed that the penetration electric fields are the primary cause of the observed daytime positive TEC enhancement at middle to low latitudes. From the case studies shown in Figures 2 and 5, we can see that CHAMP electron density increased rapidly from middle to low latitudes when Bz was southward, which suggests that the most likely cause of TEC increase at low and middle latitudes was the penetration of the high-latitude electric field to middle and low latitudes. During a CIR event, IMF Bz oscillates between southward and northward as a result of the action of Alfven waves [Burns et al., 2012]. This Bz oscillation and high-speed solar wind can last for several days, which can produce not only time-varying energy inputs to the thermosphere and ionosphere but also continuous temporal variation of high-latitude field-aligned currents and convection pattern that tends to produce penetration electric fields. Wang et al. [2008] showed that the temporal variation in the IMF Bz component can result in the occurrence of penetration electric fields. Huang et al. [2005] gave several cases of enhanced ionospheric electric fields at middle to low latitudes and suggested that the penetration of the high-latitude electric field can last for a long period of time (10 h) during the interval of varying southward IMF. It is worth noting here, however, for the low-latitude daytime positive TEC effect that occurred continuously for 2–4 days during CIR events as shown in Figure 15, other processes might also contribute to the effect in addition to penetration electric fields.

The importance of the various processes needs to be considered further here. First, let us examine whether thermospheric composition plays a significant role in the ionospheric positive response at low latitudes. The O/N2 epoch study (Figure 19) clearly shows that there was no noticeable enhancement of O/N2 in middle and low latitudes during CIR events. Thus, we can reasonably conclude that, in general, there is no significant thermospheric composition change at low latitudes that might have a large effect on the ionospheric density variations that could last for 2–4 days.

Changes in thermospheric neutral wind circulation may also contribute to the storm time change in the ionosphere. Heating around the auroral oval can enhance equatorward neutral winds. Furthermore, strong
auroral precipitation at storm time results in enhanced ionospheric electron densities and hence ionospheric conductivity. This, in turn, couples with the enhanced storm time high-latitude convection pattern to cause stronger ion drag on the neutrals and a strong neutral wind circulation. The equatorward winds can drive the plasma up along the magnetic field lines into higher altitude regions where molecular recombination is slow, which leads to an electron densities enhancement [Rishbeth, 1975]. Pedatella et al. [2009] analyzed a long-duration positive storm effect during the 15 December 2006 CME storm and pointed out that the enhanced equatorward neutral winds may be an important driver for maintaining the positive storm effect for more than 12 h. However, in the case of CIR storms, neutral wind changes may not be great, as suggested by the lack of thermospheric composition changes in GUVI O/N2 data at middle and low latitudes. Thus, in this study we cannot fully assess to what extent neutral winds contribute to the 2–4 days duration of the positive TEC effects at low latitudes.

4.3. Dependence on the Onset Time of Geomagnetic Activity

The onset time of a geomagnetic activity also has different effects at different latitudes. When CIR starts during the local daytime, TEC has a positive response at all latitudes right after the event onset, as clearly shown by the epoch analysis in this study. Previous studies also showed that the ionospheric positive storms are generally associated with magnetic activity beginning in the local daytime sector [Prölls, 1995 and references therein]. However, in our study, when CIR-induced geomagnetic storms start at night, as shown in Figures 11a, 11c, 11e, 12a, 12c, 12e, 13a, 13c, 13e, 13g, 14a, 14c, 14e, 14g, 15a, 15c, 15e, 16a, 16c, and 16e, the positive TEC response occurred in the subsequent daytime. This means that possibly a different mechanism produces the positive effect for the storms that occur at local daytime, compared with those that occur at local nighttime, as discussed in sections 4.1 and 4.2.
In addition, penetration electric fields at middle to low latitudes increase the dayside ionosphere as daytime penetration electric fields are eastward. During nighttime, these fields are westward and result in a downward motion of the ionosphere, which may decrease TEC because of the fast molecular recombination in the lower ionosphere. However, the nighttime electron density is very small because of the absence of photoionization. It is difficult to distinguish storm time effects from day-to-day variability.

4.4. The Longitudinal Effect

From Figures 11 and 12, we can see that at high latitudes the ionospheric responses to geomagnetic activity in the daytime in the American sector and in the Australia region were larger than the response in the European sector. In middle latitudes, as shown in Figures 13 and 14, the daytime absolute TEC differences in the North American and Australian sectors were larger than those in the European and Asian sectors. This longitude pattern is related to the ~12° tilt of the geomagnetic field axis [Mendillo and Narvaez, 2009]. The dipole tilt results in higher magnetic latitudes for the same geographic latitudes in the northern ~70°W longitudinal sector and in the southern ~110°E longitude sector. Solar EUV ionization is ordered by the solar zenith angle, and therefore it is the same at a given geographic latitude for all longitudes for a particular local time. On the other hand, the ionospheric F region plasma is significantly affected by the magnetic field. Thus, a significant part of the ionospheric F region responses during a geomagnetic activity are controlled by the physical processes that are ordered by geomagnetic latitude. This introduces a longitudinal difference into the response of the ionospheric F region to geomagnetic storms, as the North American sector and the Australian sector are the two regions that have the largest differences between geographic and geomagnetic latitudes.

Figure 18. The Ne percentage differences at local nighttime (20:00–4:00 LT) at different latitudes.
5. Conclusion

In this paper we have employed ground-based GPS TEC observations and CHAMP electron density measurements at about 400 km to obtain statistical patterns of the ionosphere response to 79 CIR events during 2004–2009 and to investigate the dependence of these patterns on latitude, longitude, local time, and storm onset time. Our main conclusions are as follows:

1. In the high and middle latitudes, the TEC data showed a positive effect in the first epoch day. The negative response in the following days was only evident in the high latitudes of the American sector. The Ne from CHAMP showed a positive response in the daytime and a negative response in the subauroral region. The negative response was related to the thermospheric composition (O/N₂) changes. TEC and Ne case studies showed that the positive responses were well related with the southward IMF Bz. This suggested that the ionospheric positive response could be caused by the penetration electric fields associated with the variations of solar winds.

2. In all latitudes, the TEC positive effect occurred in the following daytime for CIRs starting during local nighttime, with the maximum of the TEC difference occurring about 10–18 h after the storm onset. On the other hand, the maximum of the positive response occurred 2–6 h after CIRs onset during local daytime.

3. The TEC positive disturbance at low latitudes could last for 2–4 days, whereas that at middle to high latitudes occurred only for 1 day in most cases.

4. The daytime ionosphere response at middle to high latitudes in the American sector was relatively stronger than those in the European and Asian sectors.

5. The daytime TEC response to CIR storms appeared to be different from that of ionospheric F₂ peak densities at high and middle latitudes. NmF₂ had a long period of negative response for about 2–3 days, whereas the TEC response was mostly positive.

Figure 19. Superposed epoch of O/N₂ observed by GUVI in different longitudes and latitudes. The vertical red lines indicate the CIR start time. The thick solid red lines are the median value. The error bar represents the standard deviations from the median.
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Figure 20. The superposed epoch analysis of f0F2 in middle to high latitudes. The vertical thin lines indicate the CIR start time. The grey bar shows the maximum of the f0F2 disturbance during the daytime. The error bar represents the standard deviations from the median.
