Large-scale variations of the low-latitude ionosphere during the October–November 2003 superstorm: Observational results

C. H. Lin,1,2 A. D. Richmond,1 J. Y. Liu,2 H. C. Yeh,2 L. J. Paxton,3 G. Lu,1 H. F. Tsai,4 and S.-Y. Su2

Received 11 November 2004; revised 26 April 2005; accepted 23 May 2005; published 3 September 2005.

[1] The GPS-derived total electron content (TEC), ion drift measurements from the ROCSAT-1 spacecraft at around 600 km altitude, and far-ultraviolet airglow measured by the Global Ultraviolet Imager (GUVI) carried on board the NASA TIMED satellite are utilized for studying large disturbances of the low-latitude ionosphere during the October–November 2003 superstorm period. Two chains of GPS receivers, one in the American sector (~70°W) and the other in the Asian/Australian sector (~120°E), are used to simultaneously observe the daytime equatorial ionization anomaly (EIA) during the entire storm period. It is found from the GPS-TEC measurements that the EIA expanded to very high latitudes with large increases of TEC right after the storm started. The large expansion of the EIA was associated with strong upward \( E \times B \) drifts measured from the Ionospheric Plasma and Electrodynamics Instrument (IPEI) on board the ROCSAT-1, providing evidence of a penetration electric field and a strong plasma fountain effect. Suppression of the EIA was observed during the storm recovery, associated with downward \( E \times B \) drifts that were observed by the ROCSAT-1. Significant negative storm effects in the southern hemisphere were also observed in the GPS-TEC during the first day of the recovery phase. The areas of negative storm effects are in good agreement with reductions in the \([O]/[N_2]\) density ratio inferred from the ratio of OI (135.6 nm) to LBH emissions measured from GUVI. An enhancement of the EIA was observed on the day, 1 November, that the storm was about to fully recover.


1. Introduction

[2] Magnetic storms are capable of creating large perturbations in electric fields, neutral winds, and the global circulation of the thermosphere. During magnetic storms, magnetospheric energy and momentum are deposited in the ionosphere/thermosphere through auroral particle precipitation and ionospheric plasma convection driven by electric fields mapped from the magnetosphere. Intense auroral particle precipitation heats the thermosphere, ionizes the neutral gas, and increases the conductivity of the ionosphere. The increased conductivity combined with the magnetospheric electric field produces Joule heating in the ionosphere/thermosphere, which is the major energy source during storms [e.g., Lu et al., 1995]. Heating of the thermosphere drives equatorward wind surges and causes an upwelling at high latitudes, which carries heavier neutrals upward and increases the mean molecular mass [Rishbeth et al., 1987; Proß, 1987; Burns et al., 1991; Fuller-Rowell et al., 1994]. The region of increased molecular mass, often termed as composition perturbation zone, can be transported equatorward by the storm-time and background neutral wind fields [Proß, 1995; Fuller-Rowell et al., 1998].

[3] During magnetic storms, ionospheric electric field disturbances are observed at middle and low latitudes on different timescales. They often affect the plasma distribution of the ionosphere significantly. They result from both prompt penetration of time-varying magnetospheric fields from high latitudes to low latitudes [e.g., Nishida, 1968; Vasyl’yanas, 1970, 1972; Jaggi and Wolf, 1973; Fejer et al., 1979, 1990; Gonzales et al., 1979; Kelley et al., 1979; Spiro et al., 1988; Peymirat and Fontaine, 1994; Fejer and Scherliess, 1995; Kikuchi et al., 2000; Kelley et al., 2003, Fejer and Emmert, 2003] and longer-lasting disturbance-wind dynamo effects [e.g., Blanc and Richmond, 1980; Spiro et al., 1988; Sastri, 1988; Fejer and Scherliess, 1995; Fuller-Rowell et al., 2002; Richmond et al., 2003].

[4] Recently, there has been a growing interest in studying the low-latitude ionosphere during magnetic storms,
partly due to new findings of the interconnection between the low- and high-latitude ionosphere and plasmasphere. Observations show that thermal plasma originating from low latitudes can possibly be the source of the plasmaspheric drainage plume in the region between the inner and outer parts of the dayside magnetosphere [Foster et al., 2002]. Disturbances of the plasma distribution of the low-latitude ionosphere can also affect the midlatitude ionosphere in some large storm events [e.g., Abdu, 1997; Vlasov et al., 2003; Tsurutani et al., 2004]. The low-latitude ionosphere is unique in that the magnetic field is nearly horizontal so that zonal electric fields, produced by the neutral-wind dynamo during quiet geomagnetic times, can transport the plasma vertically through the \( E \times B \) drift. This quiet-time vertical drift is upward during the daytime, causing plasma to drift to higher altitudes, from where it diffuses down along the magnetic field to higher latitudes, creating two plasma crests on either side of the magnetic equator. This feature is called the equatorial ionization anomaly (EIA), or the equatorial anomaly for short, and the effect of transporting the plasma from the magnetic equator to higher latitudes is described as the fountain effect [Duncan, 1960; Wright, 1962; Hanson and Moffett, 1966; Anderson, 1973]. The EIA was first described by Appleton [1946] in a widely available Western journal, so that it is often called the Appleton anomaly [Rishbeth, 2000]. During magnetic storms, the significant elements of the ionospheric effects at low latitudes are caused by modifications of the EIA. The plasma density and the peak location of the EIA can be modified by changes of (1) the transport parallel to magnetic field lines through disturbance neutral winds and diffusion; (2) the loss process due to storm-produced composition perturbations; and (3) the transport perpendicular to magnetic-field lines due to storm-produced electric fields.

It is the purpose of this paper to study the variations of the low-latitude ionosphere and their connection with the middle and high latitudes during the entire period of the October–November 2003 superstorm. Chains of GPS receiver networks are used for monitoring the ionospheric total electron content (TEC) variations in the EIA region. Ion drift measurements by the low-Earth-orbiting ROCSAT-1 and the \([\text{O}]/[\text{N}_2]\) ratio inferred from TIMED GUVI measurements are both used to explain the EIA variations observed in the TEC. In section 2 we describe the magnetic storm of October–November 2003. In section 3 we briefly describe observations used in this paper. In section 4 we present the observational results and discuss them in section 5. Finally, the summary is given in section 6.

2. Overview of the October–November 2003 Events

Three solar active regions contributed to a series of dramatic bursts of activity on the Sun in October 2003 and produced some of the largest Sun-Earth connection events on record. The flare burst on 28 October was classified as X17, and the one on 29 October was a class X10 flare. These X class solar flares took place when the parent active region was close to the middle of the solar disk facing the Earth, and full halo coronal mass ejection events were observed in conjunction with the flares. In a very fast transit time, arriving at Earth in less than a day (19 hours) from the Sun, the first shock reached Earth at 0613 UT on 29 October and produced the first of three major geomagnetic storm main phases. The multiple magnetic storm sequences revealed interesting responses of the magnetosphere, ionosphere, and thermosphere. Figure 1 shows the auroral electrojet (AE) index (top) and the Dst index (bottom). The AE index was derived from 74 stations between 55 and 76 magnetic latitude, and the Dst index was derived from 41 stations below 40 magnetic latitude. After the arrival of the first shock, the AE index had a sharp increase to more than 3000 nT followed by multiple bursts that continued until early 30 October. Several hours later, another increase of the AE index started in the middle of 30 October and continued until 31 October. The bottom of Figure 1 shows that the Dst value fell to \(-222\) nT at 0900 UT on 29 October, \(-405\) nT at 2331 UT on 29 October, and \(-456\) nT at 2229 UT on 30 October.
We note times that the Dst value started to decrease to its minima by three vertical dashed lines, at 0628 UT and 1449 UT on 29 October and at 1645 UT on 30 October. After the three storm main phases, according to the Dst index, the October–November storm started to recover on 2 November.

3. Instrumentations

3.1. GPS TEC

The Global Positioning System (GPS), which consists of more than 24 satellites distributed in six orbital planes at an altitude of about 20,200 km, is ideally suited for simultaneously monitoring large areas of the ionosphere. Each GPS satellite transmits dual-frequency signals \( f_1 = 1575.42 \text{ MHz} \) and \( f_2 = 1227.60 \text{ MHz} \) from satellite altitude to ground-based receivers through the dispersive ionosphere, with two different code measurements, \( P_1 \) and \( P_2 \), and two different carrier phase measurements, \( L_1 \) and \( L_2 \). On the basis of measurement of the modulations on ultrahigh frequency (UHF) carrier phases and codes recorded by dual-frequency receivers, the ionospheric TEC can be evaluated with high accuracy [e.g., Sardón et al., 1994; Leick, 1995; Liu et al., 1996]. This powerful technique has been applied to derive regional and global ionospheric TEC maps using a global network of receivers [e.g., Ho et al., 1997; Mannucci et al., 1998; Schaer, 1999; Iijima et al., 1999]. In this paper, two GPS receiver chains from the International GPS Service (IGS) network, one with 24 receivers along the American sector \((-70^\circ W\) and the other with 18 receivers along the Asian/Australian sector \((-120^\circ E\), are used to study the low-latitude ionosphere variations during the entire October–November storm period. Figure 2 shows ground tracks (magenta lines) of the 350 km piercing altitudes to the GPS satellites observed by ground-based GPS receivers during a day. From the broad latitudinal coverage of GPS data from these two chains, a latitude, time, and TEC (LTT) map can be constructed every day in both the American and Asian/Australian sectors, with coverage between \( \pm 50^\circ \) magnetic latitudes. The method of deriving TEC from GPS signals and constructing the LTT maps can be found in the work of Liu et al. [1996] and Tsai et al. [2001].

3.2. ROCSAT-1 Ionospheric Plasma and Electrodynamics Instrument (IPEI)

The ROCSAT-1 satellite was launched into a 35° inclination circular orbit at around 600 km altitude on 27 January 1999, and it fully operated until 16 June 2004. It is a three-axis stabilized spacecraft with the z-axis pointing toward the Earth's center, the y-axis pointing to the negative direction of the orbital angular momentum, and the x-axis along the velocity direction. With a 96.7-min orbital period, and a westward precession of 7° per day, the ROCSAT-1 crosses a given longitudinal line 14 times a day and completes global coverage in local time and latitude every 52 days. Figure 2 shows three ground tracks of the ROCSAT-1 orbits (red lines). The Ionospheric Plasma and Electrodynamics Instrument (IPEI) on board the ROCSAT-1 has an ion trap (IT) to measure ion concentration, a pair of Ion Drift Meters (VDM and HDM) to measure the two cross-track ion velocity components (Vz and Vy), and a retarding potential analyzer (RPA) to infer ion temperature, major ion constituents, and the along-track ion velocity (Vx). The accuracy of the ion drift measurements is about \( \pm 10 \text{ m/s} \) [Su et al., 1999; Yeh et al., 1999]. The velocity components Vx, Vy, and Vz can then be transformed from the satellite coordinate system to geodetic coordinate system. The magnetic apex coordinate system [Richmond, 1995] is then used to compute the components of the ion drift parallel and perpendicular to the magnetic field. The electric field \( \mathbf{E} \) can also be derived through the expression \( \mathbf{E} = -\mathbf{V} \times \mathbf{B} \) [Yeh et al., 1999; Yeh et al., 2001], where \( \mathbf{B} \) is the geomagnetic field. Thus the ROCSAT-1 provides the in-situ ion density measurements and the \( \mathbf{E} \times \mathbf{B} \) drift in the upward/poleward and zonal directions within \( \pm 35^\circ \) geographic latitudes.

3.3. TIMED GUVI 135.6/LBH, Measurements

The Global Ultraviolet Imager (GUVI) is one of the four scientific instruments on board the NASA
TIMED (Thermosphere Ionosphere Mesosphere Energy and Dynamics) satellite. The TIMED satellite is in a 630-km, 97.8-min period circular orbit with an inclination of 74.1°. The GUVI has an imaging spectrograph that is able to scan cross-track (disk and limb scan) along the satellite track, providing dayglow, nightglow, and aurora investigations in five wavelength channels between 115 to 180 nm. Major emission features are H(121.6), OI(130.4), OI(135.6), and the N2 LBH bands, LBHs and LBHL [Christensen et al., 2003, and references therein]. The OI(135.6 nm) channel covers the wavelength interval [133.5–137.7 nm], and the short-wavelength N2 LBHs covers the interval [141.0–153.0 nm]. Strickland et al. [1995] quantified the relationships between the [O]/[N2] density ratio and the 135.6/LBHs intensity ratio by using different atmospheric models. They found a linear relationship between [O]/[N2] and 135.6/LBHs ratios, and the relationship is independent of atmospheric model. They concluded that one can monitor [O]/[N2] from 135.6/LBHs with best effectiveness if [O]/[N2] refers to column density ratios referenced to an N2 column density of 10^{17} cm\(^{-2}\). On the basis of the concept described in the work of Strickland et al. [1995], Strickland et al. [2004] further derived the [O]/[N2] ratio from GUVI dayglow measurements in the OI (135.6 nm) and N2 LBHs channels (135.6/LBHs) with a lookup table generated by model runs.

From the above, we are able to use the GUVI 135.6/LBHs ratio directly to infer day-to-day variations of thermospheric [O]/[N2] during the storm period.

4. Observational Results
4.1. Results From LTT Maps

Figure 3 shows the latitude, time, and TEC (LTT) maps in the Asian/Australian sector (~120°E) from 28 October to 2 November. Bold dashed lines in the bottom panel indicate times that Dst values started to decrease. The thin horizontal dashed line denotes the latitudinal location of the magnetic equator in this longitudinal sector. The local time is universal time plus 8 hours in this sector. See color version of this figure in the HTML.
wind circulation and asymmetry of the [O]/[N\textsubscript{2}] density ratio, since the northern hemisphere was closer to the winter and the southern hemisphere was closer to summer [e.g., Millward et al., 1996; Tsai et al., 2001, and reference therein]. The TEC maximum on the prestorm day was located around 23° geographic latitude (14° magnetic latitude) at 0600 UT (1400 LT) with the value around 119 TECu (1 TECu = 10\textsuperscript{16} electrons/m\textsuperscript{2}). After the first storm main phase started around 0630 UT (1430 LT) on 29 October, both the northern and southern equatorial anomaly peaks showed TEC increases and poleward expansions, with the maximum TEC value of 147 TECu located around 23° geographic latitude (14° magnetic latitude) at 0900 UT (1700 LT). It is noted that at 0900 UT (1700 LT) on 28 October, the northern anomaly peak was located at 14°N geographic latitude (≈5° magnetic latitude), with the TEC value of 81 TECu, and the southern anomaly peak was located at 2°N geographic latitude (≈−7° magnetic latitude), with the TEC value of 89 TECu, while at 0900 UT (1700 LT) on 29 October, the northern anomaly peak was located at 23°N geographic latitude (≈14° magnetic latitude) with the TEC value of 146 TECu, and the southern anomaly peak was located at −5° geographic latitude (≈−14° magnetic latitude) with the TEC value of 108 TECu. Following the first main phase, the second and the third main phases started around local midnight of 29 and 30 October, resulting in TEC decreases. The most noticeable feature shown in Figure 3 is the depression of the daytime equatorial anomaly on 30 and 31 October. The southern anomaly peaks on both days disappeared. The northern anomaly peak on 30 October moved closer to the magnetic equator, with the maximum TEC value of 88 TECu located at 15.5° geographic latitude (≈6.5° magnetic latitude) at 0800 UT (1600 LT). Note that the location of the northern equatorial anomaly on 31 October was similar to the prestorm reference day. The suppression and equatorward movement of the EIA may partly result from a reduction of the equatorial plasma fountain by disturbance electric fields and the neutral composition effects. Another interesting feature seen in Figure 3 is the TEC enhancement of both equatorial anomaly peaks on 1 November, when the Dst had almost fully recovered. Although the TEC in both hemispheres increased on 1 November, the latitudinal extent of the equatorial anomaly did not expand.

[11] Similar to Figure 3, Figure 4 shows LTT maps for the American sector (≈70°W, LT = UT − 4.7 hours), with geographical latitudinal coverage of −70° to 60°N. The magnetic equator is around −11° geographic latitude in this sector. The prestorm reference LTT map on 28 October...
is quite different from that in the Asian/Australian sector. Seasonal asymmetry is more obvious in this sector, with larger TEC values in the northern equatorial anomaly region and in the northern midlatitudes. Also note that at the early hours, 0000 ~ 0300 UT (1918 ~ 2218 LT), of the prestorm reference day, higher TEC values on each side of the magnetic equator were again the signature of the prereversal enhancement. On 29 October, the first storm main phase started around midnight in this sector and decreased the nighttime TEC until the next morning. Following the first main phase, the response of the low-latitude ionosphere to the second main phase is striking. Very strong TEC enhancements were seen in both hemispheres and the outer boundaries of strong dayside enhanced TEC regions (defined as TEC > 50 TECu; yellow and red colors) were furthest extended to 39° geographic latitude (corresponding to 50° magnetic latitude) in the northern hemisphere and ~56° geographic latitude (~45° magnetic latitude) in the southern hemisphere around 1920 UT. The largest TEC value reached more than 170 TECu at 14° southern hemisphere around 1920 UT. The largest TEC on 30 October reached 132 TECu at 13.5° geographic latitude (24.5° magnetic latitude) at 1930 UT (1448 LT). The strong increase of the TEC seen at northern midlatitudes after around 1800 UT on 30 October may again be the source of an ionospheric TEC plume. Figure A2 in Appendix A shows the global ionospheric TEC map at 1800 UT and 2000 UT on 30 October. From the figure, the ionospheric TEC plume started to form at 1800 UT and became well-developed at 2000 UT. Results on 31 October and 1 November during the storm recovery phase are interesting as well. On 31 October, a severe depletion of the ionosphere occurred around local midnight and continued to last for the entire day. The depletion in TEC appeared in the southern hemisphere, similar to what was observed in the Asian/Australian sector. This depletion in the southern hemisphere was also observed by Imel et al. [2004], using the IMAGE FUV measurements. On 1 November, similar to the response in the Asian/Australian sector on the same day, TEC enhancements of both equatorial anomaly peaks again appeared, and the peak locations expanded poleward, as compared with the prestorm reference day on 28 October.

4.2. Results From ROCSAT-1

[12] Figure 5 shows the ROCSAT-1 in situ measurements of the ion density and upward/poleward \( \mathbf{E} \times \mathbf{B} \) drift during the time intervals 2100–2200 UT and 2245–2325 UT on 28 October (blue lines), 29 October (red lines), and 30 October (green lines). In the middle panels, during 2100–2200 UT, the ion density showed the character of a trough at low latitudes and steep increases of ion density at higher latitudes on 29 and 30 October. This character is similar to the DMSP observations of very large equatorial plasma fountain effects during other severe storms [e.g., Greenspan et al., 1991; Rasmussen and Greenspan, 1993; Basu et al., 2001]. It can be seen from the top panels that the satellite flew through the northern equatorial anomaly earlier in western Pacific and then flew over the southern equatorial anomaly region in the evening sector in South America, overlapping with our GPS observations. The locations of steep increase of the ion density in the southern equatorial anomaly region (~20° magnetic latitude) on 29 and 30 October indicate that the ROCSAT-1 flew across a strongly enhanced southern equatorial anomaly region, as observed in the TEC on these 2 days. Strong upward/poleward \( \mathbf{E} \times \mathbf{B} \) drifts were simultaneously observed, indicating that strong fountain effects may have occurred during the 2100–2200 UT time intervals on 29 and 30 October. ROCSAT-1 measurements during the time intervals of 2245–2325 UT are shown in the right column of Figure 5. Densities of the northern equatorial anomaly measured on 29 and 30 October dropped to lower values above 11° latitude in comparison with 28 October, while ion densities in the southern equatorial anomaly were higher than on 28 October. During the 2245–2325 UT time intervals, upward/poleward \( \mathbf{E} \times \mathbf{B} \) disturbance drifts on 30 October were smaller than the 28 October values and also smaller than the earlier (2100–
values, as seen in the bottom panel. It is noted that Figure 5 shows dawn/dusk differences in the low-latitude ionosphere response in the early stage of the storm. Larger storm-generated $E \times B$ drifts and ion densities are seen in the dusk/American sector than in the dawn/Asian sector.

To further investigate the connection between the upward/poleward $E \times B$ drifts and the equatorial anomaly during this intense storm period, we select three successive ROCSAT-1 orbits in the American and Asian/Australian sectors during each of the three storms. Figure 6 presents three ROCSAT-1 orbits (orbits 4–6) in the Asian/Australian sector during 0500–0900 UT on 28, 29, and 30 October. The three ROCSAT-1 orbits for each day on 28, 29, and 30 October are represented by blue, red, and green lines, respectively. The left column shows three satellite orbits on 29 October in the Asian/Australian sector. The middle and right columns show the $E \times B$ drifts and ion densities, respectively. The dashed vertical lines in the middle and right columns indicate times that the ROCSAT-1 crossed the 120°E geographic longitude. In the middle column, strong upward/poleward $E \times B$ drifts of 100–200 m/s are seen for orbit 5 on 29 October (red line), indicating that eastward electric fields associated with the first arrival of the shock were penetrating to the low-latitude ionosphere at 0720 UT. The upward/poleward drifts remained strong at the next ROCSAT-1 orbit (orbit 6). Penetration electric fields tend to decrease in amplitude with decreasing magnetic latitude, $\lambda_m$; an approximate adjustment between the latitude of the ROCSAT-1 observations and the equator can be made by assuming the electric field to be constant in the magnetospheric equatorial plane [Mozer, 1970]. This translates into a $\cos^{-3}(\lambda_m)$ dependence of the eastward electric field associated with the upward/poleward drift at the 600 km altitude of the ROCSAT-1 spacecraft. If we use this scaling together with the latitudinal variation of geomagnetic field strength to project to the magnetic equator the large upward/poleward drift observed at 0712 UT and 0854 UT, times that the satellite flew across the 120°E geographic longitude, the upward/poleward drift of 130 m/s (red line, orbit 5) measured at 0712 UT (1512 LT) would correspond to an equatorial upward drift of 75 m/s and the upward/poleward drift of 175 m/s (red line, orbit 6) measured at 0854 UT (1654 LT) would correspond to an equatorial upward drift of 72 m/s. Downward $E \times B$ drifts on 30 October (green lines) were also observed by the
ROCSAT-1. If we scale the observations to the magnetic equator, the downward/equatorward drift of 100 m/s observed at 0854 UT, the time that the satellite crossed the 120°E geographic longitude at orbit 6, corresponds to 41 m/s downward drift at the magnetic equator. Finally, ion density measurements in the right column show increases on 29 October (red lines) and decreases on 30 October (green lines), corresponding to upward and downward $\text{E} \times \text{B}$ drifts, respectively.

Figure 7 shows the ground tracks of three ROCSAT-1 orbits (orbits 11–13) in the American sector during 1800–2200 UT on 28, 29, and 30 October. Again, measurements on the three ROCSAT-1 orbits for each day on 28, 29, and 30 October are represented by blue, red, and green lines, respectively. The left column shows three satellite orbits when the ROCSAT-1 crossed the area of 70°W geographic longitude. The middle and right columns show the $\text{E} \times \text{B}$ drifts and ion densities, respectively. The dashed vertical lines in the middle and right columns indicate times that the ROCSAT-1 crossed the 70°W geographic longitude. It can be seen in the middle column that upward/poleward $\text{E} \times \text{B}$ drifts on 29 and 30 October were larger than on 28 October, reaching more than 150 m/s around 2000 UT. Scaled to the magnetic equator, the upward/poleward drift of 150 m/s at 2000 UT (1518 LT) corresponds to an upward drift of 133 m/s at 600 km at the magnetic equator. Large ion densities on 29 and 30 October can also be seen in the right column of the figure. The satellite flew through the southern equatorial anomaly on orbits 12 and 13 and observed steep increases of ion density in the southern equatorial anomaly region. It appears that the increase of ion density observed on orbit 12 resulted from

Figure 6. Three ROCSAT-1 orbits (orbits 4–6) in the Asian sector during 0500–0900 UT on 28, 29, and 30 October. Measurements on 28, 29, and 30 October are represented by blue, red, and green lines, respectively. The left column shows the satellite orbits on 29 October. Black dashed lines indicate the magnetic coordinates at 600 km altitude. The middle column shows upward/poleward ion drifts (m/s) measured during the three orbits. Dashed lines indicate times that the satellite crossed 120°E geographic longitude. On top of each plot, the local time that the ROCSAT-1 crossed 120°E longitude on 29 October is denoted. The right column shows the corresponding ion density (cm$^{-3}$). See color version of this figure in the HTML.
an increase of the upward/poleward drift between the times of orbits 11 and 12, since it took time for the plasma to be raised upward and then to diffuse down toward higher latitudes. Thus the large increase of the ion density observed on orbit 13 of both 29 and 30 October corresponds more to the upward/poleward drifts measured on orbit 12 than those on orbit 13.

4.3. Results From TIMED GUVI 135.6/LBHs Ratio

[15] Figure 8 shows the GUVI 135.6/LBHs measurements from 27 October to 1 November 2003 (DOY 300 ~ 305). Fourteen contiguous satellite orbits of data are used for each GUVI image with the first beginning near 0–1 hour universal time. The UT hours shown on top of each image correspond to the equatorial crossing times of the TIMED/GUVI. The locations of the equatorial crossing are also indicated by triangle marks in the image. Note that results contained within each image cover approximately 1 day, and the local time for each equatorial crossing of the TIMED/GUVI is around 1500 ~ 1600 LT. The GUVI images on 27 October (DOY 300) and 28 October (DOY 301) are presented as the prestorm references. As discussed in section 3.3, we can usually (but not always) use the 135.6/LBHs intensity ratio to infer variations of the [O]/[N2] density ratio. It is important to note that high value areas (red and white colors) on the east side of South America are caused by measurement noise associated with particle radiation in the South Atlantic Anomaly, and results from that area should not be taken into account.

[16] From the GUVI image on 29 October (DOY 302), we can see that regions of depleted [O]/[N2] density ratio, which we call composition perturbation zones, formed and

Figure 7. Three ROCSAT-1 orbits (orbits 11–13) in the American sector during 1800–2200 UT on 28, 29, and 30 October. Measurements on 28, 29, and 30 October are represented by blue, red, and green lines, respectively. The left column shows the satellite orbits on 29 October. Black dashed lines indicate the magnetic coordinates at 600 km altitude. The middle column shows upward/poleward ion drifts (m/s) measured during the three orbits. Dashed lines indicate times that the satellite crossed –70°E geographic longitude. On top of each plot, the local time that the ROCSAT-1 crossed 70°W longitude on 29 October is denoted. The right column shows the corresponding ion density (cm⁻³). See color version of this figure in the HTML.
moved equatorward after the first storm. Equatorward extension of the composition perturbation zones is most obvious in the American-Atlantic sector, in both the northern and southern hemispheres, beginning around 1300 UT. According to generally accepted theory [e.g., Fuller-Rowell et al., 1994; Proß, 1995], we can infer that the composition perturbation zones formed in the polar region after the storm started and were carried equatorward by wind surges to middle and low latitude. Once the composition perturbation zones reach middle latitudes, they tend to corotate with the Earth. The storm-generated equatorward wind surges are largest in the midnight to dawn sector [see Proß, 1995, and references therein] and the American-Atlantic region was in the midnight to dawn sector when the first storm started. Increases of the 135.6/LBH$_6$ ratio are seen on the equatorward edge of composition perturbation zones, especially in the northern hemisphere indicating increases of the [O]/[N$_2$] density ratio. The most impressive increase was at 2200 UT around 20° geographic latitude over North America.

On the next day, 30 October (DOY 303), the GUVI image showed equatorward extension of composition perturbation zones in both hemispheres in every orbit. Note that composition perturbation zones observed on this day were created during the first and second storm main phases.

Figure 8. The GUVI 135.6/LBH$_6$ measurements from 27 October (DOY 300) to 1 November (DOY 305) 2003. Fifteen contiguous satellite orbits of data are used for each GUVI image with the first beginning near 0 hour universal time. The UT hours shown on top of each image correspond to locations of the TIMED/GUVI equatorial crossing, also indicated by triangle marks in the image. Results contained within each image cover approximate one day, and the local time for each equatorial crossing of the TIMED/GUVI is around 1500 ~ 1600 LT. White boxes in the 1 November frame denote two bright bands of 135.6/LBH$_6$ intensity ratio, which may be the signature of the equatorial anomaly. Note that high values on the east side of South America are caused by the South Atlantic Anomaly and the results from that area should not be taken into account. See color version of this figure in the HTML.
The most impressive decreases of the [O]/[N2] density ratio occurred in the southern hemisphere of the Asian/Australian sector where composition perturbation zones penetrated to the geographic equator. The expansion of the composition perturbation zones to the geographic equator was only seen in the southern hemisphere and can be explained as follows. First, when the second storm main phase started around 1600 UT on 29 October, the Asian/Australian sector was in the midnight sector where the storm-generated equatorward wind surges, together with the background quiet time equatorward winds, should be most significant. Second, the background summer-to-winter winds should have caused stronger equatorward winds in the southern (summer) hemisphere than in the northern (winter) hemisphere [Fuller-Rowell et al., 1996]. Finally, penetration of a westward electric field in the nightside produced downward/equatorward \( \mathbf{E} \times \mathbf{B} \) drifts and should have reduced the ionospheric plasma density and ion drag, thereby reducing the resisting force against the equatorward winds. The westward electric field, by producing an equatorward \( \mathbf{E} \times \mathbf{B} \) ion drift, may also have the effect of pulling the neutral atmosphere equatorward through ion drag [Tanaka, 1986].

It is noted that a downward/equatorward \( \mathbf{E} \times \mathbf{B} \) drifts in the local night of the Asian/Australian sector on 29 October (after the second storm onset) is seen by the ROCSAT-1 (not shown here), at the same time the decrease of the TEC is seen in Figure 3. Combining the effects described above, composition perturbation zones created in the midnight sector and in the summer hemisphere can penetrate to very low latitudes and corotate with the Earth to the dayside. Also on 30 October, an increase of the 135.6/LBH\(_h\) ratio was observed in Central America at 2100 UT at around 0°–20° geographic latitude. In the same longitudinal sector, the composition perturbation zones in the southern hemisphere had extended to –30° geographic latitudes, which may well explain the hemispherically asymmetric expansion of the equatorial anomaly on 30 October shown on Figure 4.

[18] On 31 October (DOY 304), the composition perturbation zones generally remained as they were on 30 October. Composition perturbation zones in the American sector extended closer to the geographic equator than on the previous days, especially in the southern hemisphere, while the composition perturbation zones in the southern hemisphere of the Asian/Australian sector had withdrawn from the geographic equator to –20° geographic latitude. The [O]/[N2] density ratio in higher latitudes started to recover to its prestorm conditions on 1 November (DOY 305), but the [O]/[N2] density ratio at lower latitudes decreased. The decrease of the [O]/[N2] density ratio at lower latitudes on November 1 can be explained as follows. After the storm-driven phases, the composition bulges not only corotated with the Earth but also moved along with the background wind fields and consequently moved equatorward, since nighttime equatorward winds are usually larger than daytime poleward winds [e.g., Fuller-Rowell et al., 1998].

[19] A very interesting feature is seen in the GUVI image on 1 November (DOY 305). Two brighter bands of higher 135.6/LBH\(_h\) values are seen on either side of the magnetic equator, more clearly in the northern hemisphere. These appear to be signatures of the equatorial anomaly. They are likely due to the contributions to OI (135.6 nm) emission by recombination emission \( \text{O}^+ + \text{e}^- \) from the equatorial anomaly region. This has been pointed out by Strickland et al. [2004] as one of the potential sources of dayglow contamination. The contamination of OI (135.6 nm) recombination emission due to the equatorial anomaly should usually be minor and lead to no discernable false enhancements in [O]/[N2], as stated in the work of Strickland et al. [2004]. However, because the [O]/[N2] values were generally low (weaker dayglow) at low latitudes and the equatorial anomaly was significantly enhanced on 1 November, as shown in Figure 4, the recombination emission in the equatorial anomaly regions became discernable on 1 November. We further compare the locations of these EIA like structures shown in the GUVI image with the EIA observed in the LTT map. Figure 9 shows GUVI images around 2000 UT and 2200 UT and the LTT plot on 1 November. The equatorial anomaly peaks from both observations coincide well in latitude. These equatorial anomaly structures shown on the GUVI image on 1 November again confirm the observational evidence of the EIA enhancement during the storm recovery phase.

5. Interpretation and Discussion

[20] In this section we will only focus on major observational results since the observations cover many days and contain much detail.

5.1. Large Expansion of the EIA During Initial Phases of the Storms

[21] In the LTT maps shown in Figures 3 and 4, expansions of the daytime equatorial anomaly accompanied by large TEC increases were observed during the initial phases of the storms. The strong upward \( \mathbf{E} \times \mathbf{B} \) drifts measured by the ROCSAT-1 indicate that stronger plasma fountain effects due to eastward penetration electric fields contributed significantly to the equatorial anomaly expansions in both the Asian/Australian and the American sectors. From the upward/poleward component of the \( \mathbf{E} \times \mathbf{B} \) drift measured by ROCSAT-1 (Figure 6), the enhanced equatorial anomaly TEC in the afternoon (0900 UT/1700 LT) of the Asian/Australian sector (Figure 3) on 29 October was likely produced by upward \( \mathbf{E} \times \mathbf{B} \) drifts during 0700–0900 UT (1500–1700 LT), with the largest value of 75 m/s at the magnetic equator derived from the ROCSAT-1 measurements. Very strong expansions of the equatorial anomaly observed in the American sector on 29 and 30 October (Figure 4) were likely produced by large upward \( \mathbf{E} \times \mathbf{B} \) drifts during 1800–2200 UT (Figure 7), with the largest values of 133 m/s at the magnetic equator derived from the ROCSAT-1 measurements. According to Greenspan et al. [1991] and Rasmussen and Greenspan [1993], an upward drift of 100 m/s at the magnetic equator is capable of creating a very large equatorial fountain effect. The strong expansion of the equatorial anomaly in the American sector was also seen by the ROCSAT-1 in situ ion density measurements, as shown in Figure 5. The ion density showed a trough at the magnetic equator and steep increases at higher latitudes, which is similar to DMSP observations during very strong equatorial plasma fountains [e.g., Greenspan et al., 1991; Basu et al., 2001]. The ROCSAT-1 ion drift measurements have provided excellent information for us to estimate the magnitude of the equatorial plasma
fountain using an ionospheric model. C. H. Lin et al. (Theoretical study of the low and middle latitude ionospheric electron density enhancement during the October 2003 superstorm: Relative importance of the neutral wind and the electric field, submitted manuscript, hereinafter referred to as Lin et al., submitted manuscript, 2005) use the upward drifts measured by ROCSAT-1 as the input to the Sheffield University Ionosphere Plasmasphere Model (SUPIM) [Bailey and Balan, 1996]. They find that the upward drifts of 100–150 m/s between 1800 and 2200 UT are able to produce poleward expansions of the equatorial anomaly peaks to ±30° magnetic latitude in the American sector.

[22] Large expansion of the equatorial anomaly in the American sector on 29 and 30 October provided a possible source of thermal plasma from the low-latitude ionosphere to the middle latitude and may further have become a plume like that described by Foster et al. [2002]. Figures A1 and A2 in Appendix A show the global ionospheric TEC maps on 29 and 30 October, respectively. Both figures show clear ionospheric TEC plume features in the American sector, indicating that the large expansion of the equatorial anomaly observed in Figure 4 contributes strongly to the source of the ionospheric TEC plume. Another possible plasma source for the greatly enhanced TEC in the ionospheric plume and its immediate source regions (equatorward latitudes of the ionospheric TEC plume) may be the westward advection which brings the plasma from the nightside to the dayside in middle latitudes due to a poleward penetration electric field [Vlasov et al., 2003; Kelley et al., 2004].

[23] In Figure 4, we can see that the dayside enhanced TEC regions (defined as TEC > 50 TECu) on 29 October extended furthest poleward, to more than ±45° magnetic latitude in both hemispheres at 1920 UT, and the maximum TEC occurred at 14° geographic latitude (corresponding to 25° magnetic latitude) at 2000 UT (1518 LT). However, on 30 October the poleward extension of the dayside enhanced TEC region can only be seen in the northern hemisphere, where the dayside enhanced TEC regions extended furthest to 42° geographic latitude (53° magnetic latitude) around 1800 UT. The dayside enhanced TEC region in the southern hemisphere on 30 October was confined equatorward of 35° geographic latitude. The asymmetry in the magnitude and latitude of the enhanced TEC regions in the northern and southern hemispheres on 30 October may be due to the neutral composition and wind effects. As can be seen in Figure 8, the composition perturbation zones (purple colors) in South America extended to a much lower latitude, around −35° geographic latitude, on 30 October than on the prestorm days of 27 and 28 October, consistent with the southern latitude limit of the TEC enhancement on 30 October in Figure 4. Therefore the poleward extension of the equatorial anomaly produced by the large
plasma fountain could only have been significant in the northern hemisphere on 30 October, since the air with low \([\text{O}] / [\text{N}_2]\) ratio extended to the southern equatorial anomaly region and increased the plasma loss in that region. It is noted that the asymmetric summer-winter neutral wind may also contribute to the hemispheric asymmetry of the equatorial anomaly peaks as observed on 29 and 30 October at the American sector. The asymmetric latitudinal and time extent of the equatorial anomaly peaks on 29 October were likely produced mainly by asymmetric neutral winds, since the composition perturbations in the southern hemisphere were poleward of \(-50^\circ\) geographic latitude, poleward of the enhanced southern equatorial anomaly. The asymmetric neutral wind effects on 30 October are more difficult to infer, since we do not have neutral wind observations and also the composition perturbation regions extended to the southern equatorial anomaly region, where both effects would be mixed together. It is possible that asymmetric neutral winds caused the asymmetric equatorial anomaly morphology like that on 29 October and that composition effects decreased the TEC magnitude in the southern equatorial anomaly region.

It is important to note that storm-generated equatorward neutral winds are capable of producing positive storm effects by lifting the ionospheric layer to higher altitudes where the loss is smaller [see Prölls, 1995, and references therein]. However, the equatorward winds can also transport plasma from the equatorial anomaly peak to the magnetic equator and decrease the plasma in the equatorial anomaly peak [e.g., Fesen et al., 1989]. The processes that result in the strongly enhanced equatorial anomaly TEC in Figure 4 appear to be the competing/combining processes of neutral winds and downward diffusion from the plasma fountain [e.g., Buonsanto and Foster, 1993]. Under conditions where a very strong plasma fountain is in process, the equatorward neutral winds could play a role in slowing plasma diffusion down along field lines after the plasma has been lifted to higher altitudes by the larger fountain effect. In other words, an equatorward wind could maintain the ionosphere at higher altitudes, where plasma loss is smaller, so that plasma can accumulate. The effects discussed above have been modeled by Lin et al. (submitted manuscript, 2005).

5.2. Suppression of the EIA and Negative Storm Effects in the Southern Hemisphere

Negative daytime storm effects were observed in both the Asian/Australian and American sectors. Decreases of the ionospheric TEC and the suppression of the equatorial anomaly are most obvious in the Asian/Australian sector on 30 October. The suppression of the daytime equatorial anomaly on 30 October was due to the downward \(E \times B\) drifts that were possibly produced by the wind disturbance dynamo [Blanc and Richmond, 1980]. The downward drift had a magnitude of 41 m/s at the magnetic equator as observed by the ROCSAT-1 (Figure 6). Meanwhile, the very low latitude extension of air with low \([\text{O}] / [\text{N}_2]\) ratio in this sector could have caused the southern anomaly peak to disappear. The severe depletions of the southern equatorial anomaly occurred on both 30 and 31 October, even though the daytime upward/poleward \(E \times B\) ion drifts had recovered close to their quiet time patterns on 31 October (not shown here). Negative storm effects were seen in the American sector on 31 October. The depletions were more severe in the southern hemisphere, which corresponded to larger extent of composition perturbation zones seen by GUVI. It is noteworthy that unlike the downward drift measured in the Asian/Australian sector on 30 October, the ion drifts measured on 31 October in both sectors showed patterns similar to those on the prestorm day (not shown). Thus the major mechanism of the negative storm effects on 31 October appears to have been the composition perturbation.

5.3. Poststorm Enhancement of the EIA

On 1 November, during the day that Dst recovered to its prestorm values, TEC increases in the equatorial anomaly regions were observed in both the Asian/Australian and American sectors, as compared with the prestorm reference...
on 28 October. It is noted that the EIA morphology on 28 October is similar to those on 26 and 27 October (not shown here) and it therefore is an adequate prestorm reference. In the Asian/Australian sector on 1 November, the equatorial anomaly peaks did not expand poleward as the TEC increased. In the American sector on the same day, the equatorial anomaly peaks expanded poleward and enhanced symmetrically. This enhancement in the American sector was confirmed by the GUVI image on the same day, shown in Figure 9. To try to explain this, we look at the ion drifts measured by the ROCSAT-1. It should be noted that direct comparison of the upward $E \times B$ drift on 1 November and 28 October has some difficulties, since the satellite orbits on 1 November and 28 October have more than 1 hour difference in local time. We can only compare ion drifts measured in similar locations but at different local times. By doing so, we found that in general, the ion drifts measured on 1 November were slightly higher than on the prestorm day. Figure 10 shows one of the comparisons of the ion drifts and densities measured in the American sector on 1 November (black lines) and 28 October (blue lines). The vertical dashed lines indicate the magnetic latitude where the satellite flew across the 70°W geographic longitude. The numbers indicate the rounded local time of the region. The ion drifts and densities were both larger than those on 28 October in Figure 10. The larger upward drift may be the driver causing the TEC increase. However, we do not know if this relatively small increase of the upward ion drift is able to create a plasma fountain strong enough to overcome the effect of asymmetric seasonal winds in order to produce the nearly perfectly symmetric equatorial anomaly peaks. Moreover, the source of the larger upward drift on 1 November is not clear. We suspect that neutral winds may play an important role for creating this phenomenon, but further study is needed to explain this unusual enhancement during the poststorm period.

6. Summary

[27] In this paper we present the observational results from the GPS-TEC, ROCSAT-1 in situ measurements, and the GUVI dayglow during the period of the 28 October to 2 November 2003 superstorm period. For the first time, we use LTT maps to monitor the low-latitude ionosphere variations during the great storm, with the aid of measurements of the upward $E \times B$ drifts and the global $[O]/[N_2]$ ratio. From the information provided by the ROCSAT-1 in situ ion drift measurements and the TIME GUVI dayglow, most of the storm features observed by GPS-TEC can be

Figure A1. The Global Ionospheric Map (GIM) at 2000 UT and 2200 UT on 29 October (DOY 302). See color version of this figure in the HTML.

Figure A2. The Global Ionospheric Map (GIM) at 1800 UT and 2000 UT on 30 October (DOY 303). See color version of this figure in the HTML.
well explained, except the unusual poststorm enhancement of the equatorial anomaly. We summarize our findings as follows.

[25] 1. The LTT maps constructed from the two GPS receiver chains in the American and Asian/Australian sectors reveal the latitude-time evolution of the low-latitude ionosphere during the entire storm period. The responses show strong local time or longitude effects during the initial and the main phases of the storms. The storm effects in the two sectors became very similar during the recovery phases of the storm on 31 October and 1 November.

[29] 2. During the initial phase of each storm, when Dst started to decrease, a large enhancement of the daytime ionospheric TEC was observed and the region of TEC increase extended to higher latitudes. The most significant TEC increases and expansions of the equatorial anomaly were seen in the American sector on 29 and 30 October. These poleward extensions of the equatorial anomaly may be explained by larger upward drifts driving an enhanced equatorial plasma fountain. Evidence of large upward drifts is provided by the ROCSAT-1 in situ measurements. Strong upward $\mathbf{E} \times \mathbf{B}$ drifts were simultaneously observed at the times and longitudes of large TEC enhancements. It is suggested that the strongly enhanced EIA in the American sector on 29 and 30 October resulted from at least 2 hours of upward plasma drifts, with the largest upward drift being around 100–130 m/s at the magnetic equator at 600 km. In addition to the enhanced equatorial plasma fountain, the storm-generated equatorward neutral winds may also be important in maintaining the ionosphere at higher altitudes, resulting in plasma accumulation as discussed in section 5.1. The strong increase of TEC and poleward expansion of the equatorial anomaly on both 29 and 30 October may be the thermal plasma source of the ionospheric TEC plumes shown in Figures A1 and A2 in Appendix A.

[30] 3. Suppression of the equatorial anomaly and a negative storm effect in the Asian/Australian sector on 30 October may be explained by the combined effects of downward drift and equatorward expansion of neutral composition changes ($[O]/[N_2]$ depletion). The magnitude of the downward drift was around 40 m/s and it was possibly produced by wind disturbance dynamo.

[31] 4. The $[O]/[N_2]$ ratio inferred from the GUVI dayglow provides the global image of the composition variations during the storm. It shows clear local time and seasonal effects of the composition perturbations, consistent with previous studies. It also, surprisingly, indicates that air with a reduced $[O]/[N_2]$ ratio was transported nearly to the geographic equator during the storm. Moreover, combining the $[O]/[N_2]$ ratio inferred from GUVI with the ROCSAT-1 drift measurements, we are able to conclude that the composition perturbation may be the main driver of the negative storm observed on 31 October.

[32] 5. Composition perturbations are able to affect the EIA significantly even when a strong equatorial plasma fountain has occurred. This is evident in the LTT map in the American sector on 30 October. The magnitude of the upward $\mathbf{E} \times \mathbf{B}$ drifts measured on 30 October was very similar to that on 29 October, but the TEC increases on 30 October were smaller. This effect was clearest in the southern (summer) hemisphere of the American sector. The dayside enhanced TEC regions (defined as TEC > 50 TECu) in the southern hemisphere on 29 October expanded as far as $-45^\circ$ magnetic latitude while the dayside enhanced TEC regions in the southern hemisphere on 30 October only reached $-24^\circ$ magnetic latitude. Meanwhile, the $[O]/[N_2]$ inferred from GUVI observations shows that the composition perturbations in the southern hemisphere extended equatorward to a similar latitude ($-24^\circ$) on 30 October. The very good agreement between the GUVI $[O]/[N_2]$ and TEC observations suggests that the composition perturbations may contribute significantly to the EIA asymmetry on 30 October in addition to other possible neutral wind effects.

[33] 6. An unusual enhancement of the equatorial anomaly was observed in both longitude sectors on 1 November. The TEC and the locations of the equatorial anomaly peaks became symmetric on this day. This effect was most obvious in the American sector and was confirmed by the GUVI image. Larger upward plasma drifts may partly explain this effect. The source mechanism for production of larger drifts during the poststorm period is not yet clear. A further study of physical processes responsible for this enhancement is needed.

[34] The observations presented in this paper show that the morphology of the low-latitude ionosphere can vary dramatically from day to day during a severe storm. It can strongly affect the midlatitude ionosphere and influence the high-latitude ionosphere. Combining the GPS, ROCSAT-1, and TIMED GUVI observations has verified some of the past model studies of thermosphere and ionosphere responses during storms [e.g., Burns et al., 1991; Rasmussen and Greenspan, 1993; Fuller-Rowell et al., 1994, 1996; Proffitt, 1995] and provide important information about ionospheric drivers for future modeling work.

Appendix A

[35] We present the global ionospheric TEC maps as the observational evident of the ionospheric TEC plume on 29 and 30 October shown in Figures A1 and A2, respectively. The global ionospheric TEC maps presented here are generated on a daily basis at University of Bern, Switzerland, using data from about 200 GPS/GLONASS sites. The vertical total electron content (VTEC) is modeled in a solar-geomagnetic reference frame using a spherical harmonics expansion, and the instrumental biases are estimated and removed. Details of constructing the global ionospheric TEC map can be found in the work of Schaer [1999]. The maps are available in the IONEX format at time intervals of 2 hours through the website of the Astronomical Institute of the University of Bern (http://www.aiub.unibe.ch/ionosphere/). It is noted that the TEC values over the ocean should have higher uncertainties compared with those over the continents. We show maps at 2000 UT and 2200 UT on 29 October and at 1800 UT and 2000 UT on 30 October. The ionospheric TEC plume is clearly seen in both hemispheres on 29 October, while the plume signature is significant only in the northern hemisphere on 30 October.

[36] Acknowledgments. This study was supported in part by the NASA Sun-Earth Connection Theory Program. We thank W.-B. Wang of NCAR/HAO for reviewing the paper before the submission and two anonymous reviewers for helpful comments. C. H. Lin thanks Y.-H. Yang.
of National Central University and S. Solomon of NCAI/HAO for useful
discussions and is grateful for the support from P. J. Huang. The global
ionospheric TEC maps are from the Astronomical Institute of the
University of Bern.

[37] Shadia Rifai Habbal thanks Mangalathayil Ali Abu and John C.
Foster for their assistance in evaluating this paper.

References
Abdu, M. A. (1997), Major phenomena of the equatorial ionosphere-
thermosphere system under disturbed conditions, J. Atmos. Sol. Terr.
Phys., 59(13), 1505–1519.
Anderson, D. N. (1973), A theoretical study of the ionospheric F-region
Appleton, E. V. (1946), Two anomalies in the ionosphere, Nature, 157,
691.
Bailey, G. J., and N. Balan (1996), A low-latitude ionosphere-plasmasphere
model, in Solar-Terrestrial Energy Program: Handbook of Ionospheric
Phys., Boulder, Colo.
Basu, S., S. Basu, K. M. Groves, H. C. Yeh, F. J. Rich, P. J. Sultan, and
M. J. Keskinen (2001), Response of the equatorial ionosphere to the
great magnetic storm of July 15, 2000, Geophys. Res. Lett., 28(18),
3577–3580.
Blanc, M., and A. D. Richmond (1980), The ionospheric disturbance
Buonsanto, M. J., and J. C. Foster (1993), Effects of magnetospheric
electric fields on global winds on the middle-latitude ionosphere
during the March 20–21, 1990, storm, J. Geophys. Res., 98(A11),
19,133–19,140.
Burns, A. G., T. L. Kellen, and R. G. Roble (1991), A theoretical study of
thermospheric composition perturbations due to an impulse geomag-
Christensen, A. B., et al. (2003), Initial observations with the Global Ultra-
low frequency (ULF) harmonic/magnetometer sensor, Geophys. Res.
Terr. Phys., 18, 89.
Farley, D. T., E. Bonelli, B. G. Fejer, and M. F. Larsen (1986), The pre-
reversal enhancement of the zonal electric field in the equatorial iono-
Fejer, B. G., and J. T. Emmert (2003), Low-latitude ionospheric disturbance
electric field effects during the recovery phase of the 19–21 October
Foster, J. C., A. J. Coster, J. Goldstein, and F. J. Rich (2002), Equatorial
electric fields during magnetically disturbed conditions: 2. Implications of
simultaneous auroral and equatorial measurements, J. Geophys.
Res., 85, 8503.
Greenspan, M. E., C. E. Rasmussen, W. J. Burke, and M. A. Abdu
(1991), Equatorial density depletions observed at 840 km during the
13,953.
Hanson, W. B., and R. J. Moffett (1966), Ionization transport effects in the
Ho, C. M., B. D. Wilson, A. J. Mannucci, U. J. Lindqvist, and D. N.
Yuan (1997), A comparative study of ionospheric total electron content
measurements using global ionospheric TEC maps of GPS, TOPEX radar,
Iijima, B. A., I. L. Harris, C. M. Ho, U. J. Lindqvist, A. J. Mannucci,
X. Pi, M. J. Reyes, L. C. Sparks, and B. D. Wilson (1999), Automated
daily process for global ionospheric total electron content maps and
satellite occultation ionospheric calibration based on Global Posi-
Inmel, T. J., N. Ostgaard, D. J. Strickland, H. U. Frey, S. B. Mende,
and G. Lu (2004), IMAGE-FUV observations of the October–November
2003 flare and magnetic storm effects on Earth, Geo Trans. AGU, 85(17),
Jaggi, R. K., and R. A. Wolf (1973), Self-consistent calculation of the
motion of a sheet of ions in the magnetosphere, J. Geophys. Res., 78,
2852–2866.
Kelley, M. C., B. G. Fejer, and C. A. Gonzales (1979), An explanation for
anomalous equatorial ionospheric electric fields associated with a north-
turning of the interplanetary magnetic field, Geophys. Res. Lett., 6,
307–310.
Kelley, M. C., J. J. Makela, J. L. Chau, and M. J. Nicolls (2003), Penetra-
tion of the solar wind electric field into the magnetosphere/ionosphere
Kelley, M. C., M. N. Vlasov, J. C. Foster, and A. J. Coster (2004), A
quantitative explanation for the phenomenon known as storm-enhanced
Kikuchi, T., H. Lühr, K. Schlegel, T. Hachihara, M. Shinohara, and T.
I. Kitamura (2000), Penetration of auroral electric fields to the equator
N. J.
Liu, J. Y., H. F. Tsai, and T. K. Jung (1996), Total electron content obtained
by using the global positioning system, Terr. Atmos. Oceanic Sci., 7,
107–117.
Lu, G., A. D. Richmond, B. A. Emery, and R. G. Roble (1995), Magneto-
sphere-ionosphere-thermosphere coupling: Effect of neutral winds on
energy transfer and field-aligned current, J. Geophys. Res., 100(A10),
19,643–19,659.
Mannucci, A. J., B. D. Wilson, D. N. Yuan, C. H. Ho, U. J. Lindqvist,
and T. F. Runge (1998), A global mapping technique for GPS-derived iono-
spheric total electron content measurements, Radio Sci., 33, 565–582.
Millward, G. H., H. Rishbeth, T. J. Fuller-Rowell, A. D. Aylward, S.
Quegan, and R. J. Moffett (1996), Ionospheric F-layer seasonal and
Mozur, F. S. (1970), Electric field mapping in the ionosphere at the equa-
Nishida, A. (1968), Coherence of geomagnetic Dp2 fluctuations with
Peirimart, C., and D. Fontaine (1994), Numerical simulation of magneto-
spheric convection including the effect of field-aligned currents and elec-
Prößl, C. W. (1987), Storm-induced changes in the thermospheric compo-
Prößl, G. W. (1995), Ionospheric F-region storms, in Handbook of Atmo-
spheric Electrodynamics, edited by H. Volland, CRC Press, Boca Raton,
Florida.
Rasmussen, C. E., and M. E. Greenspan (1993), Plasma transport in the
equatorial ionosphere during the Great Magnetic Storm of March 1989,
Richmond, A. D. (1995), Ionospheric electrodynamics using Magnetic
Richmond, A. D., C. Peymirat, and R. G. Roble (2003), Long-lasting dis-
turbances in the equatorial ionospheric electric field simulated with a
coupled magnetosphere-ionosphere-thermosphere model, J. Geophys.
Geophys., 18, 730–739.
Rishbeth, H., T. J. Fuller-Rowell, and A. D. Rodger (1987), F-layer storms
Sardus, E., A. Rius, and N. Zarrasa (1994), Estimation of the transmitter
and receiver differential biases and the ionospheric total electron content
Sastri, J. H. (1988), Equatorial electric fields of the disturbance dynamo
origin, Ann. Geophys., 6, 635.


