Theoretical study of new plasma structures in the low-latitude ionosphere during a major magnetic storm

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1 Theoretical model simulations for an intense magnetic storm show the creation of a low-latitude electron density arch aligned along the geomagnetic field created by strong uplift of the F2 layer that is driven by the penetration electric field. When the arch forms during the day, a new F2 layer is created at the original altitude by photoionization, and a density hole can be created between this new F2 layer and the arch. When the arch forms during the night, the F2 layer is not recreated and no hole forms. In a vertical profile of electron density, the daytime elevated ionospheric layer can appear distinctly from the recreated F2 layer, in which case the elevated layer is called the F3 layer. A latitude cut through the night-side arch shows the characteristics of an equatorial electron density trough, bounded to the north and south by enhanced densities associated with plasma that has diffused down along the geomagnetic field from the elevated layer. It is pointed out that the signature of the night-side arch has been seen in low Earth orbit spacecraft data, but has not been previously associated with an arch structure.


1. Introduction

2 Magnetic storms are capable of creating large perturbations in electric fields, neutral winds and composition, and the global circulation of the thermosphere. These perturbations often produce significant disturbances and redistribution of the ionospheric plasma structure in the midlatitude and low-latitude regions [Tanaka, 1986; Greenspan et al., 1991; Buonsanto, 1999; Basu et al., 2001; Foster et al., 2002; Vaslov et al., 2003; Tsurutani et al., 2004; Mannucci et al., 2005; Lin et al., 2005a, 2007; Batista et al., 2006; Heelis and Coley, 2007]. Storm-generated electric field perturbations change the altitudes of the midlatitude and low-latitude ionospheric layers, which results in significant modification of the ionosphere morphology. The eastward penetration electric field raises the ionospheric layers and produces a number of effects: a large reduction in electron density in the F2 layer, called the equatorial plasma trough [Greenspan et al., 1991; Rasmussen and Greenspan, 1993]; storm enhanced density (SED) [Foster, 1993; Foster and Rideout, 2005; Huang et al., 2005]; the equatorial plasma super-fountain [Tsurutani et al., 2004; Mannucci et al., 2005; Vaslov et al., 2003; Lin et al., 2005b]; and the creation of a new ionospheric layer above the F2 layer, called the F3 layer [Zhao et al., 2005; Paznukhov et al., 2007; Balan et al., 2008].

3 Meanwhile, the disturbances in neutral wind, global circulation, and the neutral composition can also produce positive and/or negative ionospheric storm effects [Prölls, 1995; Fuller-Rowell et al., 1998; Lu et al., 2001; Kil et al., 2003; Meier et al., 2005]. In some conditions, the combined electric field and neutral wind disturbances produce more significant variations in the low-latitude ionosphere plasma structure than either effect alone [e.g., Lin et al., 2005b].

4 In this study, the structures of low-latitude ionosphere disturbances are studied by theoretical model runs under various conditions. The model runs show the detailed formation scenario of the F3 layer and the equatorial plasma trough during the intense storm period. These features, which can appear in one-dimensional observations of the electron density (vertically for the F2 layer and latitudinally for the equatorial plasma trough), are shown to be related to two types of two-dimensional structures in the meridional plane, which we call the equatorial density hole and density arch. The physical mechanisms of these peculiar storm-time electron density structures predicted by the model runs are further revealed through various controlled model simulations.

2. Model Description

5 In this study, The National Center for Atmospheric Research (NCAR) Thermosphere-Ionosphere General-Circulation Model (TIEGCM) [Roble et al., 1988; Richmond et al., 1992]
is used for simulating the global thermosphere-ionosphere responses to the storm event. The NCAR TIEGCM calculates global distributions of the neutral gas temperature, wind, and mass mixing ratios of the major and minor constituents. The TIEGCM also calculates ionospheric electric fields self-consistently at middle and low latitudes and can simulate thermosphere/ionosphere storm effects with realistic time-dependent specifications of high-latitude ionospheric convection and auroral precipitation as inputs [e.g., Lu et al., 2001]. For simulating the 29–30 October 2003 storm event, the Assimilative Mapping of Ionospheric Electrodynamics (AMIE) procedure [Richmond and Kamide, 1988], which has inputs from both ground-based and satellite measurements, is used to specify the auroral precipitation and high-latitude convection. Since the TIEGCM has an upper boundary at around 800 km altitude, an ionospheric model that can simulate the low-latitude and midlatitude ionosphere to greater altitudes is desirable for simulating the enhanced equatorial ionization anomaly (EIA) during the storm. We therefore run the Sheffield University Plasmasphere Ionosphere Model (SUPIM), using the TIEGCM neutral winds, temperature, and composition as inputs.

SUPIM is used to simulate the low-latitude ionosphere and plasmasphere [Bailey and Sellek, 1990; Bailey and Balan, 1996]. The model solves the coupled time-dependent equations of continuity, momentum, and energy for the electrons and the O⁺, H⁺, He⁺, N₂⁺, NO⁺, and O₂ ions, using the implicit finite difference method along closed eccentric-dipole geomagnetic field lines. In this simulation, 108 field lines with apex altitudes distributed from 150 km to 25,000 km are used. Since SUPIM is a two-dimensional model that only simulates the plasmasphere and ionosphere in a single longitudinal sector, we simulate the ionospheric responses to the storm event at −70° geographic longitude (≈4° magnetic longitude), the longitude where great TEC enhancements were observed by Lin et al. [2005a]. In the calculation of the plasma transport, SUPIM uses a semi-Lagrangian method that allows field lines to move vertically and meridionally with the $E \times B$ drift velocity, and interpolates back to a fixed coordinate at each time step. The TIEGCM neutral composition, temperature, and winds are interpolated to the SUPIM grid at each time step. Above the TIEGCM upper boundary at pressure level +7 (~800 km in altitude in this simulation), the neutral winds and temperature are assumed to equal their upper boundary values, while the densities of N₂, O₂, and O are assumed to be in diffusive equilibrium. The $E \times B$ drifts derived from ROCSAT-1 measurements, scaled as described by Lin et al. [2005b] and shown in Figure 1, are used to specify field line convection in SUPIM. The scaled $E \times B$ drifts at 300 km altitude are used for field lines with apex heights between 200 and 600 km, while the scaled $E \times B$ drifts at 2000 km altitude are used for field lines with apex heights between 2000 and 4000 km. Linear interpolation is used for field lines at intermediate apex heights, and zero drift is used for the highest and lowest field lines. The $E \times B$ drifts between 4000 km and the altitude of the second outermost field line, 24,500 km, are calculated by interpolating the $E \times B$ drift at 4000 km and zero $E \times B$ drift at 25,000 km.

The simulation in this study is the same as one of those presented by Lin et al. [2005b]. It considers the storm-time $E \times B$ drifts derived from ROCSAT-1 observations and the storm-time neutral winds from the NCAR-TIEGCM runs. Since the neutral composition effect mainly contributes to decrease the electron density above ±35° magnetic latitude and to increase it in the low-latitude and equatorial region without changing the general plasma structure, the quiet time neutral composition output from the TIEGCM run is incorporated here.

The model results show the existence of an F₂ layer, an equatorial electron density hole, an equatorial density

Figure 1. Upward $E \times B$ drift derived from ROCSAT-1 measurements over the America sector where the model simulations are performed. The $E \times B$ drift measurement is projected to the apex altitude of the magnetic field line and scaled to 300 and 2000 km with approximations described by Lin et al. [2005b]. Dashed lines are the quiet time $E \times B$ drifts, and the triangles are $E \times B$ drifts derived from ROCSAT-1 measurements. Solid lines are the cubic-spline fits to the summations of the triangles and quiet time $E \times B$ drifts (adapted from Lin et al., 2005b).
trough, and electron density arches (or feature of the electron density ridges observed by in situ measurements of the low Earth orbit satellites). The details and the associated formation scenario of each density structure are described and discussed in following sections.

3. Equatorial Density Hole and $F_3$ Layer

Figure 2 shows the simulation results by considering the storm-time $E \times B$ drift and storm-time neutral winds from 16:00 UT to 24:00 UT (11:20 LT to 19:20 LT) of 29 October (Day of Year or DOY:302), with magnetic field lines indicated by white curved lines. The uplift of the $F_2$ layer starts between 18:00 UT and 19:00 UT (13:20 LT and 14:20 LT) and the layer reaches its highest altitude at 21:00 UT (16:20 LT). After 21:00 UT, the uplifted plasma shows clear downward diffusion to lower altitudes and higher latitudes, with clear enhancements at the two EIA crests. From 21:00 to 24:00 UT, an electron density hole is clearly seen between 800 and 1800 km altitude, that is, a region of low density surrounded above, below, to the north and to the south by higher densities. Newly replenished electron density forms around 500 km between the EIA maxima, and starts to form a new $F_2$ layer around 19:00 UT while the earlier uplifted layer becomes the $F_3$ layer. The new $F_2$ layer develops higher density than the $F_3$ layer at 23:00 UT (18:20 LT). The density hole is, therefore, located between the new $F_2$ and $F_3$ layers, within the field-aligned plasma structure.

Figure 2. Time-evolution of the low-latitude electron density structure during the 29 October 2003 storm at $-70^\circ$ geographic longitude, showing the formation of the electron density hole and the $F_3$ layer from 16:00 UT to 24:00 UT (11:20 LT to 19:20 LT). Magnetic field lines are indicated by white lines.

Figure 3 shows the corresponding vertical electron density profiles at the magnetic equator from Figure 2, indicating the formation of the $F_3$ layer. The electron density profiles of the $F_3$ layer signature shown in Figure 3 are very similar to the $F_3$ layer formed during magnetically quiescent period as shown by Balan et al. [1998]. The model result is further compared with the ionospheric profile observed at the same longitude sector by ground-based radar. Figure 4 shows the ionograms recorded by a Digisonde [Reinisch, 1996] located at Jicamarca during 19:00–19:45 UT on 29 October 2003, taken from the University of Massachusetts Lowell Digital Ionosonde Data Base, DID Base [Khmyrov et al., 2008]. From Figure 4, it is clearly seen that the $F_3$ layer rises to very high altitudes and becomes the $F_3$ layer between 19:15–19:45 UT. The ionogram at 19:30 UT shows the signature of the $F_3$ trace at a virtual height of 1260 km. At 19:45 UT the bottom of the $F_3$ layer goes beyond the ionosonde observation limit of virtual height (1280 km). Comparing Figures 3 and 4 confirms that the layer uplift time simulated by the theoretical model coincides well with the ionosonde observation at Jicamarca, indicating that the specification of the storm-time upward $E \times B$ drift from the ROCSAT-1 measurement agrees well with the observed condition. From the model results (Figure 3), the altitudes of the $F_3$ layer bottom and peak are 800 km and 1050 km, respectively, at 19:00 UT. Around the same time, the bottom of the $F_3$ layer (the ledge of the $F_3$ layer trace) goes to around the observation limit of the ionosonde at 1280 km virtual
height, at 19:15 UT in Figure 4. After 20:00 UT, the model results show that the peak of the F$_3$ layer goes above 1500 km, which is far beyond the sounding limit of the ionosonde. Due to this limitation, the actual altitude extent of the F$_3$ layer is not available for comparison with the model result. It should be noted that the F$_3$ layer could not be observed by the ionosonde after the equatorial electron density hole had fully formed, when the plasma frequency of the F$_2$ layer was bigger than that of the F$_3$ layer. Additionally, the strong uplift of the ionosphere layer is also seen from the profilogram constructed by the ionosondes observations starting at 18:00 UT on October 29 (see Appendix A).

[11] F$_3$ layer features similar to that shown in Figures 3 and 4 was also seen by incoherent scatter radar observations at Jicamarca (Woodman, private communication, 2008). The physical mechanism for the F$_2$-F$_3$ double-layer structure as shown in Figure 3 is straightforward, and is similar to the mechanism of the quiet time F$_3$ layer formation in the equatorial region [see Balan et al., 1998]. In both quiet and disturbance periods, the daytime upward $E \times B$ drift driven by the quiet time wind dynamo or the eastward penetration electric field raises the F$_2$ layer to a higher altitude, whereupon a new layer is formed at the original F$_2$ layer altitude when sunlight is still available for producing new ionization there. The major differences between the quiet and storm conditions are the appearance time and the necessary time for its formation. During quiet times, the F$_3$ layer is seen mainly around noon, where the normal quiet time upward $E \times B$ drift
Figure 4. Ionograms recorded by the Jicamarca Digisonde during 19:00 UT to 19:45 UT on 29 October 2003. The black solid line in each subplot is the true height profile calculated from the measured echo traces [Huang and Reinisch, 2001]. The signature of the bottom F3 layer is seen between 1200 and 1280 km virtual heights but disappeared at 19:45 UT.
During storm periods, on the other hand, a strong upward $\mathbf{E} \times \mathbf{B}$ drift resulting from an eastward penetration electric field may occur at any time that an eastward penetration electric field exists. The time needed for producing the $F_3$ layer may be shorter during storm periods, especially during an intense magnetic storm, since the eastward penetration electric field often enhances the upward $\mathbf{E} \times \mathbf{B}$ drift rapidly and accelerates the $F_2$ layer uplift.

4. Equatorial Density Arch and Density Troughs and Ridges

To examine the hypothesis of the formation mechanism of the equatorial electron density hole due to photoionization, a controlled test simulation is run by postponing the storm-driven upward $\mathbf{E} \times \mathbf{B}$ drifts for five hours, starting at around 23:00 UT (18:20 LT), so that there is no sunlight to produce new ionization after the $F_2$ layer uplift. Since the storm-driven $\mathbf{E} \times \mathbf{B}$ drift is often seen to be upward at the dusk sector [e.g., Maruyama et al., 2005], this controlled condition may exist in other storm events. Figure 5 shows the results from the controlled test run, which shows the $F_2$ layer in the equatorial region starting to rise at 00:00 UT (19:20 LT) on the next day, October 30, and reaching 2000 km altitude after two hours, at 02:00 UT (21:20 LT). It is noted that the thickness of the uplifted layer is different from that shown in Figure 2, which is due to the equatorward neutral wind effect. In the controlled test run, we postpone the storm-driven upward $\mathbf{E} \times \mathbf{B}$ drift by five hours while the storm-produced equatorward winds continue to blow from polar-latitude to low-latitude regions. According to Lin et al. [2005b], the equatorward neutral wind could transport plasma from higher to lower latitudes and result in a thicker ionospheric $F_2$ layer (see their Figure 5a).

Figure 5 shows that, instead of a density hole, an equatorial density arch is formed beginning around 01:00 UT (20:20 LT). A latitudinal cut through this density arch at 800–900 km altitude, would produce a trace similar to the Defense Meteorological Satellite Program (DMSP) observations of an equatorial density trough, as first reported by Greenspan et al. [1991] during the magnetic superstorm of March 1989. Greenspan et al. [1991] suspected this structure was formed due to a strong eastward penetration electric field that lifts the bottomside $F$ layer above the DMSP satellite altitude. This feature was later modeled by Rasmussen and Greenspan [1993], confirming the viability of the proposed theory. Similar features are often seen by satellite in situ electron density observations during major magnetic storm events [e.g., Basu et al., 2001; Lee et al., 2002; Kil et al., 2006; Heelis and Coley, 2007]. The density trough modeled here again shows the same mechanism and a similar result as Rasmussen and Greenspan [1993]. As an alternative to the theory proposed by Greenspan et al. [1991], the trough feature has recently been explained in terms of storm induced big bubbles (SIBBs) by Kil and Paxton [2006]. This theory proposes that the storm-produced big plasma bubbles are
later flattened by increasing recombination due to an increasing \([\text{N}_2]/[\text{O}]\) neutral composition disturbance. Since the SUPIM and the TIEGCM model runs do not model plasma bubbles, our study does not consider the mechanism proposed by Kil and Paxton [2006].

The controlled test run shows that when the original equatorial F\(_2\) layer and its bottomside are raised to much higher altitudes after sunset, no new ionization forms at the original F\(_2\) layer altitude, due to lack of photoionization. This controlled test run supports the theory regarding the forma-

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**Figure 6.** Latitudinal profiles of the electron density averaged between 850-km and 950-km altitude from 03:00 UT (22:20 LT) to 04:30 UT (23:50 LT) on October 30 (DOY: 303) from the controlled test simulation shown in Figure 5. Vertical dashed lines indicate the location of the magnetic equator. Dashed circles indicate the signature of the electron density arch. The equatorial density trough is seen around \(-20°–0°\) geographic latitude (\(\sim-10°–10°\) magnetic latitude).

**Figure 7.** Total ion density (cm\(^{-3}\)) measured by the DMSP F14 spacecraft at around 800–900 km height, plotted as a function of geographic latitude during the 15 July 2000 superstorm (figure adapted from Lee et al. [2002]). Dashed circles mark the possible signature of an electron density arch (density ridge).
The mechanism of the density hole occurring here is different from that of the density hole occurring during quiet solstitial periods as modeled by Huba et al. [2000]. The latter is formed due to the collisionally coupling of $\text{O}^{+}$ and $\text{H}^{+}$ at high altitudes.

Another interesting feature seen in Figure 5 is the arch-like electron density structure with high-altitude maxima seen at $-40^\circ$ and $20^\circ$ geographic latitude (corresponding to $\pm30^\circ$ magnetic latitude) starting around 02:00 UT (21:20 LT) and continuing until 08:00 UT (03:20 LT). It is clearly seen that the density arch structure is the feature of downward diffusion of the uplifted $\text{F}_2$ layer, and the density enhancements of both the northern and southern hemispheres are aligned along magnetic field lines. The density arch has not been reported before, although its signature may appear in satellite observations flying across the structure in the north-south direction.

To see how the density trough and the arch signature appear at low Earth orbit satellite altitudes, the latitudinal electron density profiles at 850–950 km altitude from the controlled test run shown in Figure 5 are plotted in Figure 6 from 03:00 UT to 04:30 UT (22:20 LT to 23:50 LT) on 30 October. The equatorial density troughs are seen around $-20^\circ$–$0^\circ$ geographic latitude ($-10^\circ–10^\circ$ magnetic latitude). The signatures of the electron density arches which appear as the electron density ridges on the northern and southern edges of a trough are indicated by dashed circles. Although the electron density (density arch–like signatures) has not been reported previously in observations or theoretical modeling, the arch signa-

**Figure 8.** Total ion density (cm$^{-3}$) measured by the DMSP F9 spacecraft at around 800–900 km height, plotted as a function of magnetic latitude for two successive passes near 21:30 LT on 14 March 1989. The labels to the right of each plot give the universal time and geographic latitude and longitude at which the spacecraft crossed the magnetic equator (figure adapted from Rasmussen and Greenspan [1993]). Dashed circles mark the possible signature of the electron density arch (density ridge).

**Figure 9.** Electron densities from 00:00 UT (11:20 LT) to 08:00 UT (19:20 LT) on 30 October 2003 (DOY: 303) from the controlled test simulation that replaces the storm-time wind by the quiet time wind and postpones the upward drift by 5 hours.
The feature shown in Figure 6 is very similar to the DMSP in situ electron density observations around 800–900 km reported by Lee et al. [2002] during another superstorm period (Figure 7). The dashed circles in Figure 7 mark an arch signature like that from the model results in Figure 6. Similar density ridge features are also seen in the observations reported by Greenspan et al. [1991]. Figure 8 shows the total ion density measured by the DMSP F9 spacecraft plotted as a function of magnetic latitude for two successive passes near 21:30 LT on 1989 March 14, adopted from the work of Rasmussen and Greenspan [1993] with the density ridges marked by dashed circles. The major difference between the density ridges shown in Figure 8 and those in Figures 6 and 7 is the narrower latitude extent/width of the former. The different latitude extents of the density arches at DMSP altitude may result from differences in the $F_2$ layer thickness prior to the uplift. To examine this hypothesis, another controlled test simulation is performed in which the storm-time neutral wind is replaced by the quiet time neutral wind. This produces a thinner $F_2$ layer prior to the uplift. Figure 9 shows that the test simulation again reproduces the equatorial density arch. The latitudinal density profiles at 850–950 km altitude shown in Figure 10 present a narrower latitude extent of the density ridge (density arch–like signatures), similar to that shown by Rasmussen and Greenspan [1993, Figure 8]. This result confirms that the thickness of the $F_2$ layer prior to the uplift determines the latitude extent of the density ridges observed at the DMSP altitude.

Comparisons of the modeled electron density troughs shown in Figures 6 and 10 with those observed by DMSP in Figures 7 and 8 show disagreement in the electron density gradient at the wall of density trough adjacent to the density ridge. The latitudinal electron density gradient between the density ridge and trough observed by the DMSP is much steeper than the model result. It is possibly due to the fact that the DMSP satellite flies across the depletion region in both the latitudinal and longitudinal directions. If the electron density depletion is distributed along the magnetic field line only at a certain longitude, the in situ measurement by the satellite flying over the region across longitudes may show a very sharp electron density decrease [Kil et al., 2006].

5. Summary

From the theoretical model simulations performed in this study, new ionospheric plasma structures are predicted.
and their formation mechanisms are explained. Moreover, the known storm-time features of the F3 layer and the equatorial density trough are also modeled and explained by controlled test simulations. We summarize the major results and new findings of this study as follows.

[18] 1. An electron density hole appears when a large storm-produced upward $E \times B$ drift occurs during daytime, where photoionization due to sunlight is still effective. The original F2 layer plasma is raised to a much higher altitude, forming an arch that corresponds to the F3 layer in a vertical cut through the feature, while new ionization is formed at the location of the original F2 layer. The electron density hole is then located between the arch and the replenished F2 layer.

[19] 2. The formation mechanism of the storm-time F3 layer by rapid uplift of the F2 layer is similar to the mechanism that produces the quiet time F2 layer. The F3 layer is modeled in either daytime or evening hours if the storm-produced uplift exists. Prior to the clear formation of an equatorial electron density hole, the F2 layer appears, as seen around 19:00–20:00 UT (14:20–15:20 LT) in Figures 2 and 3, which are consistent with the ionosonde observation at Jicamarca (Figure 4).

[20] 3. The controlled test simulation that postpones the upward drift until after sunset, when photoionization ceases, produces an electron density arch and an associated electron density trough, similar to the previous study by Rasmussen and Greenspan [1993]. The controlled simulation confirms that the formation of an equatorial density hole does not occur in the absence of photoionization.

[21] 4. Our model simulations predict a new electron density structure, the equatorial electron density arch and electron density ridge located on the northern and southern edges of a density trough. The density arch is produced by the downward field-aligned diffusion of the plasma that was raised from the original F2 layer to higher altitudes by the storm-produced upward $E \times B$ drift. The density arch signature, revealed as the electron density ridge, is seen in the in situ observations by the DMSP satellite presented by Greenspan et al. [1991], but attention has not been drawn to this feature until the present study. From the simulation results, the latitude extent/width of the density ridge feature at 800–900 km altitude depends on the thickness of the ionospheric layer prior to the uplift.

Appendix A

[22] Figure A1 shows a profilogram composed from true height analysis of ionograms recorded by a Digisonde located at Jicamarca for the period 28–30 October. The data gaps correspond to times of severe spread F where no unique electron density profile exists. The black line is hmF2 showing the fast rise starting at ~18:00 UT on 29 October.

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References


88, 563–601.
Foster, J. C. (1993), Storm time plasma transport at middle and high
Foster, J. C., and W. Rideout (2005), Midlatitude TEC enhancements dur-
ing the October 2003 superstorm, Geophys. Res. Lett., 32, L12S04,
Foster, J. C., P. J. Erickson, A. J. Coster, J. Goldstein, and F. J. Rich (2002),
Fuller-Rowell, T. J., M. V. Codrescu, R. G. Roble, and A. D. Richmond
(1998), How does the thermosphere and ionosphere react to a geomagnetic
Tsurutani et al., pp. 203–225, AGU, Washington, D. C.
Greenspan, M. E., C. E. Rasmussen, W. J. Burke, and M. A. Abdu (1991),
Equatorial density depletions observed by the Millstone Hill incoherent
scatter radar and global GPS ionograms in real time, Radio Sci.,
26(2), 335–342.
equatorial ionization anomaly peaks in the West Pacific Region during
the October–November 2003 superstorm: Relative importance of the neutral
Kil, H., and L. J. Paxton (2006), Ionospheric disturbances during the mag-
68, 1573–1582.
Kil, H., and L. J. Paxton (2006), Ionospheric disturbances during the mag-
study of the 15 July 2000 magnetic storm effects on the ionosphere-driver
of the positive ionospheric storm observed at 840 km during the great mag-
Kil, H., and L. J. Paxton (2006), Ionospheric disturbances during the mag-
Lee, J. H., X. Min, Y. P. Kh, J. Y. Kim, V. Hegai, K.-I. Oyama, F. J. Rich,
and J. Kim (2002), Large density depletions in the nighttime upper
ionosphere during the magnetic storm of July 15, 2000, Geophys. Res. Lett.,
Tsai, and S.-Y . Su (2005a), Large-scale variations of the low-latitude
ionosphere from localized observations: Technique, Geophys. Res. Lett.,
Meier, R., G. Crowley, D. J. Strickland, A. B. Christensen, L. J. Paxton,
D. Morrison, and C. L. Hackert (2005), First look at the 20 November
2003 superstorm with TIMED/GUVI. Comparisons with a thermospheric
Paznukhov, V. Y., B. W. Reinisch, P. Song, X. Huang, T. W. Bullett, and
O. Veliz (2007), Formation of an F3 layer in the equatorial ionosphere: A
result from strong IMF changes, J. Atmos. Sol. Terr. Phys., 69, 1292–
1304.
Pröss, G. W. (1995), Ionospheric F-Region Storms, in Handbook of Atmo-
spheric Electrodynamics II, edited by H. Volland, pp. 195–248, CRC
Press, Boca Raton.
Rasmussen, C. E., and M. E. Greenspan (1993), Plasma transport in the
equatorial ionosphere during the great magnetic storm of March 1989,
Reinisch, B. W. (1996), Modern Ionosondes, in Modern Ionospheric
Science, edited by H. Kohl, R. Ruster, and K. Schlegel, pp. 440–458,
European Geophys. Soc., Katlenburg-Lindau, Germany.
Richmond, A. D., and Y. Kamide (1988), Mapping electrodynamic features
of the high-latitude ionosphere from localized observations: Technique,
Richmond, A. D., E. C. Ridley, and R. G. Roble (1992), A thermosphere/ ionosphere
general circulation model with coupled electrodynamics, Geophys. Res.
coupled thermosphere/ionosphere general circulation model, Geophys.
Tanaka, T. (1986), Low-latitude ionospheric disturbances: Results for
March 22, 1979, and their general characteristics, Geophys. Res. Lett.,
13(13), 1399–1402.
Tsurutani, B., et al. (2004), Global dayside ionospheric uplift and enhance-
ment associated with inter planetary electric fields, J. Geophys. Res.,
Vlasov, M., M. C. Kelley, and H. Kil (2003), Analysis of ground-based and
satellite observations of F-region behavior during the great magnetic
Zhao, B., W. Wan, and L. Liu (2005), Responses of equatorial anomaly to