F_3 layer during penetration electric field

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[1] The occurrence of an additional layer, called F_3 layer, in the equatorial ionosphere at American, Indian, and Australian longitudes during the super double geomagnetic storm of 7–11 November 2004 is presented using observations and modeling. The observations show the occurrence, reoccurrence, and quick ascent to the topside ionosphere of unusually strong F_3 layer in Australian longitude during the first super storm (8 November) and in Indian longitude during the second super storm (10 November), all with large reductions in peak electron density (Nmax) and total electron content (GPS-TEC). The unusual F_3 layers can arise mainly from unusually strong fluctuations in the daytime vertical $\mathbf{E} \times \mathbf{B}$ drift as indicated by the observations and modeling in American longitude. The strongest upward $\mathbf{E} \times \mathbf{B}$ drift (or eastward prompt penetration electric field, PPEF) ever recorded (at Jicamarca) produces unusually strong F_3 layer in the afternoon hours ($\approx 1400-1600$ LT) of PPEF, with large reductions in Nmax and TEC; the layer also reappears in the following evening ($\approx 1700-1800$ LT) owing to an unusually large downward drift. At night, when the drift is unusually upward and strong, the *F* region splits into two layers.

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1. Introduction

[2] An additional stratification of the equatorial F_2 layer has been known since 1940s [e.g., Sen, 1949; Ratcliffe, 1951] though the stratification could not be explained (H. Rishbeth, private communication, 2000). Recent modeling studies of the equatorial plasma fountain and its effects [e.g., Hanson and Moffett, 1966; Anderson, 1981] using the Sheffield University Plasmasphere Ionosphere Model (SUPIM) [Bailey and Balan, 1996] revealed the possibility of existence of an additional layer in the equatorial F region [Balan and Bailey, 1995]. Following this prediction, the additional layer, called F_3 layer, was detected at an equatorial station Fortaleza (3°S, 38°W, dip 2°S) in Brazil [Balan et al., 1997; Jenkins et al., 1997]. A possible mechanism for the F_3 layer and its statistics of occurrence including day-today variability were also reported recently [Balan et al., 1998, 2000]. Lynn et al. [2000] presented the occurrence of

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 F_3 layer at equatorial latitudes in Southeast Asia. *Rama Rao et al.* [2005] reported the observations of the layer at three equatorial stations in India.

[3] According to the physical mechanism [Balan et al., 1998], an F_3 layer forms during daytime ($\approx 0830-1630$ LT) within $\approx \pm 10^{\circ}$ mag. lat. from the production of ionization and unique dynamics of the equatorial F region. As the daytime F_2 layer drifts upward mainly due to upward $\mathbf{E} \times \mathbf{B}$ drift and partly due to equatorward neutral wind (and other dynamical sources, not included in the model calculations), a new layer develops at lower altitudes through the usual photochemical and dynamical processes of the equatorial Fregion. As time progresses, the original F_2 layer drifts upward and forms F_3 layer while the new layer develops into usual F_2 layer. Both layers can be detected by bottomside ionosondes for sometime when the density of F_3 layer remains greater than that of F_2 layer. As time progresses further, both layers drift upward, and the density of F_3 layer decreases while that of F_2 layer increases. When the density of F_3 layer becomes less than that of F_2 layer, the F_3 layer can be observed by topside sounders as topside ledges. The F_3 layer formation ceases after sunset owing to the absence of photoionization though topside ledges can continue to exist well after sunset.

[4] Though the main driver of F_3 layer is the upward $\mathbf{E} \times \mathbf{B}$ drift, the layer is expected to form centered at that equatorial location where the combined effect of the $\mathbf{E} \times \mathbf{B}$ drift and equatorward neutral wind (and other dynamical sources) provide a vertical upward plasma velocity. On the basis of average upward drift [*Fejer et al.*, 1991] and Horizontal Wind Model (HWM) [*Hedin et al.*, 1991],

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Figure 1. Comparison of geomagnetic storm indices (Dst and Kp, Figures 1c and 1d) during 6–11 November 2004 with solar wind dynamic pressure (Figure 1a). X component (minus 37450 nT) of the geomagnetic field (Figure 1b) at a low-latitude station (Guangzhou, 23.1°N 113.3°E, 12.9°N mag. lat.) is also shown.

distinct F_3 layer is predicted to occur on the summer side of the geomagnetic equator. However, observations show that the layer occurs also in winter months [e.g., Batista et al., 2002; Rama Rao et al., 2005], which can be due to the variability of the driving sources (drift, wind, tides and waves) [Balan et al., 1998]. Uemoto et al. [2007] reported the first simultaneous observation of F_3 layer on either side of the geomagnetic equator. Since the ionosphere becomes denser and broader and daytime upward $\mathbf{E} \times \mathbf{B}$ drift remains more or less constant with increasing solar activity [e.g., Namboothiri et al., 1989; Fejer et al., 1991], the F_3 layer was predicted to occur less frequently with increasing solar activity [Balan et al., 1998]. The prediction was confirmed by the solar activity dependence of the layer observed at Fortaleza in Brazil [Batista et al., 2002] and Waltair in India [Rama Rao et al., 2005].

[5] Sayers et al. [1963] detected topside ledges in the equatorial ionosphere using a Langmuir probe onboard Ariel-I satellite. They predicted that topside ionograms should reveal the ledges as cusps. Lockwood and Nelms [1964] detected such ledges as cusps in the topside sounder ionograms from Alouette-I satellite. Raghavarao and Sivaraman [1974] observed topside ledges in Indian longitudes using ISIS-II topside sounder. Uemoto et al. [2004, 2006] reported a statistical analysis of the ionization ledge in the equatorial ionosphere using Ohzora (EXOS-C) and ISIS-2 satellite observations. They conclude that the char-

acteristics of the ionization ledge and F_3 layer are similar, and topside ledges continue to exist after sunset.

[6] Thampi et al. [2005] reported the first evidence of F_3 layer and topside ledges in total electron content (TEC). Recently, using the SUPIM model, Thampi et al. [2007] showed that while normal electrodynamics and normal neutral dynamics can produce F_3 layer and topside ledges in electron density profiles, strong (additional) localized equatorward meridional neutral wind (possibly due to waves) is required for the formation of ledges in the latitude variation of TEC. Fagundes et al. [2007] reported wave activity and an additional stratification of the F_2 layer under quiet conditions at an equatorial anomaly crest location (23.2°S, 45.9°W; 17.6° dip lat.) in Brazil. Such stratification of F_2 layer due to wave activity, which can occur occasionally at all latitudes and at all local times, does not seem to correspond to the daytime F_3 layer around the equator caused mainly by upward $\mathbf{E} \times \mathbf{B}$ drift.

[7] The observations also showed continuous geomagnetically active days when F_3 layer occurred and did not occur [Balan et al., 2000], which has not been explained. The present paper reports the observations and modeling of F_3 layer during a super double geomagnetic storm during 7–11 November 2004 when large fluctuations in equatorial vertical $\mathbf{E} \times \mathbf{B}$ drift including the strongest daytime prompt penetration electric field (PPEF) ever recorded occurred [Fejer et al., 2007]; strong PPEF during post sunset hours have been reported earlier [e.g., Batista et al., 1991; Abdu et al., 2007]. The geomagnetic storm and $\mathbf{E} \times \mathbf{B}$ drift are described in sections 2 and 3. Section 4 contains the observations of F_3 layer and associated decreases in Nmax and TEC in the equatorial ionosphere at American, Indian and Australian longitudes. The effects of the storm time vertical $\mathbf{E} \times \mathbf{B}$ drift (PPEF) and equatorward neutral wind on F_3 layer, Nmax and TEC are modeled in section 5 using SUPIM model [Bailey and Balan, 1996]. Section 6 contains conclusions. Quantitative data/model comparisons are not attempted due to the non-availability of measured neutral wind and densities.

2. Geomagnetic Storm

[8] Figure 1 shows the geomagnetic storm indices (Kp and Dst) and dynamic pressure (Figure 1a) of the extreme solar wind (or coronal mass ejection, CME) that produced the storm. The X component of the magnetic field (one-minute resolution) at a low-latitude station is also shown (Figure 1b) for comparison. As shown by Figure 1, the CME clouds during 7–8 November produced the first super storm, with storm sudden commencement (SSC) at 0253 UT and storm main phase (MP1) onset at \approx 2130 UT on 7 November; Dst reached –373 nT at 0700 UT and Kp reached 9 during 0300–0900 UT on 8 November. While the storm was recovering, the next CME clouds during 9–11 November reintensified the storm, with second MP (MP2) onset at \approx 1200 UT on 9 November; Dst reached –289 nT at 1100 UT and Kp reached 9 during 0900–1200 UT on 10 November.

3. Penetration Electric Field

[9] Figure 2 shows the vertical $\mathbf{E} \times \mathbf{B}$ plasma drift velocity measured at the equatorial station Jicamarca



Figure 2. Vertical $\mathbf{E} \times \mathbf{B}$ drift velocity measured at the equatorial station Jicamarca (integrated for five minute intervals and over $\approx 200-600$ km altitudes) in American longitude during 9–10 November 2004 (solid curve). The large upward drift at around 1500 LT on 9 November corresponds to the eastward prompt penetration electric field (PPEF). The average quiet time drift velocity (dotted curve) is also shown.

(11.9°S, 76.8°W; dip latitude 1°N) during 9–10 November; data are available only from 9 November [Fejer et al., 2007]. The dotted curve gives the corresponding quiet time average drift velocity. As shown, the velocity during the storm period undergoes large deviations from the average velocity, and the strongest upward drift (or eastward prompt penetration electric field, PPEF), with the velocity reaching 126 m s^{-1} , occurred for about two hours at around 2000 UT (1500 LT) on 9 November. A comparison of this electric field at Jicamarca (Figure 2) with simultaneous high-latitude electric field measured by EISCAT radar, magnetospheric electric field measured by Cluster spacecraft, and solar wind velocity and dynamic pressure and IMF Bz measured by ACE (Advanced Composition Explorer) spacecraft are shown elsewhere [Balan et al., 2008]. The comparisons indicate that the strongest PPEF (Figure 2) might have been generated in the interplanetary space/magnetosphere by $\mathbf{v} \times \mathbf{B}$ effect, which was mapped to high-latitude ionosphere along geomagnetic field lines and promptly penetrated to low latitudes, with an efficiency of about 10%. The other unusually large deviations of the vertical drift in Figure 2 are discussed by Fejer et al. [2007], and seem to be due to eastward and westward prompt penetration and disturbance dynamo action [e.g., Kikuchi et al., 2000; Kelley et al., 2003].

4. Observations and Discussion

4.1. American Longitude

[10] Figure 3 shows a comparison of the vertical plasma drift velocity and peak electron density Nmax measured at Jicamarca on 9 November; Nmax at another equatorial station Sao Luis (44.2°W, 2.3°S; dip angle 0.5°S), two hours to the east of Jicamarca, is also shown. The comparison shows the well known control of the vertical $\mathbf{E} \times \mathbf{B}$ drift on Nmax [e.g., *Hanson and Moffett*, 1966; *Anderson*, 1973; *Huba et al.*, 2000; *Rishbeth*, 2000]. For example, starting from sunrise to the start of PPEF, when the upward drift is less than normal, Nmax remains well above the quiet

time level. During the period of PPEF ($\approx 1900-2100$ UT), Nmax undergoes an unusually large depletion due to the equatorial upward plasma fountain becoming a super plasma fountain that removed large amount of ionization from around the ionospheric peak to high altitudes and latitudes [Balan and Bailey, 1995]. Following such a large depletion in the afternoon-evening period ($\approx 1400-1800$ LT), one would expect Nmax to decay exponentially (and disappear) with time. Instead, Nmax increases well above the quiet time level, which coincides with a large downward $\mathbf{E} \times \mathbf{B}$ drift. The downward drift can increase Nmax by compressing the equatorial ionosphere [Tan, 1982] and by bringing ionization back from high altitudes and latitudes [Balan and Bailey, 1995]. An equatorward neutral wind might have also existed during the storm period [e.g., Fuller-Rowell et al., 1994]. The mechanical and chemical effects of the equatorward wind [e.g., Roble et al., 1977; Balan et al., 2008] can contribute to the abnormal increase of Nmax (section 5.2).

[11] The above unusual effects in Nmax are also observed in TEC. Figure 4 shows the GPS-TEC measured at two lowlatitude locations (47.9°W, 15.9°S; 71.5°W, 16.5°S) close to Jicamarca and Sao Luis. As Figure 4 shows, the effects in TEC are similar to those in Nmax though the reduction in TEC during PPEF is not as much as in Nmax. That is due to the contribution in TEC of the ionization that is drifted to the topside ionosphere during PPEF.



Figure 3. Comparison of peak electron density Nmax at the equatorial stations Jicamarca (Figure 3b) and Sao Luis (Figure 3a) in American longitude on 9 November 2004 with the vertical drift velocity at Jicamarca (Figure 3c).



Figure 4. GPS-TEC at two stations close to Jicamarca (Figure 4b) and Sao Luis (Figure 4a) in American longitude on 9 November 2004.

[12] Strong and distinct F_3 layer developed during the period of PPEF. That is shown by sample ionograms together with true height profiles at selected local times at Jicamarca in Figure 5. As shown by the ionograms, a distinct F_3 layer that moves upward started developing at around 1430 LT (1930 UT). The layer became strong and distinct at around 1530 LT and ascended beyond the height range (1280 km) of the ionosonde at around 1545 LT. The difference between fo F_3 and fo F_2 is large (≈ 3.5 MHz). The maximum critical frequency of the ionosphere, which was over 14 MHz before the development of F_3 layer, reduced to about 7 MHz when F_3 layer drifted to the topside ionosphere. By the time the layer reached topside ionosphere, E \times **B** drift turned downward (Figures 2 and 3a), and fo F_2 started increasing and reached over 12 MHz at around 1730 LT. At that time, there is a peculiar appearance of the ionogram at its high-frequency end (Figure 5), which seems to be due to the topside ledge drifting downward and merging with F_2 layer as modeled in section 5.1.

4.2. Indian Longitude

[13] Under magnetically quiet conditions, the F_3 layer at the equatorial station Trivandrum (77.0°E, 8.5°N; 0.5°N magnetic) in India is weak even in summer months [*Rama Rao et al.*, 2005; *Thampi et al.*, 2007] when the layer is expected to be distinct [*Balan et al.*, 1998]. Contrary to this quiet time behavior, strong F_3 layer occurred, reoccurred and quickly ascended to the topside ionosphere during the second super storm (10 November). That is shown by the ionograms at selected local times in Figure 6. As shown by the ionograms in the left-hand panel, a clear F_3 layer developed in the morning at around 1030 LT and quickly ascended to the topside ionosphere. The layer reoccurred in the afternoon at around 1315 LT and again quickly ascended to the topside ionosphere (right-hand panel). The difference between foF_3 and foF_2 (up to 3.5 MHz, Figure 6) is high compared to the difference (up to 2.3 MHz) under quiet conditions; the ascent of the layer (in about an hour) is also fast compared to quiet conditions when the layer takes two to three hours to ascend to the topside ionosphere [e.g., *Balan et al.*, 1998].

[14] The reduction of the maximum critical frequency (or Nmax) during the development of the strong F3 layer (Figure 6) is also large (by over 5 MHz) compared to that under quiet conditions. Figure 7 shows the variation of Nmax at Trivandrum and GPS-TEC at a nearby station Bangalore (77.6°E, 13.0°N; 5.0° magnetic) during 9-10 November 2004; time resolution is 15 minutes for Nmax and one hour for TEC. As shown, though Nmax and TEC are reduced during 1000-2100 LT (10 November), there is an increase of Nmax for a small duration (around 1200 LT) in between the occurrence and reoccurrence of F_3 layer. The above features of F_3 layer (Figure 6) and Nmax and TEC (Figure 7) indicate the possibility of unusually large fluctuating vertical $\mathbf{E} \times \mathbf{B}$ drift on 10 November. The drift measured at Jicamarca shows such large velocities of over 60 m s⁻¹ during 0000-0900 UT (10 November, Figure 2), which covers the local time of strong F_3 layers at Trivandrum (Figure 4a). As shown by Figures 3a and 4b, the effects on Nmax of the $\mathbf{E} \times \mathbf{B}$ drift on 9 November are also similar in American and Indian longitudes, but shifted in local time.

4.3. Australian Longitude

[15] In Australian longitude, strong F_3 layer occurred, reoccurred and quickly ascended to the topside ionosphere during the first super storm (8 November). The layer also occurred on the comparatively less active day (9 November) though of a different character. The occurrence in the morning (around 1130 LT) and reoccurrence in the afternoon (around 1330 LT) of the F_3 layer on 8 November are illustrated in Figure 8 which shows the ionograms at selected local times at the equatorial station Vanimo (141.4°E, 2.7°S; 11.6°S magnetic latitude). The F_3 layers are strong and quickly ascended to the topside ionosphere, which might have been caused by large fluctuations in the vertical $\mathbf{E} \times \mathbf{B}$ drift. No drift measurements are available for 8 November. However, as shown by the similarities of the F_3 layers on 08 and 10 November (Figures 6 and 8) and solar wind (Figure 1) and IMF characteristics, large fluctuations in the vertical $\mathbf{E} \times \mathbf{B}$ drift might have occurred during 7-8 November as during 9-10 November.

[16] As shown by the ionograms in Figure 9, the characteristics of the F_3 layer on 9 November are different from those on 8 November. The layer on 9 November lasts for about two hours (1100–1300 LT); it is less distinct and does not ascend to the topside ionosphere; maximum critical frequency is also high (over 12 MHz, Figure 9). These characteristics indicate that the upward $\mathbf{E} \times \mathbf{B}$ drift (main driver of F_3 layer) on 9 November might have been small. The drift velocity data corresponding to the period of the F_3 layer are not available. However, the data available for later times on this day (9 November) show less than normal upward velocity (Figure 2). The characteristics of the F_3 layer on 9 November are also similar to those on quiet winter days [e.g., *Balan et al.*, 2000; *Lynn et al.*, 2000].



Figure 5. Ionograms together with true height profiles at selected local times showing the occurrence of strong and distinct F_3 layer during PPEF ($\approx 1400-1600$ LT) at Jicamarca, and possible merging of downward drifting topside ledge and F_2 layer (ionogram at 1730 LT) due to westward electric field.

[17] Figure 10 shows the variation of Nmax during 7-10 November 2004 at the equatorial stations Vanimo and Darwin (131.0°E, 12.5°S; 23.3°S magnetic latitude). As shown, Nmax on the day of strong F_3 layer (8 November) is much below the average level (dotted curves) as expected. The daytime Nmax on 10 November is depleted even below the nighttime average level; however, the corresponding ionograms (not shown) need detailed investigations to distinguish the layers. On the other hand, the daytime Nmax (at Vanimo) on the day of weak F_3 layer (9 November) is above the quiet time average level. There is also an abnormal increase of Nmax in the afternoon at around 1500 LT (0500 UT), which may correspond to a combination of large downward plasma drift and equatorward neutral wind with downwelling effect (section 5.2). The corresponding drift velocity and neutral atmosphere

data are not available for comparison. The Nmax data in Figure 10 have large gaps due to missing data.

5. Model Results and Discussions

[18] Model results are presented for American longitude where vertical $\mathbf{E} \times \mathbf{B}$ drift is available. Model results for Indian and Australian longitudes will be presented in a later paper. The SUPIM model [*Bailey and Balan*, 1996] is used in the calculations following the procedure described by *Balan and Bailey* [1995]. The model solves the coupled time-dependent equations of continuity, momentum, and energy for the electrons and ions (O⁺, H⁺, He⁺, N₂⁺, NO⁺, and O₂⁺) using implicit finite-difference method along closed eccentric-dipole geomagnetic field lines. For this study, 200 field lines with apex altitude distributed from 150 km to 12000 km are used, with apex intervals of 10 km up to



Figure 6. Ionograms at selected local times showing (left) the occurrence of F_3 layer in the morning and (right) reoccurrence in the afternoon at the equatorial station Trivandrum in India.

600 km and 25 km from 600 to 1000 km. The calculations are for the longitude of Jicamarca (75°W) for day number 314 (9 November 2004) under medium solar activity (F10.7 = 105). In the calculation of the plasma $\mathbf{E} \times \mathbf{B}$ drift, SUPIM uses a semi-Lagrangian method that follows field lines to move vertically and horizontally with $\mathbf{E} \times \mathbf{B}$ drifts and interpolates back to a fixed coordinate at each time step.

[19] The vertical $\mathbf{E} \times \mathbf{B}$ drift measured at Jicamarca on 9 November 2004, which corresponds to the average drift over 200–600 km altitude [*Fejer et al.*, 2007], is applied to all field lines and hence to all altitudes and latitudes. The possible variation of the drift at altitudes above 600 km (not available) can have minor effects on *F* region densities over the equator. The neutral wind velocities are from HWM90 [*Hedin et al.*, 1991] and neutral densities are from MSIS86 [*Hedin*, 1987]. These models provide wind velocities and densities as function of altitude, latitude, longitude and local time. The model results presented below will show the effects of the strong storm time vertical $\mathbf{E} \times \mathbf{B}$ drift, and mechanical and chemical effects of storm time equatorward neutral wind on F_3 layer and ionospheric electron density around the equator.

[20] Figure 11 shows the vertical $\mathbf{E} \times \mathbf{B}$ drift (Figure 11a) and samples of neutral wind (Figure 11b) and neutral densities (Figure 11c) used in the calculations, dotted curves for quiet (Ap = 4) conditions and solid curves for storm conditions; the drift velocity during PPEF reaches the unusually high value of 126 m s⁻¹. As shown by Figure 11b (dotted curve), the effective meridional neutral wind given by HWM is mainly poleward (southward) over the geomagnetic equator under quiet conditions. To assess the effect of a possible equatorward wind, the wind is made equatorward (Figure 11b, solid curve) by reversing the HWM quiet time wind velocities at all altitudes and latitudes (by multiplying by -1). A possible downwelling effect of the wind can increase the $[O]/[N_2]$ ratio at low latitudes [e.g., Roble et al., 1977; Stephan et al., 2008]. To account for this effect, the quiet time [O]/[N₂] ratio within $\pm 20^{\circ}$ and at all altitudes is increased by 3. However, as shown by Figure 11c (solid curve), the ratio is increased only during 1600-2200 LT; this gives reasonable agreement between measured and modeled Nmax and TEC.



Figure 7. (a) Peak electron density Nmax at the equatorial station Trivandrum and (b) GPS-TEC at a nearby station Bangalore in India during 9-10 November 2004 (solid curves). Average quiet time variations are shown by dotted curves.

5.1. F_3 Layer

[21] Figure 12 shows the electron density profiles at selected local times obtained using storm time $\mathbf{E} \times \mathbf{B}$ drift and quiet time neutral wind and densities. As shown by Figure 12a, a strong F_3 layer develops and quickly ascends to the topside ionosphere during the afternoon period of PPEF when both F_2 and F_3 layers can be observed by bottomside ionosondes. After the F_3 layer becomes a topside ledge, unlike under quiet conditions, the ledge drifts downward with the progress of time (Figure 12b). During this evening period, the density of the topside ledge increases mainly due to downward compression while the density of F_2 layer decreases mainly due to chemical loss. That results in the density of the F_2 layer becoming less than that of the topside ledge for a short period ($\approx 1700-$ 1800 LT) when both layers can again be observed by bottomside ionosondes; the two layers merge together afterward. An indication of such a merging was observed in the ionograms at Jicamarca (Figure 5, 1730 LT). The possible reappearance of the F_3 layer during evening hours (Figure 12b) is due to the unusual circumstances of the strong afternoon eastward electric field (PPEF) followed by large westward electric field (Figure 11a). This is unlike the reoccurrence of F_3 layer during daytime when the layer is produced twice due to double peaked upward $\mathbf{E} \times \mathbf{B}$ drift and ionization production, which also results in the possi-



Figure 8. Ionograms at selected local times showing the (left) occurrence in the morning and (right) reoccurrence in the afternoon of F_3 layer on 8 November 2004 at the equatorial station Vanimo in Australian longitude.



Figure 9. Ionograms at selected local times at the equatorial station Vanimo in Australian longitude showing the development of F_3 layer on 9 November 2004.



Figure 10. Peak electron density (Nmax) at the equatorial stations (a) Vanimo and (b) Darwin in Australian longitude during 7–10 November 2004 (solid curves). Quiet time average variations are shown by dotted curves.



Figure 11. Local time variations of $\mathbf{E} \times \mathbf{B}$ drift velocity (Figure 11a), and samples of effective meridional neutral wind velocity (positive northward, Figure 11b) and [O]/[N₂] ratio (Figure 11c) at 350 km altitude over the geomagnetic equator; these are from the inputs used for the model calculations on 9 November 2004, solid curves for storm conditions and dotted curves for quiet conditions.

bility of multiple layers in the equatorial ionosphere [Balan et al., 2000].

[22] The electron density profiles in Figure 13a illustrate the effects of storm time equatorward neutral wind on F_3 layer. The profiles 1, 2 and 3 in Figure 13a correspond to 1730 LT over the equator and are obtained using storm time $\mathbf{E} \times \mathbf{B}$ drift (Figure 11). The dotted profile 1 uses quiet time wind and quiet time densities while dashed profile 2 uses storm time wind and quiet time densities. The electron density in profile 2 (compared to profile 1) is higher at higher altitudes where the equatorward wind can accelerate plasma flow toward the equator from higher latitudes (along geomagnetic field lines) when the drift is strongly downward [Balan and Bailey, 1995]. The other mechanical effect of the wind (raising of ionosphere to high altitudes of reduced chemical loss) is small for the equatorial location where horizontal wind cannot change the ionospheric height except for the separation between geomagnetic and geographic equators. The solid profile 3 in Figure 13a is obtained using storm time equatorward wind and storm time neutral densities. This profile, compared to profile 2, shows higher electron density at lower altitudes due to the chemical (downwelling) effect (or $[O]/[N_2]$ increase) of the



Figure 12. Electron density profiles at selected local times obtained using storm time $\mathbf{E} \times \mathbf{B}$ drift and quiet time neutral wind and densities. Figure 12a shows development of F_3 layer in the afternoon due to eastward PPEF, and Figure 12b shows reappearance of the layer in the evening due to the following large westward electric field.



Figure 13. (a) Electron density profiles at 1730 LT over the equator using storm time drift, and quiet time neutral wind and densities (curve 1), storm time drift, storm time wind, and quiet time densities (curve 2), and storm time drift, and storm time wind and densities (curve 3). Profile Q is obtained using quiet time drift, and quiet time wind and densities. (b) Electron density profiles at 0100 and 0200 LT obtained using storm time drift, and storm time neutral wind and densities (curves 1 and 2). Profile 2Q is also for 0200 LT but was obtained using quiet time drift, and quiet time drift.



Figure 14. Local time variations of model Nmax (Figure 14a) and TEC (integrated up to 1800 km, Figure 14b) over the geomagnetic equator on 9 November 2004. Dotted curves 1 are obtained using quiet time $\mathbf{E} \times \mathbf{B}$ drift and neutral wind and densities; dashed curves 2 are similar to dotted curves but using storm time $\mathbf{E} \times \mathbf{B}$ drift; dot-dashed curves 3 are similar to dashed curves but using storm time equatorward wind; and solid curves 4 are similar to dot-dashed curves but using storm time neutral densities.

wind. The electron density profile Q in Figure 13a is also for 1730 LT but is obtained using quiet time $\mathbf{E} \times \mathbf{B}$ drift and quiet time neutral wind and densities. As shown by profile Q, a weak topside ledge evolved from the comparatively weak F_3 layer developed before noon [*Balan et al.*, 1998] exists during the evening hours under quiet conditions.

[23] The unusually large upward $\mathbf{E} \times \mathbf{B}$ drift during the night of 9 November 2004 (Figure 11a) is also found to have unusual effects on the nighttime ionosphere. The electron density profiles 1 and 2 in Figure 13b are for local times 0100 LT and 0200 LT and are obtained using storm time $\mathbf{E} \times \mathbf{B}$ drift, and storm time neutral wind and densities. As shown by these profiles, the storm time ionosphere at night over the equator splits into a weak layer at ≈ 250 km height and a comparatively strong layer at \approx 550 km; the split is found to exist during 0100–0500 LT when the nighttime drift is up to 60 m s⁻¹ (Figure 11a). The split is also found to exist irrespective of whether neutral wind is poleward or equatorward. Such a split of the nighttime Fregion is not clear in the ionograms at Jicamarca (not shown) due to strong spread F. Under quiet conditions, when nighttime $\mathbf{E} \times \mathbf{B}$ drift is downward, the nighttime ionosphere in known to have a single layer structure, which

is illustrated by profile 2Q in Figure 13b. This profile is also for 0200 LT but is obtained using quiet time drift and quiet time neutral wind and densities.

5.2 Ionospheric Depletion

[24] Figure 14 shows the local time variations of model Nmax and TEC (integrated up to 1800 km) obtained for different combinations of model inputs. The curves 1 and 2 correspond to quiet time and storm time $\mathbf{E} \times \mathbf{B}$ drifts (Figure 11a), both obtained using quiet time wind and densities. As shown by these curves, the weak storm time drift before the start of PPEF results in larger than normal Nmax and TEC, and the strong upward drift during PPEF largely reduces Nmax and TEC. The reduction in Nmax is obvious due to the upward drift of ionization. TEC also reduces during PPEF because the strong forward plasma fountain (due to PPEF) not only raises the ionization to high altitudes but also is lost to higher latitudes due to diffusion long geomagnetic field lines. As shown (Figure 14), the increase of Nmax and TEC (curves 2) during the following large downward drift is small. This also suggests that a storm time equatorward neutral wind might have existed during this period. The curves 3 in Figure 14 are similar to curves 2 but obtained using storm time equatorward wind (Figure 11b, solid curve) and quiet time densities. As shown by curves 3 (Figure 14), the mechanical effect of the equatorward wind has increased Nmax and TEC during the evening hours of downward $\mathbf{E} \times \mathbf{B}$ drift mainly by compressing the ionosphere and by accelerating equatorward plasma flow from higher latitudes (along geomagnetic field lines) [Balan and Bailey, 1995]. The curves 4 in Figure 14 are similar to curves 3 but obtained using storm time neutral densities (Figure 11c, solid curve). The variations of Nmax and TEC shown by the solid curves 4 (Figure 14) qualitatively reproduce all features in the observed variations (compare with Figures 3a and 3b). Hence, the observations and modeling indicate that the eastward PPEF and following large westward electric field on 9 November 2004 (Figure 2) might have occurred on a background of a storm time equatorward wind with downwelling effect at low latitudes during evening hours.

[25] The magnitude and latitude extent of the equatorward wind and its downwelling effect depend on the highlatitude energy input during geomagnetic storms [e.g., *Fuller-Rowell et al.*, 1994]. For that matter, the equatorward wind and increased [O]/[N₂] ratio (Figures 11b and 11c) used in the present model calculations are arbitrary. A different combination of the two may also give similar model results. However, the observations and model results suggest that an equatorward wind with downwelling effect might have existed during the super geomagnetic storm. The downwelling effect was modeled by *Roble et al.* [1977] and observed by GUVI. For example, during the peak of the geomagnetic storm on 27 July 2004, the [O]/[N₂] ratio at low latitudes increased by over three times compared to the ratio on the quiet day 22 July 2004 [*Stephan et al.*, 2008].

6. Conclusions

[26] The occurrence of F_3 layer at equatorial stations in American, Indian and Australian longitudes during the super double geomagnetic storm of 7–11 November 2004

has been presented using observations and modeling. Unusually strong F_3 layer occurred, reoccurred and quickly ascended to the topside ionosphere in Australian longitude during the first super storm (8 November) and in Indian longitude during the second super storm (10 November), all with large reductions in Nmax and TEC. The unusual F_3 layers could have been produced mainly by unusually strong fluctuations in daytime vertical $\mathbf{E} \times \mathbf{B}$ drift as indicated by the observations in American longitude. The vertical $\mathbf{E} \times \mathbf{B}$ drift measured at Jicamarca in American longitude during 9-10 November shows unusually large fluctuations including the strongest ever recorded eastward prompt penetration electric field (PPEF) and large simultaneous reductions in Nmax and TEC during the afternoon hours on 9 November. During the following evening hours, when there was unusually large westward electric field, Nmax and TEC unexpectedly increased to daytime level.

[27] The model calculations carried out for the American longitude by incorporating the measured $\mathbf{E} \times \mathbf{B}$ drift in the SUPIM model qualitatively reproduce the observations. The model results show the development of unusually strong F_3 layer that quickly ascends to the topside ionosphere during the afternoon (\approx 1400–1600 LT) period of PPEF, with large reductions in Nmax and TEC. The layer also reappears in the following evening ($\approx 1700-1800$ LT) due to an unusually large westward electric field. At night, when the drift is unusually upward and strong, the F region splits into two layers. From the studies it is inferred that sudden appearance of unusually strong F_3 layer with large reductions in Nmax and TEC can indicate strong eastward electric field (PPEF); and unusual increases in Nmax and TEC at equatorial latitudes can indicate strong westward electric field and/or increase in [O]/[N2] ratio due to downwelling effect of storm time equatorward wind.

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