First observational evidence for opposite zonal electric fields in equatorial E and F region altitudes during a geomagnetic storm period

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[1] The strong westward electrojet and simultaneous upward drift of the equatorial ionospheric peak observed over South-East Asia and Indian equatorial regions during the prolonged Dst minimum phase of an intense geomagnetic storm during 14–15 December 2006 are investigated for the altitudinal variation of zonal electric field polarity using ground based and space-borne observations. The results show first observational evidence for simultaneous existence of daytime westward and eastward zonal electric fields at equatorial E and F region altitudes, respectively, in a wide longitude sector. While the westward electric fields at E region altitudes cause westward electrojet, at the same time, the eastward zonal electric fields at *F* region altitudes cause the upward drift of the equatorial ionospheric peak and reinforcement of the equatorial ionization anomaly (EIA) even in the topside ionosphere (∼660 km). The reversal of the electric fields is found to occur at ∼280 km height. A clear bifurcation of F region plasma at ∼280 km is evident in the iso-electron density contours due to these oppositely polarized zonal electric fields, which manifests as an unusually deep cusp between F_1 and F_2 layers on equatorial ionograms.

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1. Introduction

[2] During daytime, the primary zonal electric field generated by the E region dynamo is the key for several equatorial electro-dynamical processes such as equatorial electrojet (EEJ), equatorial ionization anomaly (EIA) and formation of additional F_3 layer, etc.,. It is well known that the primary zonal electric fields undergo severe modifications during geomagnetic storm periods due to processes such as overshielding/undershielding prompt penetration electric fields [e.g., *Rastogi*, 1977; *Kelley et al.*, 2003; *Abdu et al.*, 2008] and ionospheric disturbance dynamo [*Blanc and Richmond*, 1980]. A number of earlier studies during geomagnetic storm periods also demonstrated the intensification/inhibition of EIA at F region altitudes due to eastward/westward zonal electric field perturbations [*Mannucci et al.*, 2005; *Balan et al.*, 2012] as inferred from equatorial electrojet (EEJ) observations at E region altitudes [e.g., *Tulasi Ram et al.*, 2008; *Kikuchi et al.*, 2008; *Simi et al.*, 2012, and references therein]. Hence, it is fairly believed that the induced electric field perturbations would be similar, at least in their polarity, at both E and F region altitudes. This belief would probably be due to lack of direct observations of zonal electric fields as a function of height, particularly during geomagnetic storm periods.

[3] During the geomagnetic storm of 14–15 December 2006, an interesting upward drifting F_2 layer associated with an unusually deep cusp region between F_1 and F_2 layers is observed while the underneath E region zonal electric fields are strongly westward over South-East Asia (SEA) and Indian equatorial regions. This interesting observation led to an investigation on the polarity of zonal electric fields at different altitudes. In contrast to the popular belief, our results show: (i) First observational evidence for simultaneously prevalent westward and eastward zonal electric fields at equatorial E and F region altitudes with a reversal (westward to eastward) centered at ∼280 km altitude; and (ii) clear bifurcation of F region plasma at ∼280 km due to

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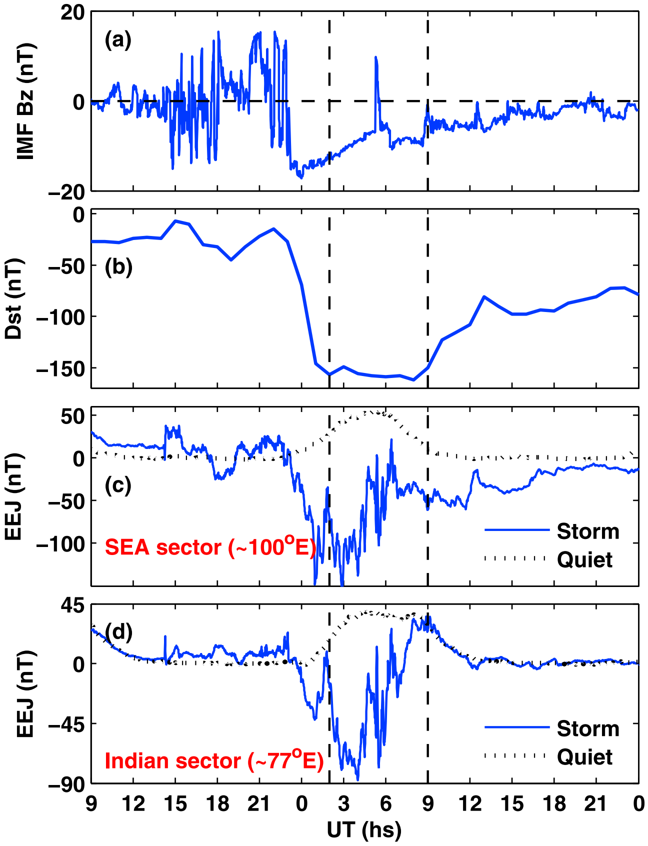

Figure 1. Variations of (a) IMF Bz, (b) Dst index, (c) EEJ strength over SEA and (d) EEJ strength over Indian sectors from 09 UT on 14 December to 24 UT on 15 December 2006. The dotted lines in Figures 1c and 1d represent the quiet day mean variations of EEJ over the respective regions. The prolonged Dst minimum phase from 0200 to 0900 UT is indicated by vertical dashed lines.

these opposite electric fields that causes a deep cusp region between F_1 and F_2 layers in the equatorial ionosphere.

2. Results

[4] A coronal mass ejection occurred on 13 December 2006 produced an intense geomagnetic storm with the arrival of initial shock at 1352 UT on 14 December 2006. Figures 1a and 1b show the variations of IMF Bz and Dst index, respectively. The main phase onset occurs at 2200 UT of 14 December with southward turning of IMF Bz, and the Dst index decreases rapidly to a value of −157 nT at 02 UT on 15 December. There after Dst exhibits only a meager decrease from −157 nT to −162 nT for the next six hour period until 0800 UT during which the IMF Bz is mostly southward except for a sharp northward pulse at around 0430 UT. The clear recovery phase starts only from 0900 UT with a positive shift in IMF Bz. The prolonged Dst minimum phase from 0200 to 0900 UT (indicated by vertical dashed lines) is the period of interest in this study, when the simultaneous opposite zonal electric fields in the E and F regions are observed.

[5] Figures 1c and 1d show the variations in the equatorial electrojet (EEJ) strength over SEA and Indian longitudinal sectors (solid lines), respectively. The EEJ strength, which is the proxy for the primary zonal electric field at E region altitudes can be derived from the difference between the ΔH values (H-component of the magnetic field after subtracting the nighttime base level) at an equatorial location and an off equatorial location (> ∼10° dip latitude) [*Reddy*, 1989; *Anderson et al.*, 2002, and references therein]. In this study, the EEJ strength is derived from the difference in ΔH values between Phuket and Kototabang over SEA; and Tirunelveli and Alibag over India. The geographic locations and dip latitudes of the various instruments/stations considered in this study are provided in Table 1. The black dotted curves in Figures 1c and 1d represent the quiet day mean variations of EEJ over the respective regions. Clearly, during the period from 0200 to 0900 UT (the period of interest in this study), the EEJ is strongly westward over SEA region (Figure 1c) indicating the presence of strong westward zonal electric field perturbations at the equator. Similarly over Indian region also (Figure 1d), the EEJ is clearly westward from 0200 to 0630 UT and remains less than its quiet day values up to 0900 UT. Therefore, the EEJ variations in Figures 1c and 1d indicate that strong westward zonal electric field perturbations are prevailing at E region altitudes of SEA and Indian equatorial regions, probably, associated with ionospheric disturbance dynamo fields [*Blanc and Richmond*, 1980].

[6] Interestingly during the periods of prevailing westward *E* region electric fields, an upward drifting F_2 layer and an associated deep cusp between F_1 and F_2 layers is observed at the equatorial stations of SEA and Indian regions. For example, Figures 2a and 2b show a series of ionograms at Chumphon (SEA) and Trivandrum (India), respectively. From Figure 2a, the stratification of F_1 and F_2 layers with the base of F_2 layer around ∼270–280 km can be seen at 0230 UT over Chumphon (Figure 2a). At later times, the base of F_2 layer appears at higher altitudes (for example around ∼300 km at 0340 UT). The most impressive observation from Figure 2a is that the F_2 layer between 0445 and 0700 UT is found to drift continuously upward over Chumphon as indicated by the arrow. Similarly over the Indian equatorial station Trivandrum (Figure 2b), the stratification of F_1 and F_2 layers can be seen from 0300 UT, and the cusp between F_1 and F_2 layers becomes sharp and distinct at 0415 UT. As time progresses the cusp between F_1 and F_2 layers becomes deeper until around 0630 UT. More importantly, the observed F_2 layer exhibits a continuous

Table 1. Geographic Locations and Dip Latitudes of the Various Instruments/Stations Considered in This Study

Station Name	Geog. Latitude (°N)	Geog. Longitude (°E)	Dip Latitude (°N)
	Magnetometers		
Phuket	7.9	98.39	−0.4
Kototabang	−0.2	100.32	−10.1
Tirunelveli	8.7	77.8	0.6
Alibagh	18.5	72.9	12.9
	Ionosondes		
Trivandrum	8.5	76.5	0.7
Waltair	17.7	83.3	11.6
Chumphon	10.72	99.37	3.0
ChiangMai	18.76	98.93	12.7

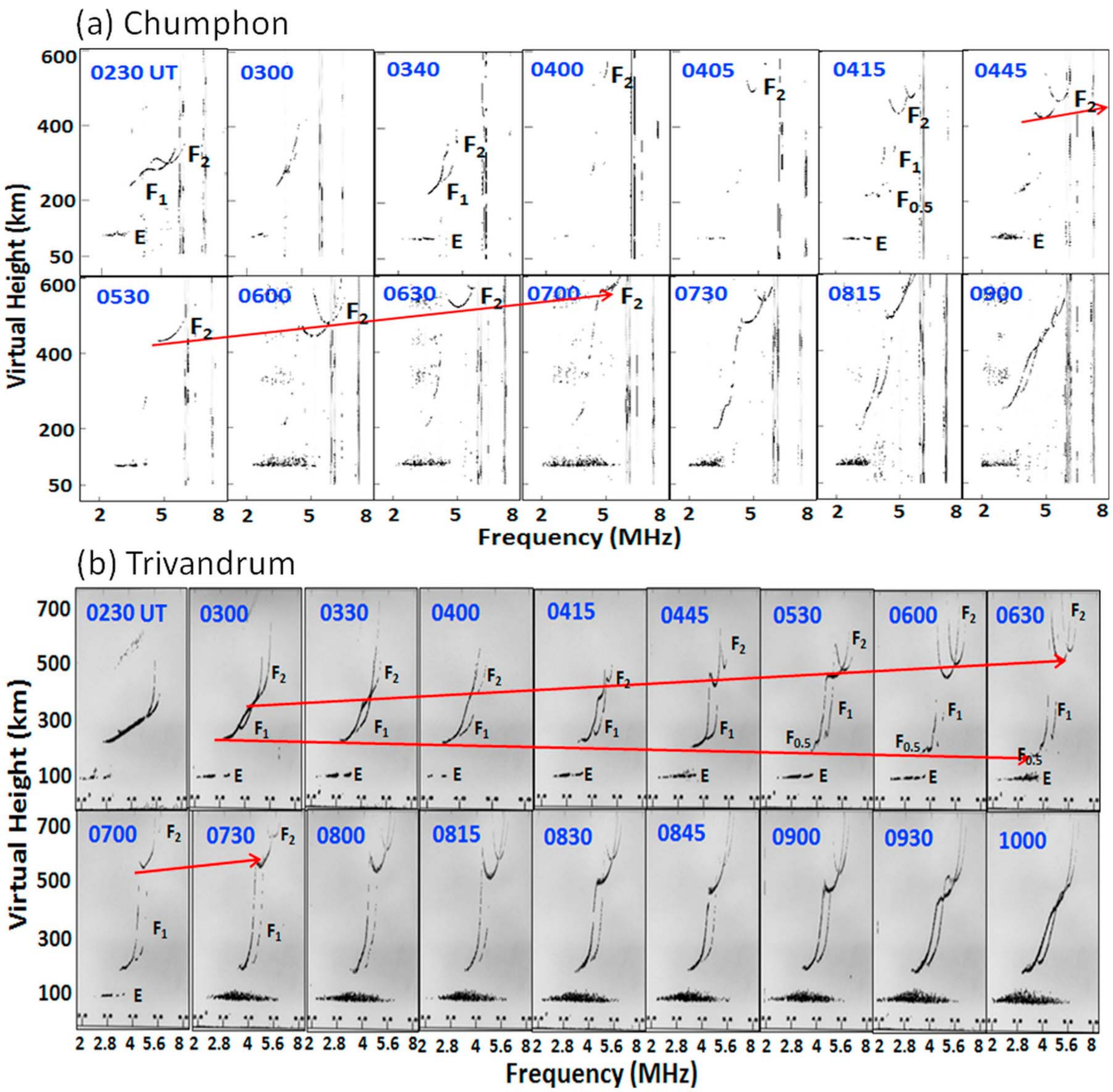

Figure 2. Series of ionograms showing upward drifting F_2 layer associated with deep cusp region between the F_1 and F_2 layer at the equatorial stations of (a) Chumphon (3°N dip.lat) and (b) Trivandrum (0.7°N dip.lat) over SEA and Indian regions, respectively. The times in UT are labeled on ionograms. The local time at Chumphon is UT + 6 h 40 min and at Trivandrum is UT + 5 h 30 min.

upward drift from 0300 to 0730 UT as indicated by the arrow. On the other hand, the base (virtual) height of the F region (h′F) over Trivandrum (Figure 2b) does not show any upward drift, and in fact, exhibits small downward drift between 0300 and 0630 UT and remains more or less at the same altitude up to 0900 UT. We are unable to describe the base height variation over Chumphon due to poor visibility of ionogram traces.

[7] Figure 3 shows the variations of F_2 layer critical frequency (f_oF_2) at Chumphon and ChiangMai over SEA (Figure 3a), and at Trivandrum and Waltair over Indian longitudinal sectors (Figure 3b). The f_oF_2 is a parameter that is proportional to the square root of the peak electron density (N_{max}) in the ionosphere. Therefore, from the variations of f_oF_2 shown in Figure 3a, it can be observed that the peak electron density at low-latitude station, ChiangMai, is significantly higher than that at the equatorial station, Chumphon, during most of the day time hours i.e., between 0100 and 1200 UT (0740 and 1940 LT) except for about 45 min period from 0415 to 0500 UT. Similarly over the Indian region, the peak electron density at the low latitude station Waltair is significantly higher than that at the equatorial station Trivandrum during entire day time (0000–1345 UT or 0530–1925 LT) except for few minutes at ~0500 UT.

[8] The observed larger peak electron densities (N_{max}) at low latitude stations than at equatorial stations indicate the presence of well-developed equatorial ionization anomaly (EIA) driven by eastward zonal electric field via equatorial fountain process (upward $\boldsymbol{E} \times \boldsymbol{B}$ drift). This clearly suggests that the zonal electric field around the altitudes of peak electron densities is eastward at both SEA and Indian regions during this period. Figures 1–3 therefore show clear evidences for the existence of simultaneous westward and eastward zonal electric fields at equatorial E region and

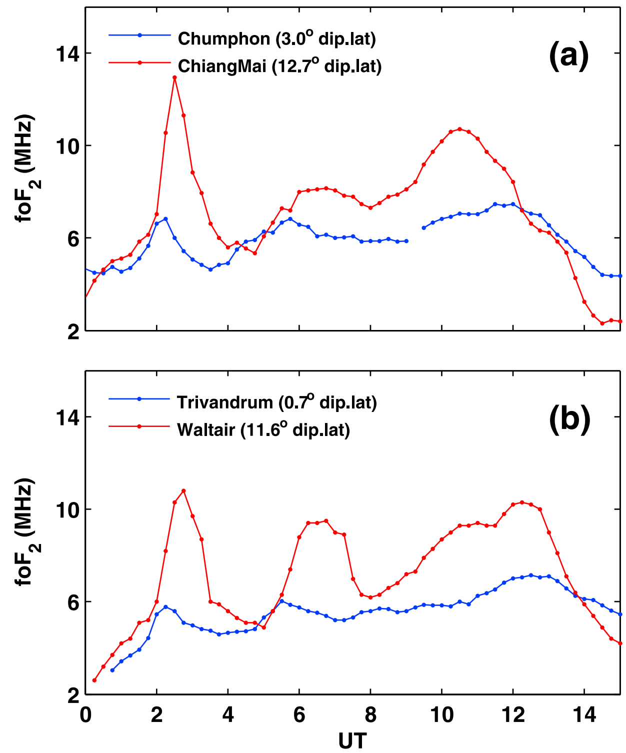

Figure 3. Variations of F_2 layer critical frequencies (foF_2) at (a) Chumphon and ChiangMai over SEA and (b) Trivandrum and Waltair over Indian regions on 15 December, respectively.

F region altitudes, respectively. Note that our discussion is only restricted to the variation of zonal electric field polarity at different altitudes during the period of interest (0200 to 0900 UT); however, the temporal variations of electric field perturbations during different phases of the storm is not addressed this paper.

[9] Further evidence for F region eastward electric fields in the topside ionosphere is presented in Figure 4, which show the latitudinal variations of ion density at ~660 km altitude observed from DEMETER (Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions) satellite. Figure 4a shows the ground tracks of three successive DEMETER orbits (solid curves in blue, green and red colors and numbered as 1, 2 and 3) between 0300 and 0623 UT on 15 December 2006. The dotted curves in gray color represent the ground tracks of DEMETER around the same UT times as orbits 1, 2 and 3, but on a previously quiet day (13 December 2006). The black horizontal line in Figure 4a represents the dip latitude. Figures 4b–4d show the latitudinal variations of the ion density for the three successive orbits 1, 2 and 3 respectively on the storm day (15 December); the corresponding quiet day variations (gray curves) are also shown for comparison. The vertical dotted line in Figures 4b–4d indicates the location of dip equator. The geographic equator crossing times of DEMETER in UT and LT are noted in the figures.

[10] The most striking feature that can be observed in Figures 4b–4d is the well-developed EIA even at the altitude of ~660 km (topside ionosphere) with a clear trough over the dip equator and crests on either side. There were some data gaps around 20 to 40°N geographic latitudes; however, the EIA crests in southern hemisphere can be clearly identified at ~10°S–15°S geographic latitudes. Though the ion density is low, one can clearly visualize that the strength of the EIA (crest to trough ionization ratio) is significantly large on 15 December compared to previously quiet day. This provides further evidence for the strong eastward zonal electric fields prevailing at upper F region altitudes that reinforced the EIA even in the topside ionosphere (~660 km) over SEA and Indian regions.

3. Summary and Discussion

[11] In summary, the following observations can be recalled: (i) During the geomagnetic storm of 14–15 December 2006, the Dst index exhibits a prolonged minimum phase between 0200 and 0900 UT on 15 December while the IMF Bz is mostly southward. (ii) During this period, the EEJ

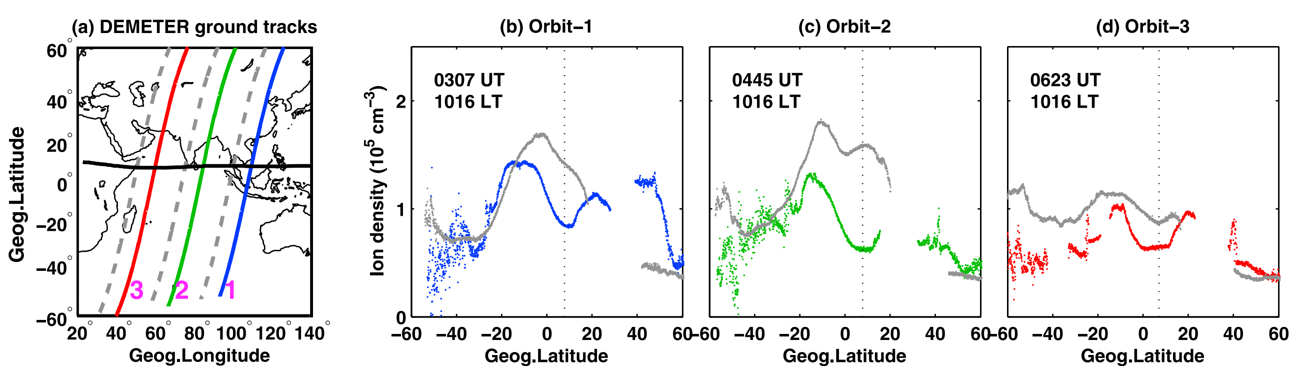

Figure 4. (a) Ground tracks for the three successive orbits of DEMETER satellite over SEA-Indian regions between 0300 and 0623 UT on 15 December 2006 (orbits in solid blue, green and red colors and numbered 1, 2 and 3). The dotted curves in gray color represent the DEMETER ground tracks around the same time on previously quiet day (13 December). (b–d) The latitudinal variations of the ion density (blue, green and red colors) for the three successive orbits 1, 2 and 3 respectively; the corresponding quiet day variations (gray curves) are also shown for comparison. The vertical dotted lines indicate the location of dip equator.

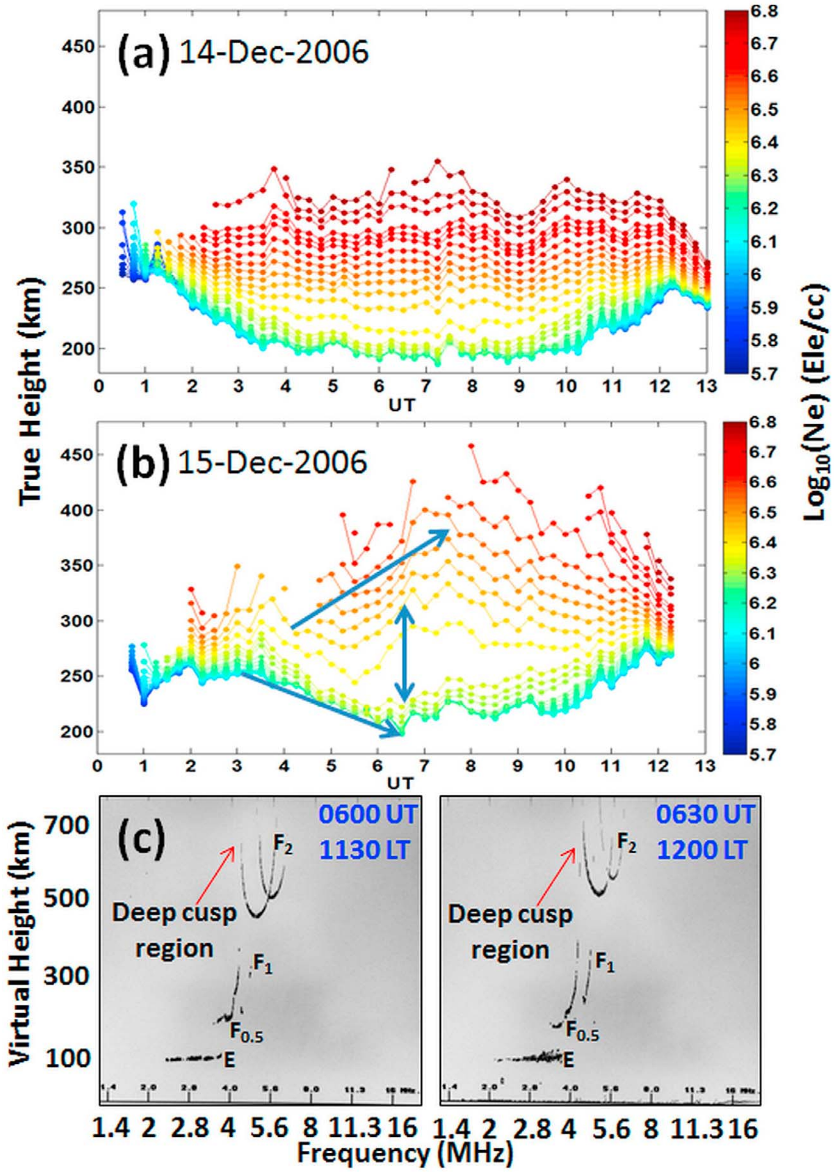

Figure 5. Iso-electron density contours over Trivandrum between 00 and 13 UT (0530 and 1830 LT) on (a) 14 December and (b) 15 December 2006. The downward/upward directed arrows in Figure 5b indicate the downward/upward drifting of lowered/higher plasma density layers. The vertical double headed arrow indicates the wide separated region between the two layers. (c) The examples of unusually deep cusp region between the two (F_1 and F_2) layers.

strength over SEA and Indian regions is strongly westward indicating the presence of prevailing westward zonal electric fields at *E* region altitudes (Figure 1). (iii) Within the same period, an interesting upward drifting F_2 layer is observed between 0445 and 0700 UT over SEA and between 0300 and 0730 UT over Indian equatorial regions (Figure 2). These observations vindicate the simultaneous existence of westward and eastward zonal electric fields at E region and F region altitudes, respectively. (iv) The h′F over Trivandrum exhibits a small downward motion during 0300–0630 UT (Figure 2) suggesting that the inferred westward electric field in the E region extends also to lower F region altitudes. In contrast, (v) the f_oF_2 observations as well as the latitudinal variations of ion-density at ~660 km exhibit well-developed EIA over SEA and Indian regions (Figure 3) during the same period (0300–0630 UT). This further confirms the existence of strong eastward zonal electric field around the F region peak altitudes and above, which reinforces the EIA even in the topside ionosphere.

[12] Since the field lines are horizontal over the dip equator, the vertical transport of plasma is primarily controlled by zonal electric field via $\boldsymbol{E} \times \boldsymbol{B}$ drift. Thus, a careful examination of the vertical plasma drift at various altitudes in the F region can reveal the altitudinal variation of zonal electric field. Hence, true-height analysis is carried out on ionosonde observations over Trivandrum using POLAN [*Titheridge*, 1985], and iso-electron density contours are constructed for the period between 00 and 13 UT (0530 and

1830 LT) on 14th (previous quiet day) and 15th December (storm day) as shown in Figures 5a and 5b, respectively.

[13] Several interesting features can be observed from Figure 5b. First, the region of lowered plasma density (contour lines with blue, green and light yellow colors) in the bottomside exhibits a downward drift from ∼250 km at 0300 UT to ∼190 km at 0630 UT (∼4.76 m/s) as indicated by an arrow. This downward drift is consistent with the downward motion of h′F seen in Figure 2. Two possible mechanisms can account for this downward drift: (i) Apparent downward drift due to continued photoionization during the morning to noon hours and (ii) true downward $\boldsymbol{E} \times \boldsymbol{B}$ drift due to westward electric field. It can be noticed from Figure 5a that the apparent drift due to photoionization between 0300 and 0630 UT (0830 and 1200 LT) on the previous day is very small. Since the photoionization rate, which is principally controlled by solar zenith angle variation, does not change significantly between two successive days, the significant downward drift of the bottomside lowered plasma density region on 15 December can be attributed to the contributions from the westward zonal electric field around those altitudes.

[14] Another important feature that can be observed from Figure 5b is that the higher plasma density region (contour lines with dark yellow to red colors) above ∼280 km altitude exhibits a continuous upward drift from 0415 to 0730 UT (0945 to 1300 LT) as indicated by the arrow. Since the field lines are nearly horizontal over the dip equatorial station Trivandrum the large upward drift of higher plasma density region would only be possible due to strong eastward electric field via $\boldsymbol{E} \times \boldsymbol{B}$ drift at these altitudes. On the other hand, the westward electric field at E region and lower F region altitudes at the same time does not allow the bottomside lowered plasma density region to drift upward, and in fact, causes a downward drift. Therefore from these observations, it is evident that a reversal in the zonal electric field from westward to eastward occurs at ∼280 km altitude.

[15] Further, the opposite westward and eastward electric fields below and above of ∼280 km altitude cause a bifurcation of F region plasma in to two oppositely drifting layers. A clear separation between the two layers can be observed at ∼280 km starting from 0415 UT, which is precisely the time when the cusp between F_1 and F_2 layers becomes sharp and distinct at Trivandrum (Figure 2). As time progresses the separation between the two layers widens and maximizes at 0630 UT as indicated by the vertical double headed arrow in Figure 5b. This wide separated region manifests as an unusually deep cusp region between the two (F_1 and F_2) layers on the ionograms (Figure 5c). Therefore, these results provide first observational evidence for the simultaneous existence of opposite zonal electric fields (westward and eastward at the altitudes below and above of ∼280 km) at the equator that causes a bifurcation of F region plasma in to two oppositely drifting layers.

[16] In addition, the similarity of the westward EEJ, upward drifting F_2 layer and enhanced EIA observed at both SEA (∼100°E) and Indian (∼77°E) longitudinal sectors suggests that the observed opposite zonal electric fields at equatorial E and F region altitudes is not a local phenomenon, instead, spans over a wide longitudinal sector. The simultaneous in situ electron density data from CHAMP (∼360 km) at ∼180°E longitude (not shown for the lack of corresponding magnetometer and ionosonde data) also show very clear evidence for strong eastward electric field at F region altitudes, which seems to further support the possible existence of opposite westward and eastward zonal electric fields at E and F regions altitudes in a wide longitude sector.

[17] Our discussion has been restricted to the variation of zonal electric field polarity at different altitudes over the equator during the prolonged Dst minimum phase. The plausible mechanism(s) for the witnessed opposite zonal electric fields is beyond the scope of this paper; however, we attempt to speculate along the following lines. Since the field lines are equipotential due to high field aligned conductivity, the zonal electric field at various apex altitudes over the equator can be determined by the electric fields at latitudes corresponding to the base of field lines fixed to E region dynamo altitudes (since the *F* region dynamo is ineffective during daytime). Hence, the latitudinally varying zonal electric fields at E region could map to different apex altitudes leading to altitudinally varying zonal electric fields over the equator.

[18] It is known that the storm time zonal electric fields are severely modified by the processes such as ionospheric disturbance dynamo (IDD) [*Blanc and Richmond*, 1980] and undershielding/overshielding prompt penetration electric fields (PPEFs) [*Kelley et al.*, 2003; *Kikuchi et al.*, 2008]. Since the present observations are at several hours after the initial phase (and after the convectional main phase), the IDD can be effective and may induce westward zonal electric field perturbations in the day side ionosphere. At the same time, undershielding PPEF would also be effective since the IMF Bz is southward between 0200 and 0900UT, which would induce eastward electric field perturbations during day time. Hence, the relative contributions from these processes may produce a favorable altitude variation of zonal electric fields with opposite polarities at E and F region heights over the equator as the observations indicate. However, detailed in-depth investigations are necessary on the combination of different electric field components that leads to the opposite zonal electric fields at equatorial E and F regions, which will be considered in a future study.

4. Conclusions

[19] The prolonged Dst minimum phase of the geomagnetic storm on 15 December 2006 over SEA and Indian equatorial regions is investigated for the altitudinal variation of zonal electric fields using ground based and space-borne observations. The results provide first observational evidence for opposite daytime zonal electric fields at equatorial E and F region altitudes in a wide longitude sector. While the westward electric fields at E region altitudes cause westward electrojet, at the same time, the strong eastward zonal electric fields at *F* region altitudes causes upward drift of F_2 layer, and also intensification of the EIA even in the topside ionosphere (∼660 km). The westward to eastward reversal in the zonal electric field centered at ∼280 km causes a bifurcation of F region plasma into two oppositely drifting layers with an unusually deep cusp region between the two. We believe that these new and unexpected observational results will have immediate impact, and stimulate further studies on opposite *E* region/*F* region electric fields

during geomagnetic storms and their plausible mechanisms through theory and modeling.

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