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Signatures of substorm related overshielding electric field at equatorial latitudes under steady southward IMF Bz during main phase of magnetic storm

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Abstract

During the geomagnetic storm periods, the convection electric field penetrates promptly to equatorial latitudes, causing an eastward electric field in the dayside ionosphere. Occasionally, the polarity of the dayside ionospheric electric field is inverted when the Interplanetary Magnetic Field (IMF) turns northward. In this paper, interesting observations of the strong westward electric field in the day side equatorial latitudes are presented, as evidenced by strong Counter Electrojet (CEJ) at Indian and Japanese sectors under the steady southward IMF Bz. The westward electric field perturbations are quite large with CEJ amplitude of ~ -120 nT over the Indian sector (14–15 December 2006) and ~ -220 nT for Japanese sector (7–8 November 2004). The plausible mechanisms for the observed overshielding electric fields under steady southward IMF Bz have been investigated in light of the possible role of substorm activity. The clear signatures of substorm were observed at geosynchronous particle flux measurements from LANL (Los Alamos National Laboratory) satellite and associated with sudden decrease in AL index. The observed variations of asymmetric ring current shows the enhancement of Partial Ring Current (PRC) at the dusk sector further supporting the substorm onset during that period which will probably enhance the overshielding due to increased Region 2 Field-Aligned Currents (R2 FACs). The observations of such significantly large amplitudes of CEJ associated with the substorm related overshielding events are sparse and the results bring out the important role of substorm onset and the development of PRC in accordance with the R2 FACs during intense magnetic storms which alter the day time equatorial electric field perturbations.

Keywords: Equatorial electric fields; Magnetic storm; Substorm; Overshielding electric field; Counter electrojet

1. Introduction

In response to solar wind variations, the magnetospheric electric fields can promptly penetrate into the equator during geomagnetic storms and closely related to the southward Interplanetary Magnetic Field (IMF) Bz orientations (Nishida et al., 1966; Gonzales et al., 1979; Fejer et al., 1979; Kelley, 1989; Sastri et al., 1997). The interaction between the solar wind and the magnetosphere drives the large-scale convection electric fields caused by the Region 1 Field Aligned Currents (R1 FACs),

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transmitted from high to low latitudes. These currents are often shielded by the Region 2 Field Aligned Currents (R2 FAC) (Huang et al., 2005a, 2005b; Wei et al., 2008). The global magnetic field signatures of near-instantaneous rapid propagation modes, in the Earth-ionosphere waveguide at the speed of light, is proposed by Kikuchi and Araki (1979) and the propagation of electromagnetic waves by TMo mode from high latitude to equator is explained in detail by Kikuchi (2014). The high – low latitude electric field coupling is generally described with overshielding and undershielding (Kelley et al., 1979; Wolf et al., 2007) conditions in inner magnetosphere, which mainly depends on IMF Bz orientation. These signatures can be clearly seen as DP2, Equatorial Electrojet (EEJ) currents and reverse currents or Counter Electrojets (CEJ) at equator (Kikuchi et al., 2008; Veenadhari et al., 2010), indicating the instantaneous transmission of magnetospheric electric fields. The undershielding and overshielding can be explained by the strength, imbalance of R1 and R2 FACs and their development is related to changes in IMF Bz. The rapid increase in southward component of IMF Bz will cause intense R1 FACs, but R2 FACs will take longer time (a few hours) to grow stronger than R1 FACs, because R2 FACs depend on the gradients of hot ions and plasma pressure in the inner magnetosphere (Kikuchi et al., 2010). Overshielding conditions develop when the shielding electric field becomes stronger than the convection electric field (R2 FACs > R1 FACs), in case of sudden changes in IMF Bz from southward to northward after a prolonged southward orientation. This could be due to increased pressure gradients in the inner magnetosphere which sustains the R2 FACs for some time even after the sudden decrease in the convection electric field (Spiro et al., 1988; Peymirat et al., 2000). The clear observations of overshielding has been evidenced in earlier investigations on the basis of ground based geomagnetic field and radar observations (Ebihara et al., 2008 and reference there in). The transition to overshielding from undershielding and good shielding is closely interrelated to gradual and sharp northward turning of IMF Bz, is confirmed by the some case studies that demonstrate the enhancement of R2 FACs due to occurrence of substorms (Goldstein, 2006; Wolf et al., 2007; Wei et al., 2011). However, the delayed variations of day time ionospheric electric field at equator, after the enhanced storm activity is driven by the high latitude equatorward wind that is called ionospheric disturbance dynamo (DD) which plays an important role in altering the equatorial electric fields, mainly driven by enhanced energy deposition into the high latitude ionosphere, with the delay of few to several hours (Blanc and Richmond, 1980). These electric fields are probably due to equatorward currents produced by southward and westward disturbance winds that builds up a high electric potential at lower latitudes (Fejer et al., 2007; Blanc and Richmond, 1980), maximizing their effect at pre-midnight than at daytime during equinox months (Huang et al., 2005a, 2005b; Huang and Chen, 2008).

The polarity of ionospheric electric field perturbations at equatorial latitudes during the substorms became an interesting topic in recent years due to contradicting theories. Some studies suggests that, after the onset of substorms, the convection electric field still grows continuously (Kamide et al., 1996; Kikuchi et al., 2000; Miyashita et al., 2008). The plasma motion in the inner magnetosphere, driven by convection electric field builds up high-pressure plasma in the dusk sector, which produces the partial ring current and R2 FACs that is directed in and out of the ionosphere in the dusk and dawn sectors, respectively (Wolf, 1970; Wolf et al., 2007 and references there in). The existence of overshielding conditions at day side equator during substorm expansion phase is often observed when IMF turns northward (Rastogi and Patel, 1975; Kikuchi et al., 2000, 2003; Sastri et al., 2001, 2003). On the other hand, during the sawtooth events, which has all well-known characteristics of magnetospheric substorms and represents one substorm, the convection electric field and EEJ continue to increase at equator during the expansion phase of substorms under steady southward IMF Bz suggested by Huang et al. (2004) and Huang (2012). However, some substorms can generate strong westward electric field perturbations that produce CEJs at equatorial latitudes on the dayside ionosphere caused by the imbalance between the R1 and R2 FACs, when R2 FACs increases more than the reduction in R1 FAC caused by northward turn of IMF Bz (Wei et al., 2009). Earlier studies have given substantial information on variations of equatorial electric fields for clear isolated substorms. However, less attention has been given to occurrence of substorms during the main phase of intense magnetic storms and associated changes in FACs and partial ring current (PRC), due to complexity involved in identifying their signatures.

Many of the earlier studies demonstrated that the westward penetration electric fields observed during isolated substorms are actually due to northward turning of IMF Bz (Huang et al., 2004; Huang. 2009, 2012), and in contrast, the day side equatorial electric field perturbations are eastward in concurrent with positive magnetic field perturbations (positive bay) during storm time substorms under steady periods of southward IMF Bz. However, in this study, we present two interesting cases wherein the observed day side equatorial electric field perturbations are indeed westward and geomagnetic field perturbations are negative at the substorm onset, during the main phase of geomagnetic storms under steady periods of southward IMF Bz. The responsible mechanisms are discussed in view of complex changes in the PRC and R2-FAC in the inner magnetosphere during the substorm onset and expansion phases.

The main objective of this paper is to investigate the plausible mechanisms for the existence of overshielding electric fields under long hours of southward IMF Bz during the main phase of two intense magnetic storms. The interesting characteristics of overshielding electric fields are addressed to understand the significant role of a

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substorm for the existence of overshielding electric field, evidenced as strong CEJ observations at Indian and Japanese sectors. In the present study, we examine the role of PRC and coupled R2 FACs for the prevailing westward electric fields over the Indian and Japanese equatorial latitudes at morning to noon sectors under steady southward IMF Bz which helps to study the longitudinal effects of penetration of electric fields. An attempt has been made to identify the signatures of PRC and R2 FACs using ground magnetic data of H component for different MLT sectors, asymmetric variation in D component to discuss the complexity of inner magnetosphere processes for better understanding of equatorial dynamics.

2. Data

The Horizontal component of the Earth's magnetic field (H) perturbation data of one minute resolution, from Yap, Macronesia (YAP, Geomagnetic Latitude, GML, 0.38°S), Okinawa (OKI, GML, 16.87°N) from Japanese sector, Tirunelveli (TIR, 0.11°N, GML) and Alibag (ABG, 10.36°N, GML) from Indian sector are used to study the day time equatorial electric field perturbations during the two severe magnetic storms of 14–15 December 2006 and 7–8 November 2004. The YAP and TIR are located over geomagnetic equator and ABG and OKI are located sufficiently away from the equator (outside the EEJ region). The difference (in H component) between equator (YAP and TIR) and low latitudes (OKI and ABG) gives an estimate of the strength of EEJ, particularly during storm to estimate the variations of equatorial DP2 currents. The equatorial storm time electrojet index is computed by subtracting ΔHsd (ABG) from ΔHsd (TIR). The ΔHsd represents the difference between ΔH (storm day) and ΔH (quiet day) for each station and similar procedure used for YAP and OKI stations. The nighttime H value is removed from baseline and represented by ΔH. The interplanetary parameters of solar wind, IMF Bz and IMF By data are taken from the Advanced Composition Explorer (ACE) spacecraft, at L1 point. The auroral eastward and westward electrojet currents represented by AU and AL indices, which are considered to be good indicators of substorm activity and the symmetric and Asymmetric variations in H and D components (SYM-H, ASYM-H, ASYM-D) respectively, are used in this study. The SYM-H, ASYM-H, ASYM-D are derived from a group of 10 low and mid latitude stations, representing (Iyemori and Rao, 1996) are obtained from WDC Kyoto, Japan. The ASYM-D index is assumed to be an indicator of the total FACs, as it is not affected by the ring current and Chapman-Ferraro current and mainly the D component perturbations are similar to FACs variations (Shi et al., 2005). These geomagnetic indices were obtained from the World Data Center for Geomagnetism, Kyoto University, Japan. The ΔH of worldwide low latitudes stations is used to estimate the asymmetric ring current development during the magnetic storm period at different magnetic local time (MLT) sectors from INTERMAGNET (I*nter*national *R*eal-time *Mag*netic Observatory *Net*work), a global network of magnetic observatories and also taken from WDC Kyoto, Japan. The ΔH component and ΔD component data from 210 meridian chain stations are used to study the mid latitude day time ionospheric currents which connects with the equatorial electric field and details are given in Table 1. We have used the Electron flux variations in the four energy channels (∼50–73 keV, ∼72–104 keV, ∼102–148 keV, ∼143–218 keV) as measured by the Synchronous Orbit Particle Analyzer (SOPA) instrument from on-board four Los Alamos National Laboratory (LANL) satellites (LANL 1989–046, LANL 1994-084, LANL-01A and LANL-02A), provides the energetic particle fluxes and placed at geosynchronous altitudes. The LANL satellites are positioned around the geographic equator with approximately fixed geographical longitude. The geographic longitudes of LANL 1989-046, LANL 1994-084, LANL-01A and LANL-02A are −145, −157, 8 and 71 respectively.

3. Observations and results

3.1. Interplanetary magnetic field and geomagnetic variations for equatorial and low latitude from Indian and Japanese sectors: Magnetic storm of 14–15 December 2006

Fig. 1 shows the temporal variations of solar wind density (Nsw) and velocity (Vsw), Interplanetary magnetic field components IMF By, IMF Bz, (top four panels) observed by ACE satellite for the magnetic storm of 14–15 December 2006. The bottom panels show the ground geomagnetic variations in ΔH for YAP and OKI from Japanese sector and ΔH for TIR, and ABG from Indian sector along with SYM-H for the same period. The time interval is 24 h from 14 December (1200 to 1200 UT) to 15 December 2006. The local time at Indian stations is UT + 0530 h and, UT + 0900 h for Japanese stations. The CME that occurred on 13 December 2006 manifested itself as a fast solar wind stream and a magnetic cloud structure with large magnitude of southward IMF Bz, is responsible for the intense magnetic storm on 14 December 2006. The solar wind velocity sharply increased to ∼900 km/s around 1400 UT and maintained an average of ∼700 km/s up for most of the storm period. The IMF shows large oscillations during 1400–1800 UT and the IMF Bz then remained positive for almost four hours before exhibiting alternatively positive and negative fluctuations with typical periods of ∼30 mins and ranging from −12 nT to +15 nT in magnitude between 2100 and 2300 UT. The IMF Bz again turns steady southward at ∼2310 UT (on 14 December) and remains southward for several hours except for a short northward impulse between 0445 and 0510 UT. These intervals are suitable to investigate the equatorial electric field variations during day time at both sectors with associated variations of IMF Bz, which will be discussed in later sections.

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Table 1
The ΔH of worldwide stations from INTERMAGNET network from global magnetic observatories, WDC Mumbai, India and WDC Kyoto, Japan used in Figs. 3 and 7.

Station name	Code	Geo. Lat	Geo.Long	Geo.mag. Lat	Geo.mag. long	CGM lat
Alibag	ABG	18.64	72.87	10.12	146.07	11.81
Alma Ata	AAA	43.25	76.92	34.22	152.69	38.36
Apia	API	−13.80	188.22	−15.16	262.99	−15.34
Ascension Island	ASC	−7.95	345.623	−2.52	57.07	NA
Bar Gyora	BGY	31.72	35.09	28.24	112.42	24.75
Beijing Ming Tombs	BMT	40.3	116.2	30.04	186.94	34.33
Chichijima	CBI	27.1	142.18	18.38	211.52	19.6
Eilat	ELT	29.67	34.95	26.25	111.84	22.28
Esashi	ESA	39.24	141.35	30.37	209.3	32.1
Guangzhou	GZH	23.09	113.34	12.78	184.74	16.11
Guimar	GUI	28.32	343.56	33.84	60.54	16.7
Hatizyo	HTY	33.07	139.82	24.11	208.67	25.8
Honolulu	HON	21.32	202	21.62	269.6	21.67
Kakioka	KAK	36.23	140.19	27.28	208.64	29.04
Kanoya	KNY	31.42	130.88	21.79	200.65	24.44
Kanozan	KNZ	35.26	139.96	26.3	208.55	28.05
Kourou	KOU	5.21	307.27	14.98	19.56	10.74
Lanzhou	LZH	36.09	103.85	25.77	175.99	30.19
M'Bour	MBO	14.38	343.03	20.17	57.39	2.06
Mizusawa	MIZ	39.11	141.2	30.23	209.18	31.97
Okinawa	OKI	26.75	128.22	16.87	198.41	NA
Phu Thuy	PHU	21.03	105.96	10.69	177.76	13.85
Qsaybeh	QSB	33.87	35.64	30.25	113.42	27.39
San Juan	SJG	18.11	293.85	28.41	5.98	28.79
Tamanrasset	TAM	22.79	5.53	24.69	81.7	9.22
Teoloyucan	TEO	19.75	260.81	28.84	330.25	29.04

The geomagnetic data from both sectors is useful to see the longitudinal (and local time) variations of storm time electric fields, as both sectors were at local morning and noon. The arrival of the shock at 1352 UT on 14 December followed by Sudden Commencement (SC) of the storm occurred at 1414 UT with an amplitude of 22 nT (for SYM-H). The SC is clearly seen in ΔH for TIR, ABG, YAP and OKI and remained high for almost 1.5 h. There is a sharp decrease in AL (−1500 nT) after SC (not shown), indicating the substorm activity and IMF Bz is very fluctuating during 1415 UT to 1740 UT. Hence, the prolonged initial phase of the magnetic storm before the onset of main phase, at 2251 UT (14 December) and continued up to 0057 UT (15 December), the ΔH started to decrease in all four stations indicating the development of ring current. The quasi periodic oscillations seen in ΔH for YAP data during 2130–2330 UT (14 December 2006), is in agreement with IMF Bz fluctuations, indicating the changes in convection and reduction of electric field, which are discussed in detail by Kikuchi et al. (2010), thus not repeated here. The oscillations are also observed in TIR, but with lesser amplitude because it is post mid night hours (0300–0500 LT). The recovery phase started at 0057 UT and prolonged for several hours.

3.2. Case 1: Equatorial Counter electrojet and overshielding electric field

A close-up view of the same event with solar wind dynamic pressure Psw, IMF Bz, AU, AL indices, ASYM-D, SYM-H, ASYM-H along with storm time EEJ from both sectors are shown in Fig. 2. The solar wind dynamic pressure shows sudden increase up to 20 nPa after the shock and shows variations during 2000–2300 UT in conjunction with IMF Bz variations. The storm time EEJ is derived by removing the quiet day ΔH for the respective stations for both sectors (mentioned in Data section) are shown in Fig. 2 to observe the signatures of penetration of convection and overshielding electric fields originated in the magnetosphere. The first observation, DP2 fluctuations are clearly noticed with associated variations in IMF Bz and solar wind dynamic pressure for the period of 2130 – 2330 UT (14 December 2006). The alternating eastward and westward electrojets in the equator caused by the prominent DP 2 fluctuations, which were in turn produced by the southward and northward turning of the IMF Bz respectively. These perturbations are shown in Polar Cap Potentials (PCP) with associated enhancements and reductions in R1 FACs (Kikuchi et al., 2010), will not be mentioned again. The DP2 signatures were not observed in Indian sector perhaps due to low ionospheric conductivity in the post-midnight sector. The ionospheric electric field perturbations noticed on early hours of 15 December 2006 is the main focus of the present study.

Around 2312 UT, the oscillating IMF Bz turned southward and continued for almost six hours. The long interval of steady IMF Bz plays pivotal role to have a continuous reconnection of magnetospheric plasma and support the penetration of convection electric field to equatorial latitudes. Hence, one would expect the steady penetration of

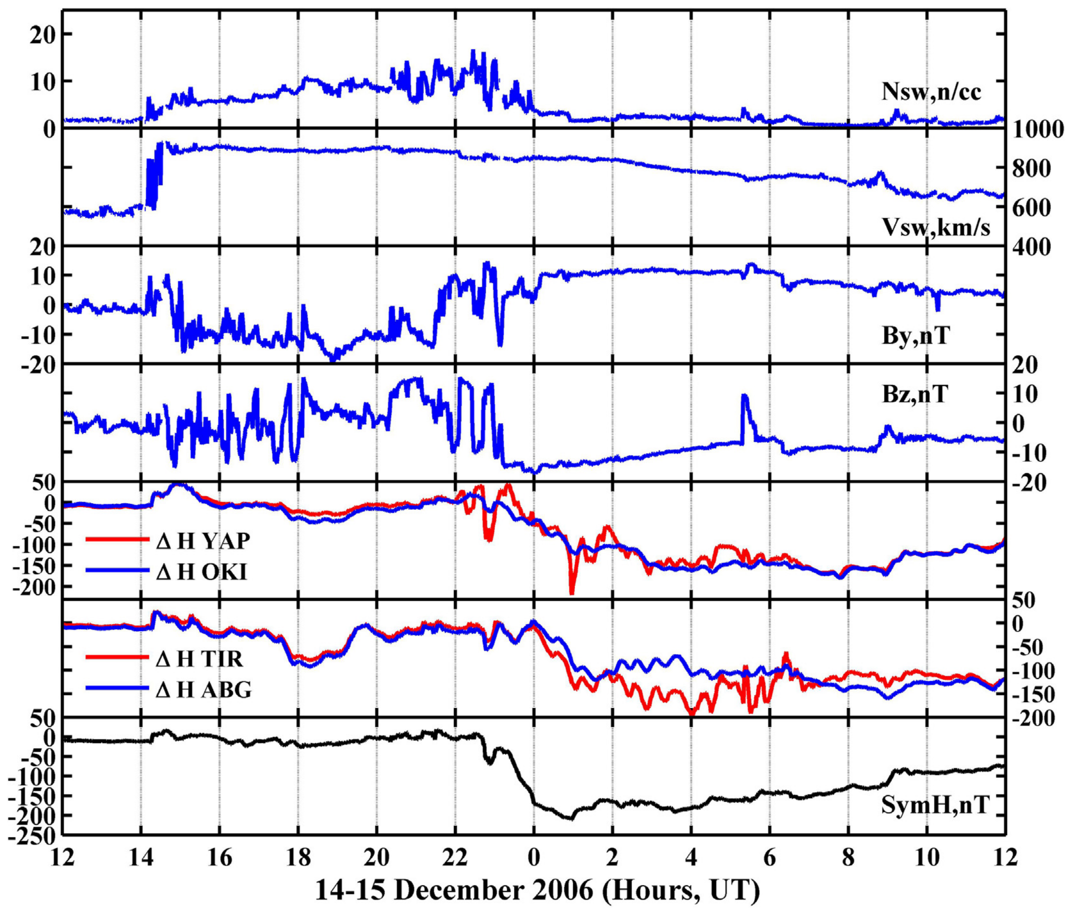

Fig. 1. Magnetic storm of 14–15 December 2006 with ΔH of TIR and ABG from Indian sector and ΔH of YAP and OKI from Japanese sector. The SYM-H index is shown along with interplanetary magnetic field component (IMF) Bz, By and solar wind velocity (Vsw) and Density **(Nsw)** from ACE data.

convection electric field from high latitudes without the interruption by the shielding electric field as suggested by Huang et al. (2005a, 2005b) and enhancement of eastward electric field at day side equatorial latitudes. In contrast, the storm time EEJ exhibits (Fig. 2) the negative deflections as the signatures of strong CEJ at both sectors indicating the presence of intense westward electric field, particularly after 0140UT. The sharp decrease in storm time EEJ at 0100 UT (Japanese sector) could be due to small change in solar wind dynamic pressure and another decrease in storm time EEJ at 0525 UT (Indian sector) is associated with sharp northward turning of IMF Bz is not a part of discussion in this work. The most important observation is during the interval of 0200–0400 UT (0730–0930 LT) for Indian sector and 1100–1300 LT for Japanese sector, the marked interval between two red vertical lines), where we notice the large decrease of storm time EEJ at Indian sector and moderate decrease at Japanese sector. The maximum magnitude of decrease of storm time EEJ is −106 nT and −90 nT for Indian and Japanese sectors, respectively. The period between 0200 and 0400 UT, is the focus of interest in this study and hereinafter referred as interval 1. It should be mentioned here that during the same period, the solar wind dynamic pressure is steady while the IMF Bz remained almost southward and slowly changed from −12 nT to −8.4 nT. However, it is interesting to observe that there is a large and sudden decrease in AL (Fig. 2) with magnitude of more than −1500 nT during interval 1, indicating the substorm activity during storm main phase. The possible cause-and-effect relationship between negative deflections (overshielding condition) and the associated mechanisms will be discussed later in the discussion section.

To emphasize the possible effect of the substorm activity at equatorial latitudes and associated changes in electric fields, we have plotted AU, AL, SYM-H, ASYM-H, ASYM-D along with storm time EEJ variations from both sectors (Fig. 2). The asymmetric ring current (ASYM-H) started to increase during main phase of the storm, suggesting the strengthening of PRC and started to decrease at around 0100 UT. Again after the onset of sudden decrease in AL (0200 UT), the ASYM–H enhances indicating the development of PRC and continuously remained high during interval 1. Therefore, the large negative departures in equatorial storm time CEJ for both sectors can be interpreted as the signatures of overshielding effect which could be caused by R2 FACs enhanced by the strengthening of PRC which could be due to occurrence of substorm activity

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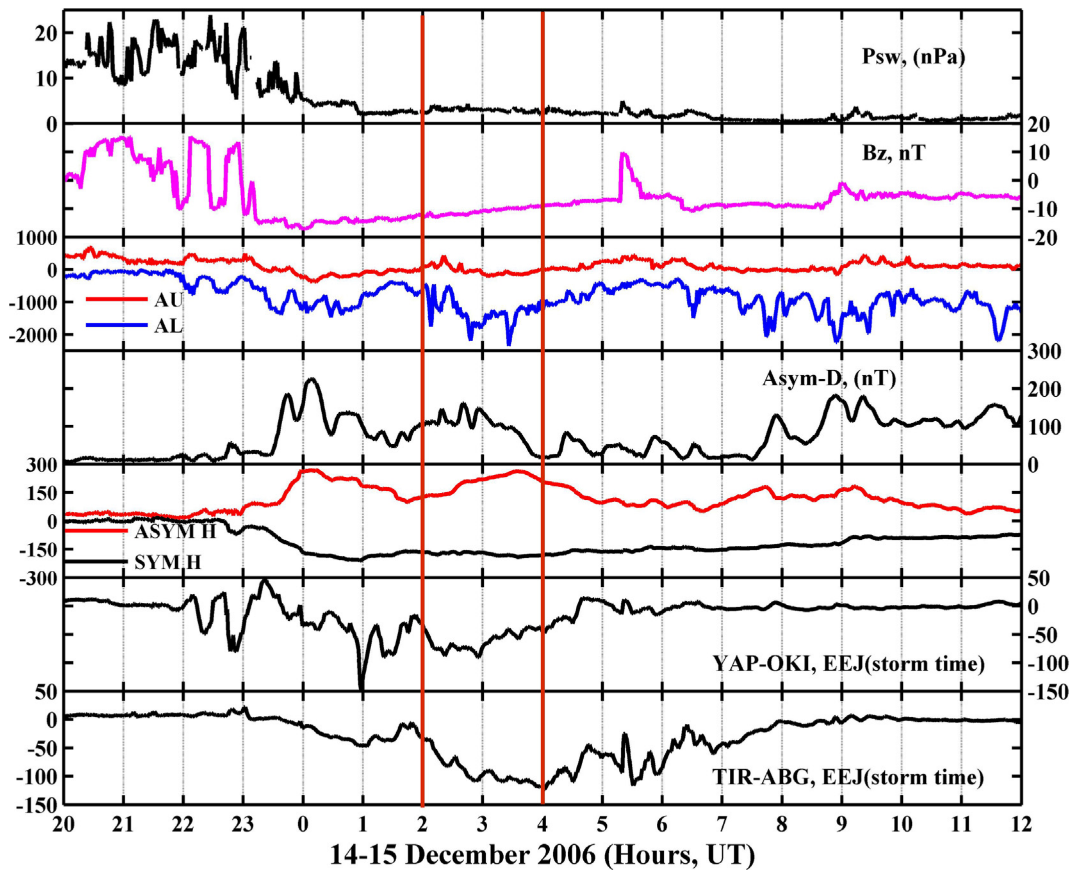

Fig. 2. The dynamic pressure of solar wind (Psw), IMF Bz along with storm time EEJ from Indian and Japanese sectors. The Auroral electrojet indices AU and AL, the symmetric ring current index SYM-H and asymmetric ring current index ASYM-H and ASYM-D component for the period from **2000** UT, 14 December, to **1200** UT, 15 December 2006. The portion between the thick vertical lines indicates the strong westward electric field at both sectors during steady southward IMF Bz during **0200-0400** UT (see text).

(Wei et al., 2011). Kikuchi et al. (2003) observed the equatorial CEJ condition during clear isolated substorm events and explained the decrease in the convection electric field caused by related R1 FACs, under the state of strongly developed shielding electric field, generated by R2 FACs. In the near Earth magnetosphere, the earthward plasma convection enhances the plasma pressure in the inner magnetosphere generating strong PRC which produces R2 FACs in the evening and afternoon magnetosphere (Jaggi and Wolf, 1973; Xie et al., 2006). The PRC becomes the symmetric ring current after the southward IMF ceases or turns to northward (Clauer and McPherron, 1980). Interestingly, the ASYM-D shows the enhancement during interval 1, indicating the increase of R2 FACs. Generally ASYM D can be used as indicator for the strength of the FACs as other currents like ring current and Chapman-Ferraro current do not contribute to change in D component.

To obtain the clear signatures of development of PRC in different MLT sectors, we have used H component data for 12 low latitude stations (Table 1) for interval 1. Fig. 3 shows the asymmetric ring current development from 0000 to 2400 MLT, if contributions from the other current systems are ignored or not significant. The ΔH of all low latitude stations covering different MLT timings for a particular UT time and the storm time asymmetry during dawn, dusk, noon and mid night sectors of MLT. The four panels (top to bottom) shows the signatures of development PRC at different UT times which covers the main phase (0015 UT, Fig. 3a), onset of recovery phase (0130 UT, Fig. 3b), during the interval 1 (0250 UT, Fig. 3c) and after the interval 1 (0430 UT, Fig. 3d) respectively. The horizontal lines represent the SYM–H value at that particular UT time. During the main phase (at 0015 UT, Fig. 3a), ΔH shows a strong dependence on MLT. It is clearly seen that ΔH is higher than SYM-H (~180 nT) during post midnight to noon sector (0000–1200 MLT) and decreases to below SYM-H value during dusk sector (1400–2000 MLT), indicating the large asymmetry between dawn and dusk MLT sectors showing the well-developed PRC. After starting of recovery phase (0130 UT, Fig. 3b), the MLT dependence of ΔH becomes less significant, most likely indicating reduction of the asymmetric ring current. During the crucial interval 1, at 0250 UT (Fig. 3c), again asymmetric ring current develops. This could be assumed as a result of enhancement of plasma pressure in dusk sector in inner magnetosphere which enhances the R2 FACs during substorms (Hashimoto et al., 2002). After 0430 UT (Fig. 3d), the asymmetric ring current ceased due to recovery phase of the magnetic

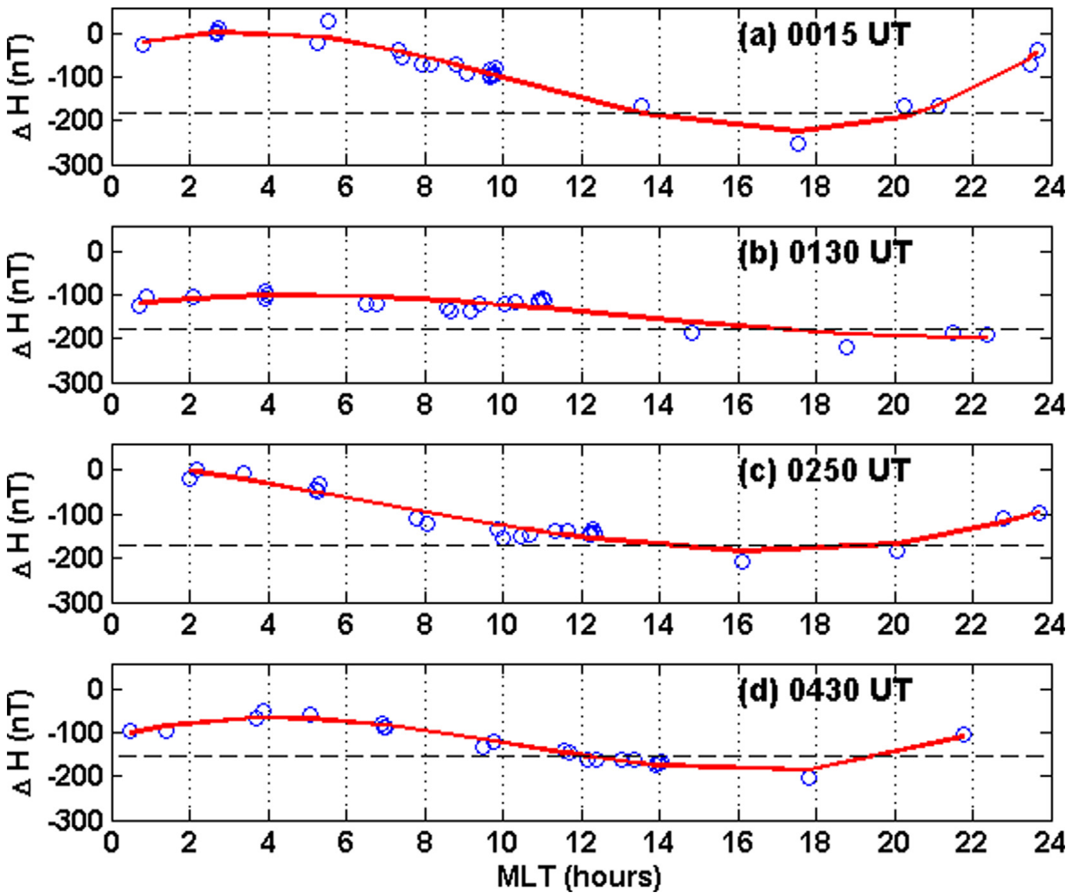

Fig. 3. ΔH component data of 12 low latitude stations (Table 1) is used to show the asymmetric ring current development from **0000** to **2400** MLT for different UT time for main and recovery phase of the storm on 15 December 2006. The horizontal lines represent the SYM –H value at that particular UT time.

storm. During substorms, Hashimoto et al. (2002) found that the variations in H component are due to the PRC which started to grow concurrently at all local times with delay of 5–11 mins from the developed ionospheric convection. It is observed that the occurrence of substorm during interval 1, with concomitant of enhanced PRC (Fig. 3) due to strengthening of R2 FACs could be the possible cause to get significant westward electric field observed at both sectors. It cannot be ruled out that the disturbance dynamo could have been effective as the storm was in progress and caused the westward electric field at equatorial latitudes during daytime. But the largest magnitudes are observed during late night sector than day (Fejer et al., 2007).

3.3. Observations in electron flux in LANL data

Fig. 4 elicits (from top to bottom) the variations in the energetic electrons in the four energy channels (~50–73 keV, ~72–104 keV, ~102–148 keV, ~143–218 keV) as measured by the Synchronous Orbit Particle Analyzer (SOPA) instrument from on-board four Los Alamos National Laboratory (LANL) satellites (LANL 1989–046, LANL 1994-084, LANL-01A and LANL-02A) at geosynchronous altitudes. The 1989-046 and 1994-084 satellites were on the dusk side and 01-A and 02-A were on the midnight and dawn sector respectively during the event (marked with vertical lines in Fig. 4). These satellites registered a moderate drop in electron flux starting prior to 0000 UT and a strong drop in flux at ~0300 UT followed by dispersion-less particle injection at ~0430 UT. The observations by the LANL-01A satellite in the midnight sector on 15 December 2006 reveal increase in geosynchronous fluxes at ~0220 UT and dispersion-less injection signature at ~0430 UT similar to the 1989-046 and 1994-084 satellites. It is also noted that dispersed injections are observed by LANL-01A (midnight) satellite at about 0130 UT. It is to be noted that energy dispersion associated with substorms is thought to be caused by energy-dependent drifts of the particles outside the injection region (Reeves et al., 1991). In the dawn side (LANL-02A), the rapid fluctuations seem to be the signatures of magnetopause crossings. It is, therefore, apparent that there were substorm activities in the dusk-midnight sector during the early hours of 15 December 2006. Therefore, the intensifications of AL and ASY-H during 2300–0130 UT and 0200–0500 UT can possibly be related to substorms.

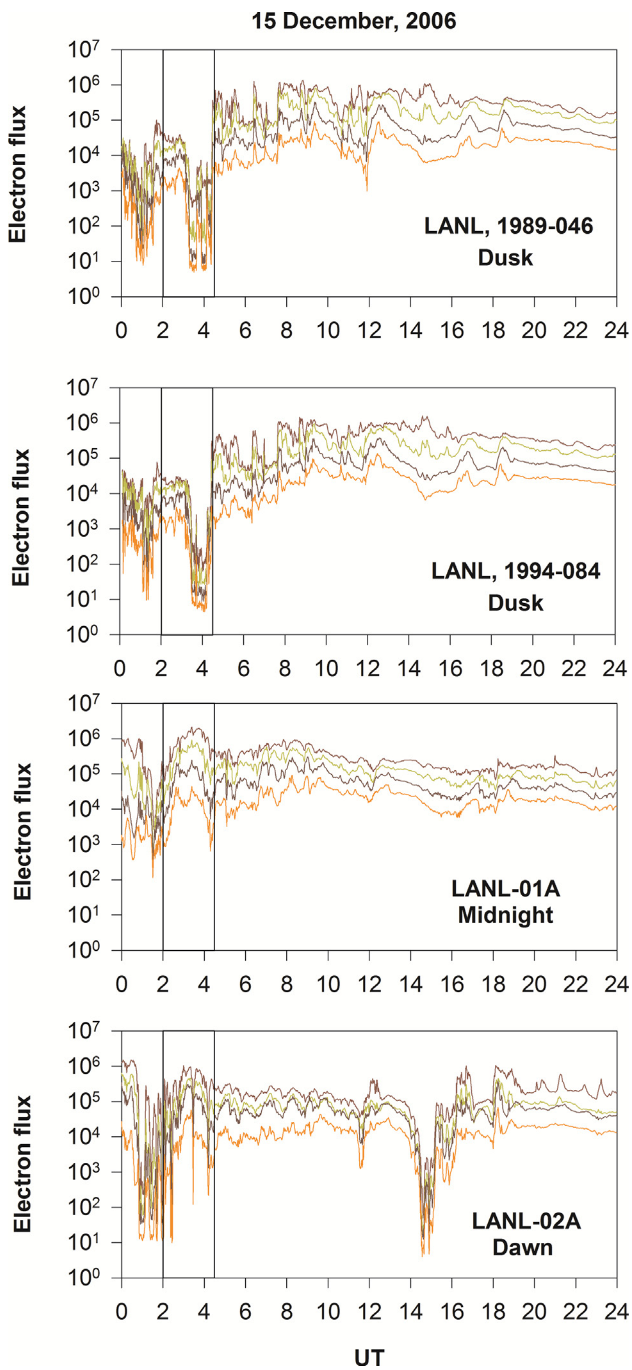

Fig. 4. Shows the (from top to bottom) variations in the energetic electrons in the four energy channels (∼50–73 keV, ∼72–104 keV, ∼102–148 keV, ∼143–218 keV) as measured by LANL satellite on 15 December 2006. The clear variations in electron flux noticed between 0000 and 0400 UT during westward electric field observed at both Indian and Japanese sectors. The vertical lines shows the duration of the event.

3.4. Interplanetary magnetic field and geomagnetic variations for equatorial and low latitude from Indian and Japanese sectors: Magnetic storm of 7–8 November 2004

An interesting observation of variations in equatorial electric fields is noticed for another intense magnetic storm event of 7–8 November 2004 represented by Fig. 5. The super intense magnetic storm occurred due to a strong CME during descending phase of a solar cycle 23. The SC occurred at 0300 UT on 7 November 2004 and followed by unusual large initial phase of 18 h (SC not shown in Fig. 5). The main phase onset occurred at 2100 UT on 7 November and attained its maximum Dst −373 nT (-394 nT, Sym H) at 0556 UT on 8 November 2004 and had secondary minima of −280 nT at 2104 UT on 9th and at 10th November, which is not a focus of this present study. Fig. 5 depicts the solar wind velocity (Vsw), density (Nsw), interplanetary magnetic field components IMF By, IMF Bz, (top four panels) observed by ACE satellite during the magnetic storm of period of 7–8 November 2004. The bottom panels show the ground geomagnetic variations in ΔH for YAP and OKI from Japanese sector and ΔH for TIR, and ABG from Indian sector along with SYM-H for the same period. The IMF Bz varies with large fluctuations and remains strong southward long hours of around 08 h during main phase of the storm with maximum magnitude of almost 50 nT. The ring current development initiated slowly, shown in the decrease in the Sym H and ΔH from both sectors. For the same event of 7–8 November 2004, the electric field variations during 1500–1600 UT (on 7 November 2004) are reported using radar measurements from the Jicamarca Radio Observatory and associated changes in magnetometer data from Pacific sector with related ionospheric response from Brazil are studied (Fejer et al., 2007). The main focus of this work is, the strong overshielding electric field observed at both Japanese and Indian sectors for 7–8 November 2004 magnetic storm is not reported earlier.

3.5. Case 2: Equatorial Counter electrojet and overshielding electric field

Fig. 6 depicts an close-up view of the solar wind dynamic pressure Psw, IMF Bz, AU, AL indices, ASYM-D, SYM-H, ASYM-H along with storm time EEJ from both sectors for the period of 2000 UT to 1200 UT of 7–8 November 2004 magnetic storm. The increased levels of solar wind dynamic pressure (∼20 nPa) continued till 0000 UT with fluctuations in IMF Bz. It is noted that the IMF Bz is intense with magnitude of −50nT for the period of 2300 UT to 0450 UT with large perturbations in AL in ASYM-D along with ground magnetometer data from both sectors. Fejer et al. (2007) discussed the same event using Jicamarca radar observations clearly shows the strong upward drifts (eastward electric field) at around 2015 UT with sudden increase in solar wind electric field in conjunction with drop in PCP to 300 kV and not observed any noticeable perturbations in pacific magnetometer data (Japanese magnetometer stations YAP and OKI) as the sector in night side, and later observed large westward current perturbations throughout the interval of 2115 UT to 2215 UT (local sunrise period). They have not focused on large positive and negative enhancements which are prominently seen in storm time EEJ during 0000 to 0400 UT (0900 to 1300 LT, Japanese sector) and

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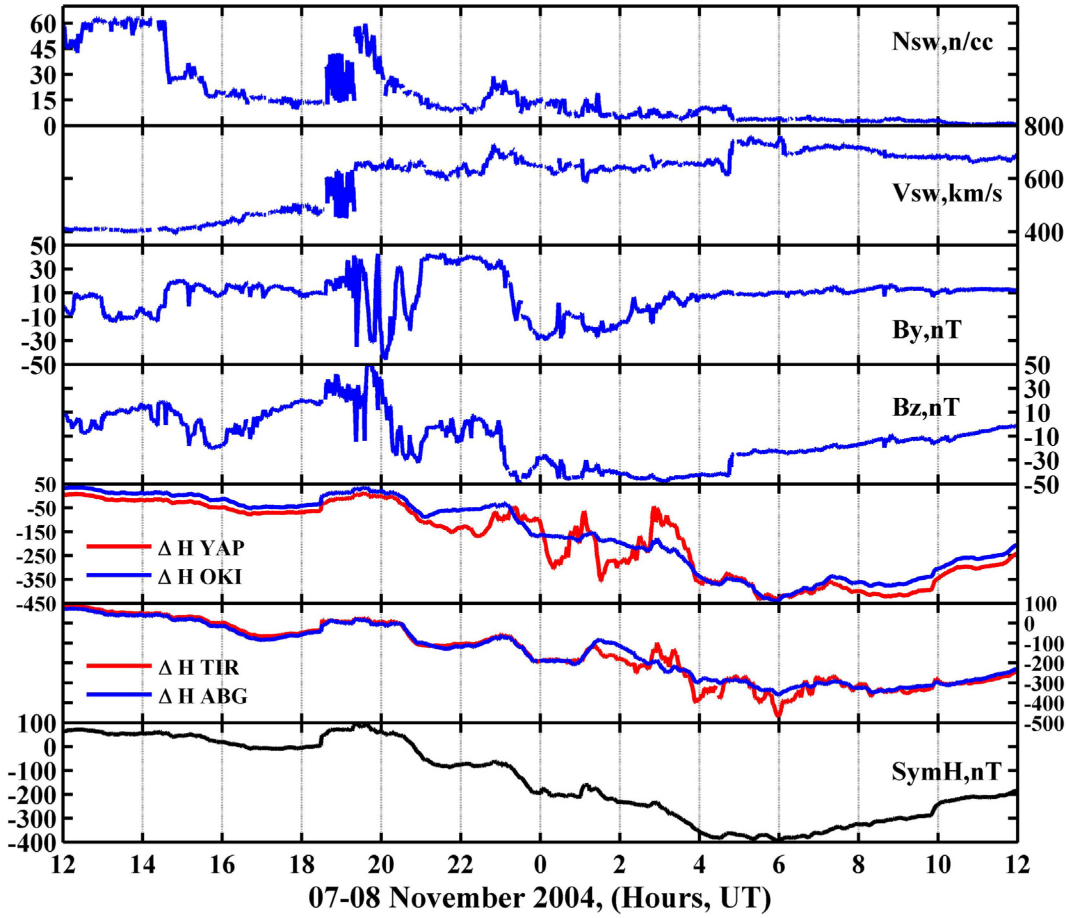

Fig. 5. The same parameters of Fig. 1 but for the intense magnetic storm of 7–8 November 2004.

during 0100 to 0600 UT (0630 to 1130 LT, Indian sector), which is the main aim of this work. As mentioned earlier, the strong southward IMF Bz persists during same interval, it is expected to observe long eastward electric fields with the intensification of convection electric field and the large increase in storm time EEJ during the day time equatorial latitudes for both sectors. However, in contrast, it is interesting to observe that the strong CEJ measured at 0100 UT (Japanese sector), 0330 UT (Indian sector), as evidences of strong overshielding electric field during main phase of the storm. The visibly sharp decrease in AL index indicates the substorm event at 0100 UT (first vertical red line), in concurrence with sharp rise in ASYM-D as a signature of increased R2 FAC, which plays an important role in production of overshielding electric field. The prominent observation CEJ is marked with magnitude of ∼-220 nT at Japanese sector and ∼−60 nT at Indian sector. After 0135 UT, the overshielding electric field decreased with a rise in the storm time EEJ as indication of increase in eastward electric field, peaked at around 0300 UT at both sectors. The second CEJ observed at 0323 UT with the gradual drop in AL index and moderate rise in ASYM H and ASYM D, as an implication of slow development of R2 FAC which influences the production of overshielding electric field. Both the CEJ events clearly signifies the observations of strong overshielding electric fields could be due to substorm occurrence during main phase of the storm, under steady southward IMF Bz. During 0100 to 0400 UT, very minor variations in solar wind dynamic pressure are noticed, mostly remained at less than 10 nPa. The possibility of disturbance dynamo effect may not be responsible for rapid variations in equatorial electric fields, as evidenced by the steady higher values of PCP drop values (Fejer et al., 2007). Fig. 7 depicts the variations in H component of geomagnetic field at two stations ASC (close to mid latitude) and MBO (low latitudes) which were in the midnight sector and another set of low latitudes stations, API, HON which were in noon sector at the time of substorm onset (0100 UT). The stations details have been included in Table 1. The electron flux variations from LANL at mid night and noon local times show clear signatures of substorm onset at 0100 UT (marked as a dashed vertical line). The large positive with negative variations in ΔH of stations during midnight (Fig. 7d) and noon (Fig. 7e) sectors indicates the positive bay and negative bay in the midnight and noon sectors, respectively with the substorm onset. Similar gradual variations have been noticed at 0330 UT, with related positive and negative perturbations in ΔH during mid night and noon sectors with moderate increase in electron flux in LANL data during

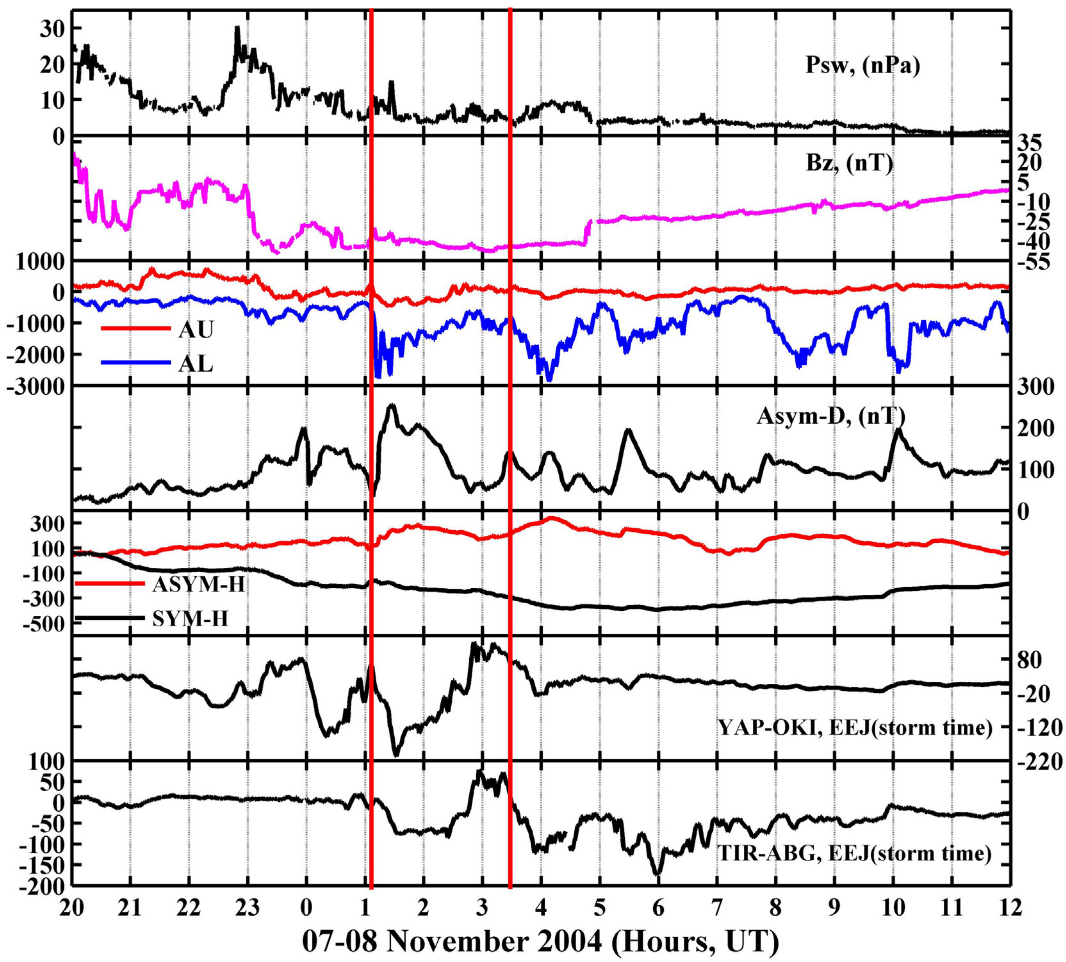

Fig. 6. The same parameters of Fig. 2 but for the intense magnetic storm of 7–8 November 2004. The marked vertical lines shows the onset of overshielding electric fields at both sector (See text for details).

midnight sector. These rapid negative variations in association with sudden AL decrease significantly marks the substorm onset which intensifies R2 FACs, as noticed by clear signatures in ASYM-D (Fig. 6), thereby driving the dusk-dawn electric fields to equatorial latitudes (Kikuchi et al., 2003; Wei et al., 2009).

4. Discussion

On investigating daytime equatorial electric field variations for the two intense magnetic storms, 14–15 December 2006 and 7–8 November 2004 under steady strong IMF Bz period has revealed some interesting results. The main observations in this study are summarized here, (i) The storm time ΔH variations represents the signatures of strong daytime CEJ during main phase of magnetic storm at equatorial latitudes over both Indian and Japanese sectors under the steady southward IMF Bz for several hours. (ii) The strong westward electric field variations indicate the existence of overshielding electric field conditions (iii) The clear signatures of substorm onset are observed in AL index in association with disturbances in electron flux in LANL observations during noon and mid night sectors. (iv) The development of asymmetric ring current is clearly shown in different MLT sectors as an enhancement of PRC, which strengthens the observed overshielding electric fields at day time equatorial latitudes (both sectors) when IMF Bz is steady southward. The possible mechanism responsible for the large magnitude of variations in EEJ and CEJ at day time electric field disturbances is due to the transient Prompt Penetration Electric Fields (PPEFs) from high latitudes to equatorial latitudes when IMF Bz is southward (Kikuchi et al., 2008; Veenadhari et al., 2010). The importance of DD electric field effects appear with a time lag of ~3–4 h (relative fast) after increase in convection electric field and slow disturbances (~4–12 h) are explained due to storm time enhanced equatorward winds from high latitudes (Fejer and Scherliess, 1997; Blanc and Richmond, 1980; Fejer, 2002; Xiong et al., 2015). For some case studies, both PPEF and DD exist together, and the resultant effect is determined by their relative strength of amplitudes and polarities at equatorial latitudes. The DD can also cause the westward electric field, CEJ, on the day side during storm time and it takes several hours to become efficient. The rapid variations in H component are not attributed to DD, because of its slow

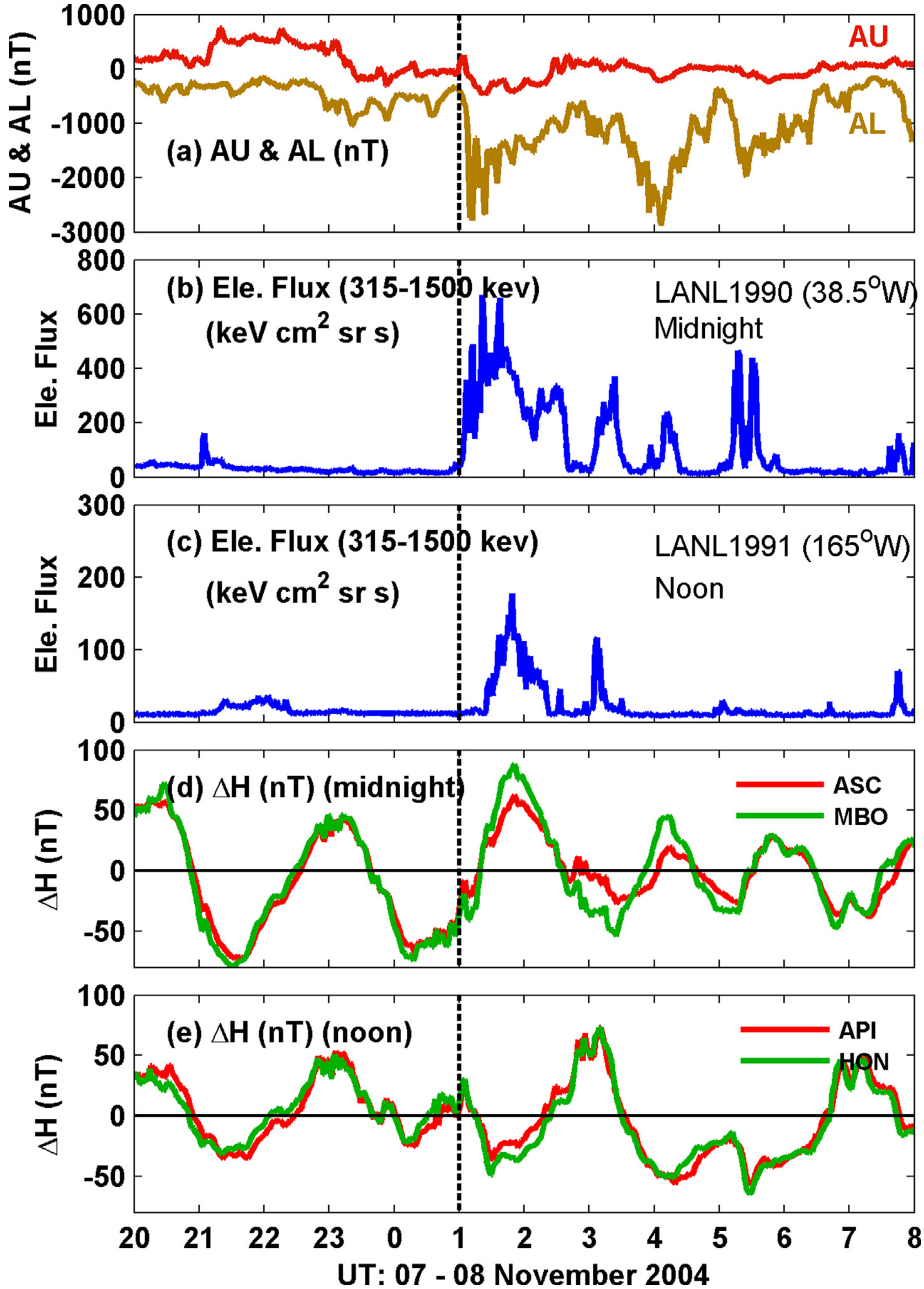

Fig. 7. The temporal variations of (a) AU and AL indices, (b) energetic electron fluxes from LANL at geosynchronous orbit at mid night, (c) LANL observations at Noon sector (d) ΔH at ASC and MBO from the midnight sector, and (e) ΔH variations at API and HON from the noon sector during 2000 UT (7 November 2004) to 0800 UT (8 November 2004). The black dotted vertical line indicates the time of substorm onset.

propagation speed. However, in the present case, the instantaneous and transient nature of electric field perturbations observed in association with sudden IMF Bz variations are mainly due to DP2, undershielding and overshielding electric fields and associated changes in ground ΔH component at equatorial and low latitudes. An earlier investigation shows the simultaneous occurrence of CEJ at equator, during substorms is observed when IMF turned northward in concurrent with sharp decrease in PCP. This CEJ condition is explained by the equatorward penetration of the electric field produced by the R1 FACs is inhibited under the state of a well-developed shielding electric field generated by R2 FACs (Kikuchi et al., 2003). Contrary, Huang et al., (2004) observed the eastward electric field variations at equatorial latitudes due to substorms during stable southward IMF Bz. However, Wei et al., (2009) confirmed the theory proposed by Kikuchi et al. (2003) and suggested that the westward electric field perturbations, drive CEJs at equatorial latitudes on the dayside ionosphere during substorm events and attributed it to the imbalance in R1 and R2 FACs, leading to overshielding conditions mainly due to increase in R2 FACs than decrease in R1 FACs for sudden northward turning IMF Bz. The observed westward electric field explained through polar cap shrinkage and magnetic field dipolarization are due to substorm processes. Our main observation of overshielding condition (westward electric field) for both sectors (Figs. 2 and 6) at day side equatorial latitudes could be attributed to occurrence of substorms during main phase, which enhances the R2 FACs, during steady southward IMF Bz. It is also noticed that substorms may occur at periods when there is no further development in ring current (peak of main phase) or when ring current is recovering (stable). These processes can act as a driver for producing geomagnetic storms on the basis of information theory approach to the storm – substorm relationship using AL and SYM-H indices (De Michelis et al., 2011). The sharp reduction and enhancement in electron flux from LANL observations (Fig. 4) during noon to midnight sector are apparent that there were substorm activities in the dusk-midnight sector during interval 1 on 15 December 2006. At the same time, the increase in ASYM-D for both cases (Figs. 2 and 6) with one to one correspondence with decrease in storm time ΔH at both sectors evidently shows westward electric field signatures closely related to PRC and FACs. Though ASYM-D represents the total sum effects FACs (R1 + R2), the PRC enhancement during interval 1 (Fig. 3) confirms the increase of R2 FACs was significant.

The development of PRC has an important role during substorms and enhances the R2 FACs in inner magnetosphere due to increased plasma pressure in the inner magnetosphere by the earthward plasma convection in the near Earth magnetosphere. Generally, the signatures of PRC are the decrease in the H-component at low latitudes, during southward IMF periods and further intensifies during substorm expansion phase (Kikuchi, et al., 2000, 2003 and references there in). The PRC begin to grow concomitantly at all local times along with the development of convection electric field with delay of 5–11 mins (Hashimoto et al., 2002). The asymmetric ring current ceases and turns into symmetric ring current without noticeable delay when convection electric field starts to decrease due to drop in southward IMF or northward turning of IMF Bz. This feature is clearly seen in Fig. 3, as PRC enhancement and reductions during main phase and recovery phase at different MLT sectors. The development of PRC and enhancement of R2 FACs could be caused by substantial increase plasma pressure in the dusk side of inner magnetosphere. The most probable generator for R2 FAC current is believed to be the inhomogeneous distribution of the plasma pressure in the inner magnetosphere, particularly in the ring current region. Briefly, FACs can be produced due to the misalignment between the gradients of plasma pressure and the magnetic field due to the isotropic plasma pressure (Ebihara et al., 2008 and references there in). The strength and the effects of the shielding mainly depends on the plasma pressure in the inner magnetosphere and the ionospheric conductivity. (Wolf, 1970; Spiro and Wolf, 1984; Ebihara et al., 2004). Tanaka et al.(2010) suggested using the global MHD simulations model, at the onset of substorm, plasma pressure in the near-Earth magnetotail strengthens due to the magnetic tension associated with the magnetic field dipolarization, thus producing PRC and the R2 FACs in the nightside inner magnetosphere.

Using global magnetometer data from auroral to equatorial latitudes and SuperDARN (Super Dual Auroral Radar Network) convection maps for 133 isolated substorms, Hashimoto et al. (2011) observed the westward electric field currents at subauroral-to-equatorial latitudes during the onset of substorms and noticed enhanced convection electric field at auroral latitudes. These observations shows that on dayside both R1 and R2 FACs grows simultaneously and further observed a positive bay at mid night sector due to current wedge at mid latitude. The substorm related strong R2 FACs can cause westward electric field (CEJ) at equator and observed reversed electric fields at the subauroral latitude. This suggests that the substorm begins with the intensification of R2 FAC as one of the responsible factor for the equatorial CEJ (Hashimoto et al., 2011) and the same could be possible for the existence of overshielding electric field at day time equatorial latitudes (Figs. 2 and 6). The other possible theory is convection - driven negative bays related to weak and infrequent substorms which can be driven by a continuous southward IMF period during intense geomagnetic storms (with AE at ~ 500–1000 nT) in the night side auroral zone (Pytte et al., 1978).

Recently, Ebihara et al. (2014) demonstrated that the overshielding electric field conditions can be recognized in the inner magnetosphere after substorm onset without northward turning of IMF Bz. They have used the MHD simulation model and with simultaneous observations of global ground magnetic variations at sub auroral latitudes and a strong CEJ at day side equatorial latitudes for an isolated substorm. First time, the simulation model explained in detail, the possible reasons for the enhancement of R2 FACs the overshielding conditions after the onset of substorm with steady southward IMF Bz, is supportive for present investigations. If this is insufficient to cause the overshielding condition efficiently, on the basis of simulation. The other condition is, at the onset of substorm, the plasma pressure is largely increased on the nightside of inner magnetosphere with enhanced R2 FAC is connected to moderately low conductivity regions of equatorial latitudes. The overshielding condition is also due to separation of the equatorward boundary of both auroral region and R2 FAC current, which generates the dusk-dawn electric field and causes CEJ at dayside equator. This condition can be established on the duskside when the ion plasma sheet penetrates to the inner region deeper than the electron plasma sheet does, and can be established in usual storms/substorms. During this event, the gap between the inner edge of the ion plasma sheet and that of the electron plasma sheet was unusually widen due to some reason, leading to the long-lasting overshielding condition. If the

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intensification of R2 FACs was the direct cause of CEJ for the interval 1 (Fig. 2), it would be speculated that some internal acceleration processes could have taken place for the development of the PRC as plasma pressure enhanced in the inner magnetosphere during substorm. The strength of PRC is important for the development of overshielding condition, can also be a reason for obstruction of the development of ring current even though southward IMF Bz continues (Ebihara et al., 2014).

5. Conclusions

This paper addresses the presence of strong CEJ, westward electric field observations, (overshielding electric fields) at the dayside equatorial latitudes over both Indian and Japanese sectors under the steady southward IMF Bz, during main phase of the intense magnetic storm 14–15 December 2006 and 7–8 November 2004. The clear signatures of substorm are observed in electron flux variations in LANL data during night and dusk sector. The observations further indicate that the occurrence of substorms during main phase of the magnetic storm enhances the partial ring current at dusk sector of inner magnetosphere, which intensify the R2 FAC and leads to overshielding condition at daytime equatorial latitudes. The development of asymmetric ring current is clearly shown in different MLT sectors as an enhancement of PRC, which strengthens the observed overshielding electric fields at day time equatorial latitudes (both sectors) when IMF Bz is steady southward. On other hand, it could also be possible due to the convection - driven negative bays, which can be due to continuous southward IMF Bz and characterized by the typical substorms which are weak, infrequent which occurred during intense magnetic storms. These results are helpful to understand the complex phenomena involved in the occurrence of substorms during magnetic storms and associated processes in inner magnetosphere. However, further investigations are needed to address the issues related to enhancement of the PRC during main phase of the magnetic storm and substorms, and associated variations in polar cap shrinkage and magnetic field dipolarization with simultaneous observations at the equatorial, mid and subauroral latitudes.

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