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Post sunset equatorial spread-F at Kwajalein and interplanetary magnetic field

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Abstract

We connect the time sequence of changes in the IMF-Bz to the development of spread-F at an equatorial station Kwajalein on three different nights in November 2004, one during a geomagnetic quiet period and other two during geomagnetic disturbed periods. The chosen days show clear and smooth variations of IMF-Bz without any large fluctuations thereby enabling one to correlate changes in equatorial spread-F with corresponding changes in IMF-Bz. It is shown that a slow and continuous increase in the IMF-Bz over a duration of few hours has a similar effect on the equatorial ionosphere as of a sudden northward turning of the IMF-Bz in causing an electric field through the polar region and then to the equator. We conclude that the Spread-F at equatorial and low latitudes are due to echoes from ionization irregularities that arise due to the plasma instabilities generated by an eastward electric field on the large plasma density gradient in or below the base of the F-layer during any period of the night time along with the gravity driven Rayleigh-Taylor instability.

Keywords: Equatorial ionosphere; Equatorial spread-F; Geomagnetic storms

1. Introduction

The role of the F-layer height rise in the onset of equatorial spread-F (ESF) is known since 1938. The F-layer over Huancayo rose by 100 km or more in the post sunset hours and was found to be closely associated with the later occurrence of scatter and diffuse echoes from the F-region over a wide range of frequencies, now known as ESF (Booker and Wells, 1938). The phenomenon was later observed over other equatorial stations, Singapore (Osborne, 1951), Ibadan (Wright et al., 1956), Kodaikanal (Bhargava, 1958), and many other stations established since the International Geophysical Year (1957–58).

Chandra and Rastogi (1972) described the occurrence of spread-F on ionograms at Thumba, close to the magnetic equator in India. The irregularities were shown to start at the base of the F-layer and were assumed to be horizontal layers of scattering centers causing Range Spread-F on the ionogram images. Rastogi (1984) compared the Modified Range Time Intensity (MRTI) records of VHF radar at Jicamarca with simultaneous ionograms at Huancayo. The altitude of range spread echoes in the ionograms corresponded very well with the altitude of the maxima in the intensity of scatter echoes in MRTI records. It was concluded that the range spread-F echoes at HF on ionograms are due to scattering by layers of sharp plasma density gradients. Sometimes with rapid rise of the F-layer, Spread-F started with both range and frequency type.

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A major breakthrough in the understanding of ESF came with the measurements of vertical F-region drifts by the VHF radar at Jicamarca. Farley et al. (1970) using the VHF radar data at Jicamarca concluded that the observations rule out the then existing theories of their origin and the density gradient and drift velocity remain as possible sources of the instability. Dungey first (1956) proposed gravitational instability as the cause of Spread-F. Reid (1968) had suggested the gradient drift instability for causing Spread-F. At that time both these theories required experimental evidence. Woodman and La Hoz (1976) suggested that the drift instability was the best candidate for the irregularities at the steep rise of the F region. Balsley et al. (1972) proposed the collisional Rayleigh-Taylor instability (RTI) to account for the irregularities seen both on the bottom side and topside. Large-scale plasma depletions due to RTI rise to topside and instabilities grow on gradients caused by the primary instability. Woodman and La Hoz (1976) reported plume like structures in radar maps and suggested them as an evidence of plasma depletions. Plasma depletions were later confirmed by satellite-borne in-situ measurements (McClure et al., 1977). Besides the gravitational term, electric field and neutral winds contribute to the growth of irregularities and the generalized Rayleigh-Taylor (GRT) instability mechanism is considered to explain the ESF. Eastward electric field contributes to the growth rate of irregularities for upward plasma density gradients, and also lifts the F-layer to higher altitudes where the growth rate of the RT instability is higher.

Sales et al. (1996) made co-located measurements of an optical imager for post-sunset appearance and movements of depletions and a digisonde from Agua Verde in Chile near the southern crest of ionization anomaly (11^{o} magnetic latitude). The digisonde was also operated in an interferometric mode in between the ionograms recordings to identify the location of irregularities. The HF sounder located the irregularities inside the depleted regions and encountered orthoganility with the geomagnetic field within the depleted bubble southern from the site. This demonstrated that the spread-F signatures on ionograms are due to coherent scatter from irregularities within the walls of depletions.

There have been several studies to relate the ionospheric parameters to ESF that can be used as precursors to predict ESF. Later evening reversals of F-region electric field on ESF days than on non ESF days was shown from the spaced receiver drift measurements at Thumba (Chandra and Rastogi, 1978) and Tiruchirapalli (Vyas and Chandra, 1991). Stronger ionization anomaly on ESF days than on non ESF days was shown from the ratio of electron density over Ahmedabad (anomaly crest) and Waltair around 1800 LT (Raghavarao et al., 1988), from TEC measurements near the crest region and trough region (Rastogi et al., 1989) and from the ratio of 630 nm day glow measurements made from Waltair pointing to north and south in the afternoon hours (Sridharan et al., 1994). In the American sector Mendillo et al. (2001) and Valladares et al. (2001) showed stronger anomaly on ESF days from TEC measurements. Whalen (2001) studied anomaly and plasma depletions based on a chain of ionospheric sounders and airglow imager measurements. For strong ESF and macroscopic bubbles a threshold limit of about 50 m/s for the vertical drift velocity was noted. Alex et al. (2003) examined ESF at a chain of stations in American sector during IGY and obtained vertical drift of 42 m/s for days with ESF at both Huancayo and Bogota (crest). Thus electrodynamics plays an important role in the onset of ESF. Fagundes et al. (2009) suggested that the planetary waves in the thermospheric wind cause day-to-day variations in the zonal electric field near sunset hours causing day-to-day variability in the post sunset rise of the F layers and on the generation of ESF.

Rastogi and Woodman (1978) showed ESF can appear at any time of the night other than the post sunset period following the abnormal reversal of the vertical F-region drifts to upward direction, with a delay of about 1–2 h. Rastogi and Patel (1975) showed that large and fast northward turning of IMF is viewed by Earth as an Interplanetary Electric Field (IEF) equal to -V×Bz, where V is the solar wind velocity and Bz the IMF component perpendicular to the ecliptic (IMF-Bz). The solar wind impact on the Earth's magnetic field is transmitted through the polar region to the equatorial ionosphere without any time delay. A northward turning of the IMF-Bz imposes a dusk to dawn electric field over the Earth, which is eastward in the night side and westward during the dayside of the ionosphere. Rastogi (1977) reported the generation of ESF at Huancayo after a northward turning of IMF-Bz at 0340 LT on 3 July 1968. The greatest advance in the study of the ESF was provided by the VHF backscatter radar at Jicamarca and by the development of the digisonde at the University of Massachusetts, Lowell, USA (Reinisch et al., 2009)

In this paper we present results on ESF at Kwajalein Island (KWJ; 8.7^{o}N, 167.7^{o} E, dip 8.9^{o}) in relation to the changes in IMF-Bz during geomagnetic disturbed periods. The two events chosen are when IMF-Bz is changing smoothly without any large sudden fluctuations. The local time at Kwajalein is 11.15 h ahead of UT.

2. Results

2.1. Spread-F on the night of November 03–04, 2004

Fig. 1 shows the occurrence of ESF on the night of November 03–04, 2004. The upper panel shows the variations of the minimum virtual height of the F-layer (h'F), IMF-Bz and SYM/H index during the night. It can be seen that the SYM/H indices were very low suggesting a weak disturbance ring current. The IMF-Bz too remained within ± 5 nT indicating no solar wind disturbances during the night. The lower panel of Fig. 1 contains selected ionograms showing the development of ESF during this night.

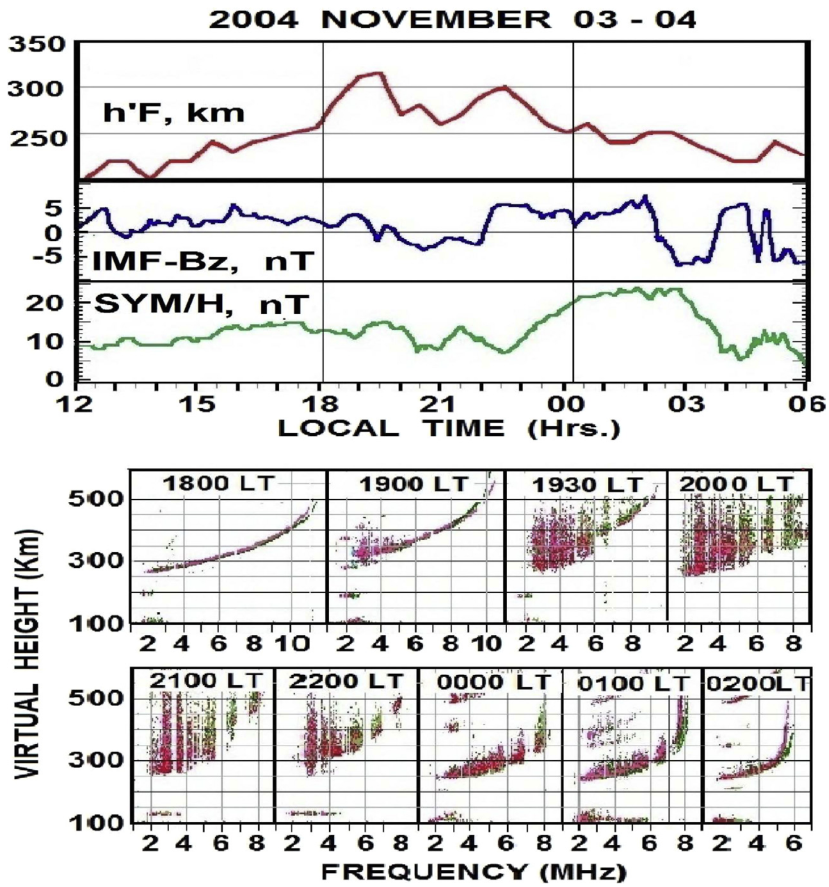

Fig. 1. (Upper Panel) The variations of h'F, IMF-Bz and SYM/H index during the night of 3–4 November 2004. (Lower Panel) Selected ionograms at Kwajalein during the night of 3–4 November 2004.

At 1800 LT the ionogram trace was very clear with h'F, about 250 km. In the absence of appreciable ionization below F-layer during night h'F is a fair indicator of the base height of the F-layer. At 1900 LT, some range type of spread started to develop at the lower frequency end of the trace, and the ordinary (red) and extraordinary (green) traces corresponding the two modes of radio propagation through ionosphere remain clear at the higher frequencies making the ordinary and extraordinary critical frequencies of the F layer clearly identifiable. At 1930 LT the ESF grew stronger and extended to higher frequencies; still the critical frequencies were clearly marked. Note that some of the ESF echoes occurred below the h'(f) trace. At 2000 LT and 2100 LT no clearly identifiable h'(f) echo trace exists and the F2 layer critical frequencies, foF2 and fxF2, are no longer identifiable for the very irregular F region plasma distribution. For 2000 LT and 2100 LT h'F values shown in Fig. 1 are interpolated from the ionogram. At later times the intensity of the spread decreased and ESF finally disappeared by 0200 LT. In summary, the IMF-Bz as well as SYM/H indices were low throughout the night. The virtual height of the F layer, h'F, increased by about 50 km after sunset and slowly decreased through the night. The ionograms at 1900 LT show some ESF at the lower frequency end of the ionogram. Later on strong range type Spread-F developed at 1930 LT with spread echoes reaching from 50 km below h'F to 400 km above. At 2000 LT, ESF extended throughout the whole F layer. This represents the normal development of ESF on a quiet day.

2.2. Spread-F on the night of November 08–09, 2004

Fig. 2 (upper panel) shows the temporal variations of SYM/H index, IMF-Bz and h'F at Kwajalein during the night of November 8–9, 2004. This period followed a major geomagnetic storm on 8 November 2004. The event was a complex magnetic storm with three pulses of sudden commencement (SC) at 0257 UT, 1051 UT and 1827 UT on 7 November 2004. There was a large negative SYM/H index of -394 nT in the evening (1715 LT), recovering slowly to about -100 nT by 06 LT next morning. IMF-Bz was abnormally large and southward, about -45 nT around 14 LT, changed sharply to -20 nT at 16 LT and then steadily increased to about + 10 nT by midnight. The variation of h'F, showed a small increase from 215 km at 15 LT to 290 km at 19 LT before decreasing to about 250 km around 2230 LT. The ionograms for this night are reproduced in Fig. 2 (lower panel). As there was no significant post sunset rise of F-layer there was no ESF following the small post sunset height rise. At 2200 LT, h'F was about 250 km with

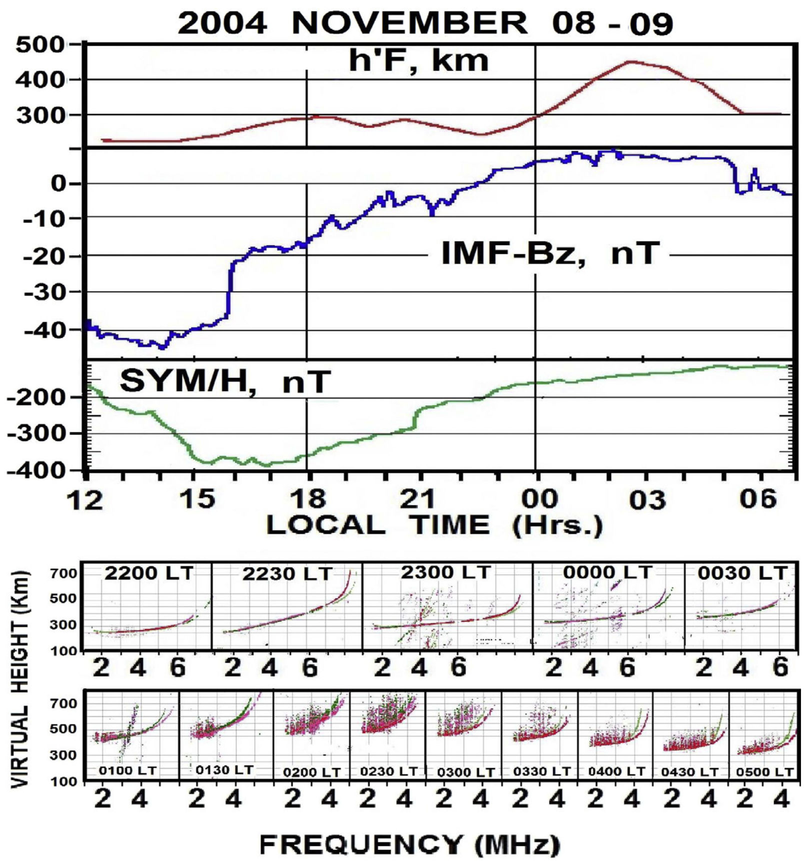

Fig. 2. (Upper Panel) The variations of h'F, IMF-Bz and SYM/H index during the night of 8–9 November 2004. (Lower Panel) Selected ionograms at Kwajalein during the night of 8–9 November 2004.

normal width of the trace. At 2230 LT h'F was still at 250 km when the F2 layer began moving up and h'F reached values of 450 km at 0230 LT when IMF-Bz was +10 nT. Additional spread echo traces, with larger radar ranges than the overhead h'(f) trace, are produced by off-vertical reflections and coherent scatter from density depletions (bubbles) located a (few) 100 km east and west of Jicamarca producing the "range spread" seen in the ionogram at 0230 LT. At 0030 LT h'F rose to 360 km, but no high multiple traces were seen. At 0100 LT some weak range type of ESF was recorded at the lower frequency end of the trace. The F layer continued to ascend until 0230 LT with simultaneous increase of Spread-F intensity. Afterwards the whole F-layer started to descend reaching a level of 300 km at 0500 LT. It is to be noted that the critical frequencies of the F-layer are clearly identifiable suggesting that the density depletion (bubble) did not extend to the layer peak. It must be noted that though IMF-Bz changed gradually from -20 nT at 16 h LT to zero at 2230 LT, there was no rise of h'F during this period. From 2230 LT to 02 h LT IMF-Bz increased from zero to about 10 nT and during this period h'F rose from about 250 km to 450 km. Thus a consistent positive gradient of IMF-Bz over a few hours seems to be very effective in generating and sustaining ESF irregularities.

2.3. Spread-F on the night of November 10–11, 2004

Fig. 3 (upper panel) shows the temporal variations of h'F, IMF-Bz and SYM/H during the night of 10–11 November 2004. The SYM/H index was about −275 nT around 2030 LT on 10 November 2004 and then rose steadily to −120 nT at 06 LT on 11 November 2004. The magnetic storm event was preceded by the SC at 1850 UT on 9 November 2004 (0605 LT on 10 November 2004). Thus, the period of study was the recovery phase of the geomagnetic storm. There were no large fluctuations in the SYM/H index during this period. IMF-Bz was around −25 nT at 18 LT and steadily increased to 00 nT by 2230 LT. It remained close to zero up to 0600 LT. Fig. 3 (lower panel) shows a set of selected ionograms at Kwajalein during the night. At 1800 LT a clear trace was recorded with h'F of 340 km. The F-layer rose later with h'F 370 km at 1810 LT, 410 km at 1820 LT and 500 km at 1830 LT. Strong ESF echoes were recorded at 1830 LT. At 1840 LT a very interesting ionogram was recorded when the irregularity base height was 550 km and the regular h'-(f) trace was seen at much higher altitude with h'F close to 700 km. At 1850 LT and 1900 LT to 2000 LT the layer seemed to descend, and the single trace is replaced by a number of different traces at virtual ranges from 600 to 1200 km. At 2200

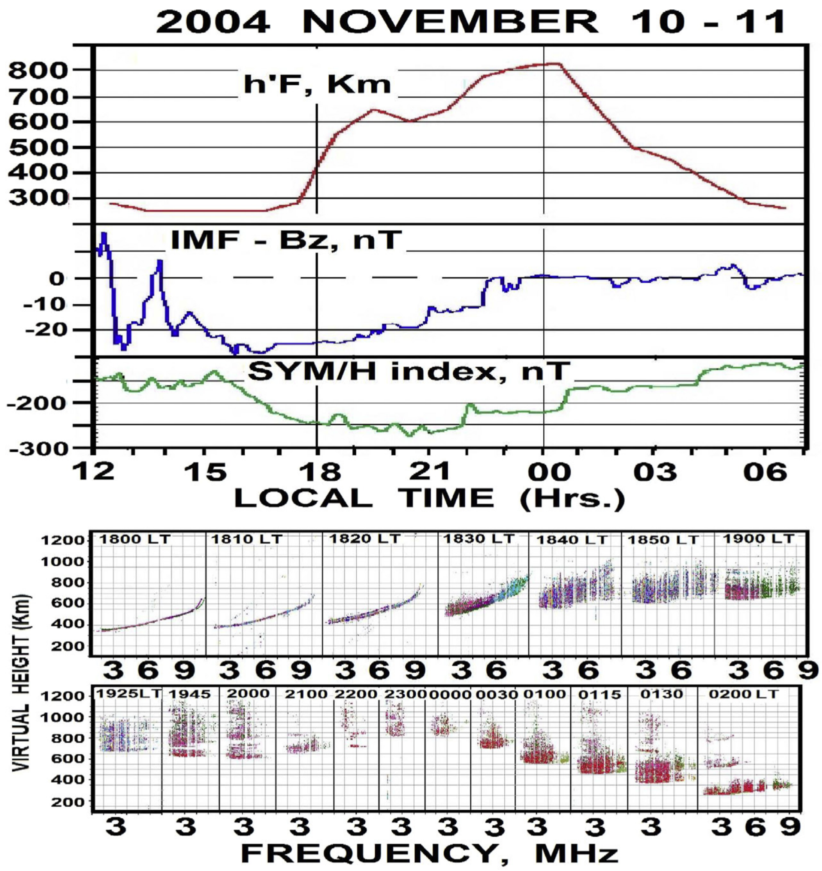

Fig. 3. (Upper Panel) The variations of h'F, IMF-Bz and SYM/H index during the night of 10–11 November 2004. (Lower Panel) Selected ionograms at Kwajalein during the night of 10–11 November 2004.

LT the layer is reduced to a small spread of irregularity at 700 km. At 2100 LT the layer started going up, and oblique echo traces from neighboring depletions with ranges of up to 800 km were recorded at 2300–0000 LT. A small sudden northward turning of IMF-Bz (-10 nT to zero) was seen at 2200 LT. The ionogram at 2300 LT reminds in appearance of the plume structures first seen in the VHF range-time displays reported by Woodman and La Hoz (1976). At later hours the layer continued to descend till it reached to 250 km at 0200 LT. This represents a unique example of blow up of the F-layer with Spread-F irregularities over the magnetic equator associated with the IMF-Bz turning northward. The layer rise was abnormally high.

3. Discussion and conclusions

Interplanetary and polar electric fields promptly penetrate to equatorial latitudes as dawn-dusk electric fields during the onset and growth phases of a geomagnetic storm with time scales of the order of an hour to several hours. These are partially balanced by the development of a shielding layer in the inner magnetosphere (Vasyliunas, 1972; Kelley et al., 1979). Rapidly changing polar electric fields penetrate to equatorial latitudes unaffected by shielding layer (Kikuchi et al., 1996). The prompt penetrating electric field (PPEF) is eastward on the dayside and westward during night, therefore it enhances the daytime eastward electric field. In the recovery phase of the storm the electric field due to shielding layer penetrates to equatorial latitudes as an over shielding electric field or penetration electric field (PEF) with opposite polarity, westward during day and eastward during night (Kelley et al., 1979).

Many authors have described the ESF during large magnetic storms associated with a number of large northward and southward turnings of IMF-Bz. Abdu et al. (2003) studied the major geomagnetic storm of 26 August 1998 based on multi-station and multi-instrument network at equatorial and low latitudes in Brazil. Southward turning of the IMF-Bz and associated auroral (AE) intensifications in the Brazilian dusk sector produced intense prompt penetration electric field that caused large vertical F-region drift and development of intense post-sunset EIA and strong spread-F lasting the night as seen by ionosondes and all-sky imagers. The bubbles showed low eastward velocity that turned into steady westward velocity till morning hours. The results point to the dominant role of the disturbance dynamo electric fields (DDEF) to maintain the westward pointing electric field. They suggested the westward velocity, normally attributed to the disturbance dynamo effect, due to prompt penetration electric field in the course of a disturbance sequence lasting several hours attributed to Hall effect under enhanced ionospheric conductivity due to the storm associated particle precipitation in the Brazilian sector.

The magnetic storm of 8–10 November 2004 was a complex storm and studied by several authors ((Maruyama, 2006; Mannucci et al., 2008; Fejer et al., 2007; Abdu et al., 2009; Ramarao et al., 2009; Rastogi et al., 2012). A strong geomagnetic storm occurred on 8 November 2004 with minimum SYM/H value of -394 nT at 0556 UT preceded by three SC pulses at 0257 UT, 1051 UT and 1827 UT on 7 November 2004. Anothar big storm occurred on 10 November 2004 with minimum SYM/H value of -289 UT at 0932 UT preceded by SC at 1850 UT on 9 November 2004.

Fejer et al. (2007) studied the event of November 2004 using Jicamarca VHF radar, magnetometers in Peruvian (Jicamarca and Piura) and Pacific (Yap and Okinawa) regions and ionosonde data from Sao Luis in Brazil. For the event on 7 November 2004, the drifts at jicamarca were upward between 13 UT and 17 UT, negative between 17 UT and 1830 UT and very small between 1830 UT to 2015 UT. Large vertical drifts of 30 m/s were observed at 2015 UT. Later information from magnetometer data in the Pacific ($\sim 130^{\circ}$ E) showed that the electrojet current fluctuated, being negative from 2115 UT to 23 UT, 00 UT to 0030 UT, 0015 UT 0215 UT and positive from 23 UT to 00 UT, 0030 UT to 0115 UT, and from 0215 UT onwards to 07 UT. Fejer et al. (2007) concluded that these were due to the strong westward prompt penetration electric field at the beginning of the storm main phase and large overshielding fields around 0000 UT and 0100 UT in the absence of northward Bz.

For the event following the SC at 1850 UT on November 9 upward drift increased reaching a value of about 120 m/s around 2000 UT during the main phase of the storm. The magnetometer data from Pacific region also showed exceptionally large westward current perturbation peaking around same time. Relatively large downward drift was observed from about 2100 to 0130 UT but magnetometer data was of quiet day pattern except for rapid perturbations indicating that while the initial decrease of drift was due to prompt penetration, longer lasting downward drifts were mainly due to the disturbance dynamo fields. Large disturbances were again seen between 0130 UT and 0700 UT both in the Pacific and Peruvian regions. The drifts over Jicamarca were predominantly upward. Large upward drift and westward current perturbations between 0400 to 0700 UT, a period of steady solar wind and reconnection electric field and decreasing Dst index indicated that except for brief periods of rapid changes in either solar wind and magnetosphere drivers, equatorial PPEF were either absent or smaller than the DDEF. Between 0700 and 0900 UT large and short lived velocity perturbations indicated over shielding electric fields. Fejer et al. (2007) concluded that during the main phase of the November 9, 2004 storm event the PPEF (eastward) had a life time of about one hour. Westward electric field lasting for about 4 h, were mainly due to disturbance dynamo. Large magnitude short-lived PPEF and long lasting DDEF were observed in the night side over Jicamarca and in the dayside in the Pacific during 10 November 2004. In this case DDEF largely dominated.

Ramarao et al. (2009) have studied the total electron content at a number of stations in India during the magnetic storm event of 6–11 November 2004. The strength of the equatorial electrojet showed a day long counter electrojet on 8 November 2004. The counter electrojet event from 06 LT to 12 LT was also present on 10 November 2004 followed by a normal electrojet from 12 LT to 18 LT. The local time in India is five and half hour ahead of UT.

Abdu et al. (2009) examined few magnetic storm events and showed for the first time that the evening pre-reversal enhancement of vertical drift can be totally suppressed by PEF of westward polarity (over-shielding). Abdu (2012) studied the role of the disturbance electric fields on ESF in a comprehensive way by considering the local time variations. The undersielding PPEF can enhance the ESF development conditions from sunset to premidnight. Over shielding type PEF can cause its interuption or disruption between midnight and morning. DDEF dominate the low latitudes within a few hours (3–4) from the start of the storm with maximum drift in post sunset hours (polarity opposite to PPEF) and it can suppress the ESF. In contrast DDEF beginning around 22 LT can cause large vertical drift of F layer leading to ESF. The longitudinal extent of irregularities depends on the storm duration (90–180°).

Mannucci et al. (2014) analyzed the interplanetary magnetic field during eight super storms and found that increasing daytime TEC during super storms only occurs for large reconnection electric fields when the By magnitude is less than Bz. The data suggested that Bz is a far more important factor in the TEC response than the reconnection electric field. They also found that TEC decreased following its peak storm-time value for two super storms, even though Bz remained large and By magnitudes were less than Bz. Such decreases during the geomagnetic disturbance indicate the role of magnetospheric shielding currents, or of changes in the thermosphere that have developed over the prolonged period of large solar wind electric field. They concluded that further analysis is warranted covering a wider range of storm intensities on the role of By in affecting the daytime TEC response for a range of storm intensities.

In summary, we have shown that a slow, continuous increase in the IMF-Bz over a few hours duration could have a similar effect on the equatorial ionosphere as a sudden northward turning of the IMF-Bz. Both the events shown here follow a major magnetic storm. In the first case of 8–9 November 2004, prominent height rise of the F layer starts just before midnight and ESF from 0100 LT. The height rise is associated with the Bz changing smoothly to northward without any rapid changes though there could be a possibility of DDEF also causing this. But in the second example of 10–11 November 2004, F layer rise and onset of ESF starts regularly in the post sunset period and then the F layer rises again from about 21 LT reaching to peak at 23 LT. This is again associated with the steady rise of Bz to northward. The electrojet in Indian longitude region was normal from 12 LT (corresponding to 1745 LT at Kwajalein) on 10 November 2004 (Ramarao et al., 2009). Therefore possibility of the role of DDEF in this case is unlikely. More case studies of the slow IMF-Bz changes are necessary to understand the role of IMF-Bz in the development/suppression of ESF.

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