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Ionospheric storm of early November 1993 in the Indian equatorial region

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Abstract. An investigation is made of the response of equatorial ionosphere in the Indian (75^0E) sector to the major magnetic storm of November 3, 1993, using data from the ionosonde and magnetometer networks spanning the region 0.3-34.5^{0}N dip. Some outstanding and new aspects of the storm time ionospheric behaviour are revealed. An anomalous and striking positive gradient in f_0F_2 from the magnetic equator to 34.5^0 dip developed under counter electrojet (CEJ) condition in the morning on November 4, corresponding to the early stage of the storm main phase. This storm effect is attributed to plasma transport by a poleward surge in transequatorial winds due to large scale atmospheric gravity waves (AGWs) launched by auroral heating. Remarkable wave-like variations in hpF_2 and f_0F_2 immediately followed at locations away from dip equator till local sunset, with concomitant disruptions in the development of the equatorial ionization anomaly (EIA). Rapid variations in meridional neutral winds due to large-scale AGWs are assessed as the cause of the oscillations in hpF_2 and the associated cyclic sequence of development and inhibition of EIA as the outcome of the combined effects of plasma transport due to meridional winds and the plasma "fountain" driven by **EXB** drift. Just after the onset of the storm recovery phase at 1800 LT, a sudden and anomalous drop (54-57%) in f_0F_2 prevailed throughout the anomaly region over the interval 1915-2330 LT, with an apparent time delay in occurrence toward the magnetic equator. This premidnight collapse of equatorial F region is interpreted in terms of horizontal transport of plasma across the equator toward the opposite hemisphere by an equatorward surge in meridional winds. The case study showed that besides disturbances in the zonal electric field due to prompt penetration and ionospheric disturbance dynamo effects, perturbations in neutral meridional winds played a prominent role in the ionospheric storm of November 4, 1993, in the Indian equatorial region.

1. Introduction

The behaviour of the neutral and ionized components of Earth's upper atmosphere deviates quite significantly from the average/quiet day pattern during geomagnetic storms. This departure commonly referred to as "ionospheric-thermospheric storm" is a major topic of current research in Solar-Terrestrial Physics [see e.g., *Rishbeth et al.*, 1987; *Prolss*, 1995; *Buonsanto et al.*, 1997; *Knipp et al.*, 1998, and references therein]. The polar thermosphere-ionosphere system (TIS) responds directly and dramatically to the enhanced energy and momentum deposition there during geomagnetic storms through particle precipitation, convection electric fields, field-aligned currents, and heat flows [e.g., *Schunk*, 1987; *Lu et al.*, 1998]. The response is characterized by elevated neutral temperatures and attendant changes in the neutral wind field and chemical composition as well as in ionospheric structure and dynamics due to strong plasma-neutral coupling. The geomagnetic storm effects at middle and low latitudes are in contrast subtle and indirect and arise from electrodynamical/ dynamical coupling of high-latitude- -low- latitude TIS [e.g., see *Fesen et al.*, 1989; *Burrage et al*, 1992; *Burns et al*, 1995; *Abdu*, 1997; *Fejer*, 1997; *Fuller-Rowell et al*, 1994, 1997; *Emery et al*, 1999, and references therein].

Equatorial ionospheric storms of primary concern here result from modifications in zonal electric field, meridional neutral winds, and neutral gas temperature and chemical composition [e.g., *Rishbeth*, 1975; *Sastri*, 1980; *Mikhailov et al.*, 1994; *Abdu et al.*, 1991, 1993, 1997, and references therein]. The common perception among researchers is that electric field disturbances are by far the most important contributor to the storm time behaviour of equatorial F region. This is logical because the structure and dynamics of quiet time ionosphere is determined by the dynamo-generated electric field and the plasma "fountain" process associated with it, with meridional winds acting as a modulator of field-aligned plasma transport associated with the fountain process [see *Anderson*, 1981; *Preble et al.*, 1994; *Bailey et al.*, 1997, and references therein]. Storm time modifications in equatorial zonal electric fields field fall into two broad groups. The first group is the rapid and short-lived (2-3 hours) changes that most often occur in close temporal association with sudden changes in interplanetary magnetic field (IMF) Bz, polar cap potential drop, auroral electrojets, and symmetric/asymmetric

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ring current activities, all of which are intricately related to each other [see *Fejer*, 1997; *Abdu*, 1997, and references therein; *Sastri et al.*, 1997; *Sobral et al.*, 1997; *Fejer and Scherliess*, 1997]. These are due to direct (prompt) penetration to low latitudes of perturbation electric fields at high latitudes associated with rapid changes in polar cap potential drop (magnetospheric convection) and field-aligned current systems [e.g., *Fejer et al.*, 1990; *Senior and Blanc*, 1984; *Tsunomura and Araki*, 1984]. Smoothly varying and longer-lasting (several hours duration) perturbations that follow magnetic activity with a delay > 6 hours constitute the other group [see *Fejer*, 1997; *Abdu*, 1997, and references therein; *Scherliess and Fejer*, 1997; *Sobral et al.*, 1997; *Abdu et al.*, 1997]. These are interpreted in terms of the ionospheric disturbance dynamo (IDD) mechanism wherein modifications in global thermospheric circulation brought about by energy deposition in high latitude TIS leads to generation of electric fields at low latitudes with a polarity opposite to quiet time pattern both by day and at night [*Blanc and Richmond*, 1980]. It is to be noted that storm time electric fields can some times exhibit signatures of a complex interplay between direct penetration, short- and longer-term IDD fields, as demonstrated by recent studies [*Fejer and Scherliess*, 1997; *Scherliess and Fejer*, 1997; *Sobral et al.*, 1997; *Abdu et al.*, 1997].

Moreover, global scale perturbations in thermospheric density, temperature, and wind field that result from enhanced energy and momentum deposition in high-latitude TIS during geomagnetic storms may some times take the form of large-scale, large-amplitude atmospheric gravity waves (AGWs), which propagate away from the source region and reach the equator with a speed of ~700 m/s [e.g., *Fesen et al.*, 1989; *Hajkowicz*, 1991; *Burns and Killeen*, 1992; *Balthazor and Moffett*, 1997; *Emery et al.*, 1999]. The superposition of large-scale AGWs on the quiet time neutral circulation due to solar forcing may lead to convergence/divergence of neutral wind flows over/from the equator and at times to strong transequatorial winds. Rapid variations in the amplitude and direction of meridional winds due to AGWs thereby become an important means of plasma transport in the equatorial region and can significantly influence the behavior of EIA acting either individually or in conjunction with the field-aligned plasma diffusion set up by the fountain process. It is increasingly being realized, in fact, that large-scale AGWs of auroral origin could at times play a prominent role in the behavior of equatorial TIS under disturbed conditions [e.g., *Fesen et al.*, 1989; *Hajkowicz*, 1991; *Burns and Killeen*, 1992; *Balthazor and Moffett*, 1997; *Knipp et al.*, 1998].

A major and prolonged geomagnetic storm occurred during November 3-11, 1993, due to the transit at Earth of a recurrent high-speed solar wind flow from a distended coronal hole with transients and a corotating interaction region embedded therein. This storm which led to tumultuous changes in the near-Earth space environment is the subject of extensive origin-to-end studies under CEDAR and SOLTIP programs [see *Knipp et al.*, 1998; *Emery et al.*, 1999, and references therein]. Most of these studies are, however, limited to evaluation and interpretation of the perturbations in TIS at high and midlatitudes and, to our knowledge, the response of the equatorial TIS to the storm remained unassessed. To fill in this gap, we have carried out a detailed study of the equatorial ionospheric effects though limited to the Indian (750E) sector. In this paper we present and discuss the results of the study which point to a significant role of plasma transport due to rapidly varying meridional neutral winds besides the well-known **E**×**B** drift effects in the storm time behaviour of the F region across the equatorial ionization anomaly (EIA) region.

2. Database

We have analyzed quarter-hourly ionograms of the four Indian stations, Ahmedabad (23^0 01'N, 72^0 36'E, dip 34.0^{0}N), Sriharikota, SHAR (13^0 42'N, 80^{0}30'E, dip10^{0}N), Kodaikanal (10^{0}14'N, 77^{0}29'E, dip 4^{0}N) and Trivandrum (8^{0}30'N, 76^{0}54'E, dip 0.5^{0}N). This ionosonde network permits evaluation of only the gross features of the northern part of the equatorial ionization anomaly (EIA) in the Indian sector. For example, a precise determination of the location and amplitude of the EIA crest can not be made due to the absence of stations on either side of Ahmedabad (dip 34.5^{0}N). The parameters scaled from ionograms are $h'F$, the minimum virtual height of F region that is widely taken to represent the height of bottomside F region; the critical frequency of F layer, f_0F_2 , which represents the peak density of the layer, N_mF_2; and hpF_2 , which is an approximate measure of the height of peak density h_mF_2. Since hpF_2 is derived assuming a parabolic fit near the layer peak, it could differ from h_mF_2 depending on local time and layer shape. This, however, is not considered a serious limitation because the primary interest here is not in the absolute values of layer height but in specific featúres of its temporal variations, which reflect in both hpF_2 and h_mF_2. We have also made use of the ground based magnetometer data of Trivandrum (8^{0}30'N, 76^{0}54'E, dip 0.3^{0}N) and Alibag (18^0 38'N, 72^{0}52' E, dip 24.5^{0}N) to assess the changes in equatorial electrojet strength and hence in the zonal electric field that drives it. The parameter ΔSdl, calculated from the hourly averages of H component of geomagnetic field at the two stations following the procedure of *Kane* [1973] is taken to represent the electrojet strength. Of the station pair, Trivandrum is very close to the axis of the electrojet, while Alibag is well isolated from the electrojet influence. Simultaneous H component data from these two stations is well suited and widely used for estimation of the electrojet strength both for quiet and disturbed conditions [e.g., *Rastogi and Patel*, 1975; *Bhargava et al.*, 1980; *Sastri*, 1989].

3. Results

3.1. Overview of Geomagnetic Storm and Associated Equatorial Ionospheric Storm

The geomagnetic storm of November 3-11 developed against a background of unusual magnetic quiescence that prevailed for most part of November 2 and 3. The sharp decrease in *Dst* index signaling the start of storm main phase began at 2200 UT on November 3 and *Dst* index reached the first minimum of main phase just before 0100 UT of November 4. *Dst* attained its most negative value of -116 nT (signifying strong ring current effects) 10 hours later due to a combination of prolonged and strong southward IMF and high values of solar wind flow speed and density. The recovery phase of the storm began by 1300 UT of November 4 and continued over the next 7 days till 0000 UT of November 12. The auroral electrojet index *AE* [*World Data Center* for Geomagnetism, 1996] underwent a precipitous drop just after 0100 UT on November 4 due to a transient northward excursion of IMF *Bz*. *AE* index rose to unusually high values after 0300 UT indicative of severe auroral zone disturbances. The high level of disturbance persisted for most part of November 4 and substorming was practically continous despite intermittent reductions in *AE* index. Auroral zone activity quietened down only by the latter half of November 11. These broad characteristics of the magnetic storm can be seen from the time histories of *Dst* and *AE* indices shown in Figure 1. Further details of this "severe" storm, the causative solar wind features and attendant magnetospheric and high-latitude ionospheric phenomena are available in *Knipp et al.* [1998].

Figure 1 presents the diurnal profiles of the electrojet parameter, ΔSdI and f_0F_2 at the four Indian stations over the period 1200 UT of November 3 through 1200 UT of November 7. We have taken November 2, which is one of the designated quiet days of the month (Ap= 4, ΣKp=8+), as the reference or control day and the diurnal pattern of the various parameters on this day is superposed in Figure 1 to help assess the characteristics of the ionospheric storm. The behavior of hpF_2 at the four stations is shown in Figure 2 in the same format as of Figure 1. Careful perusal of Figures 1 and 2 shows that significant perturbations in ΔSdI , f_0F_2 and hpF_2 prevailed in the Indian equatorial region but confined to November 4, the most disturbed day of the storm period

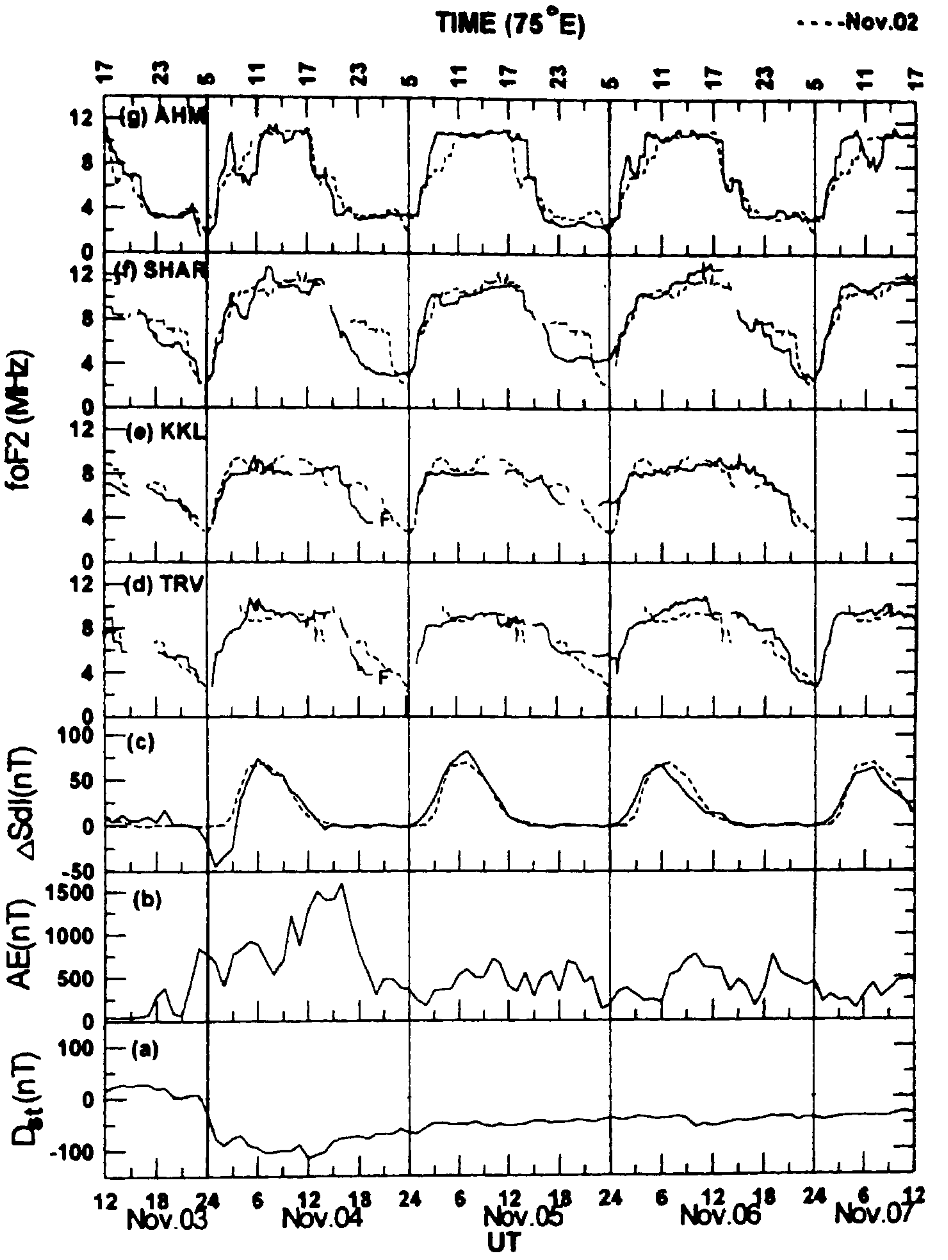

Figure 1. Time variation of (a) equatorial *Dst* index (b) auroral electrojet index, *AE*, (c) equatorial electrojet strength, ΔSdI and (d-g) f_0F_2 at the four Indian stations (TRV, Trivandrum; KKL, Kodaikanal; SHAR, Sriharikota; AHM, Ahmedabad) spanning the equatorial anomaly region (see text for details of station coordinates) over the period 1200 UT of November 3 to 1200 UT of November 7, 1993. The diurnal variation of f_0F_2 for the reference quiet day, November 2 (Ap= 4, ΣKp=8+) is superposed to provide an overview of the ionospheric storm.

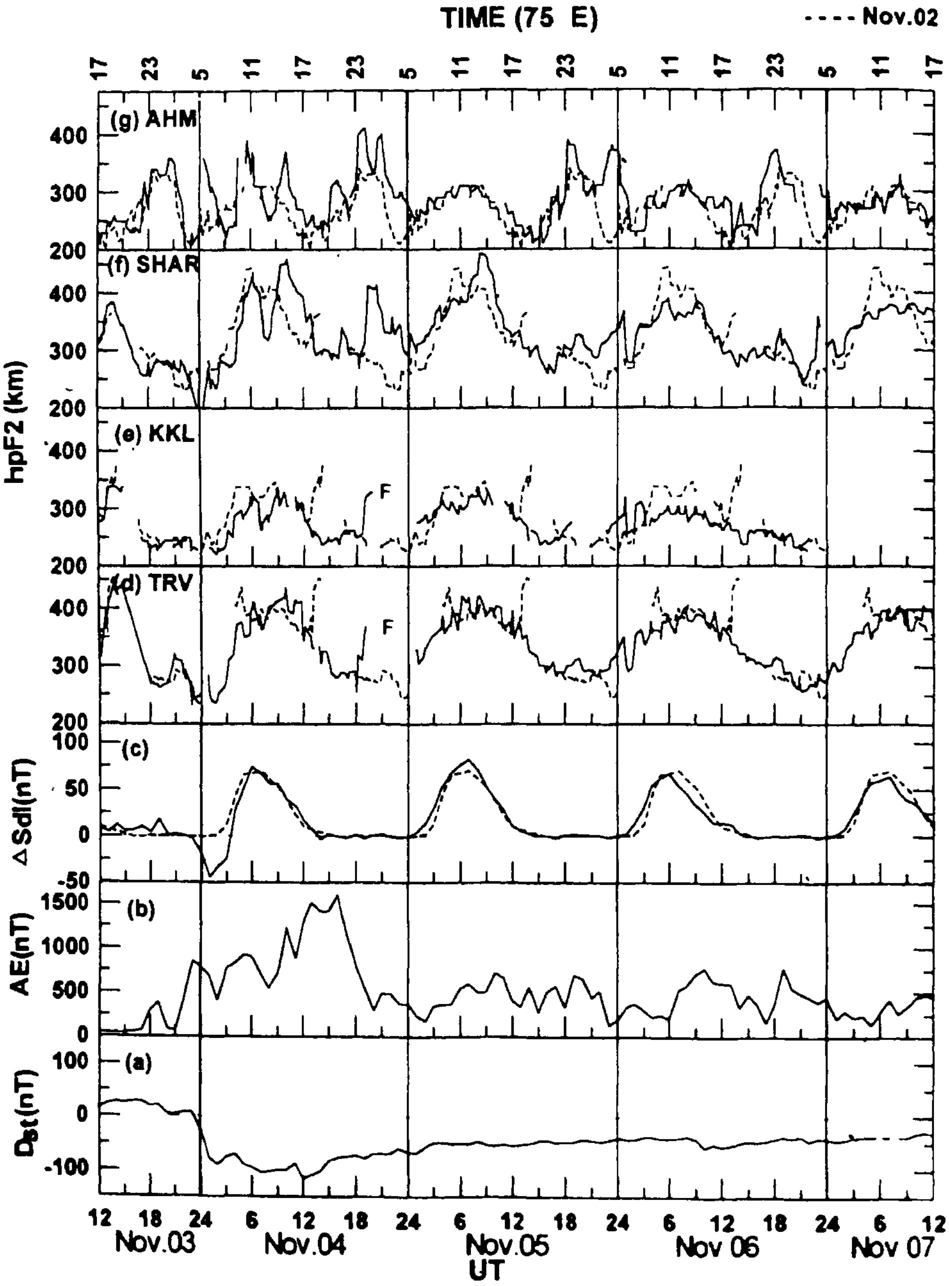

Figure 2. Same as in Figure 1 but for hpF_2 at the four Indian stations.

(Ap=77; ΣKp=47). We shall now present the salient characteristics of the ionospheric storm on November 4 and discuss their implications in the next section.

3.2. Morning Counter Electrojet and EIA

Figure 3 shows the time variation of ΔSdI and AE index on November 4. A prominent negative perturbation (relative to the more or less constant nighttime level) in ΔSdI till 0830 LT (0330 UT) characteristic of counter electrojet (CEJ) condition is obvious in Figure3. Such a negative perturbation over the same time interval is also seen (not shown here) in the parameter, ΔH (Trivandrum)- ΔH (Alibag), which is also used to represent the electrojet strength (ΔH is the deviation of H field from the mean nighttime level). The inference of CEJ condition is further corroborated by the continuous absence of equatorial sporadic E (E_{sq}) at Trivandrum (dip 0.3^{0}N) till 0830 LT. It is to be recalled here that the presence of E_{sq} during daytime is a regular feature at and close to the dip equator, and its morning onset and evening disappearance are closely related to the diurnal pattern of the equatorial electrojet strength [see *Kane*, 1976, and references therein]. This well-known characteristic of E_{sq} is seen on all the days of the period November 2-8 except on November 4. More explicitly, the delayed onset of E_{sq} at 0830 LT is seen at Trivandrum only on November 4. These facts testify that the prominent depression in ΔSdI and absence of E_{sq} (CEJ condition) on the morning of November 4 is indeed a magnetic storm-related effect. The time history of hourly average AE index in Figure 3 indicates that the CEJ condition is associated with a decrease in AE index and in the polar cap potential drop by ≈45 kV between

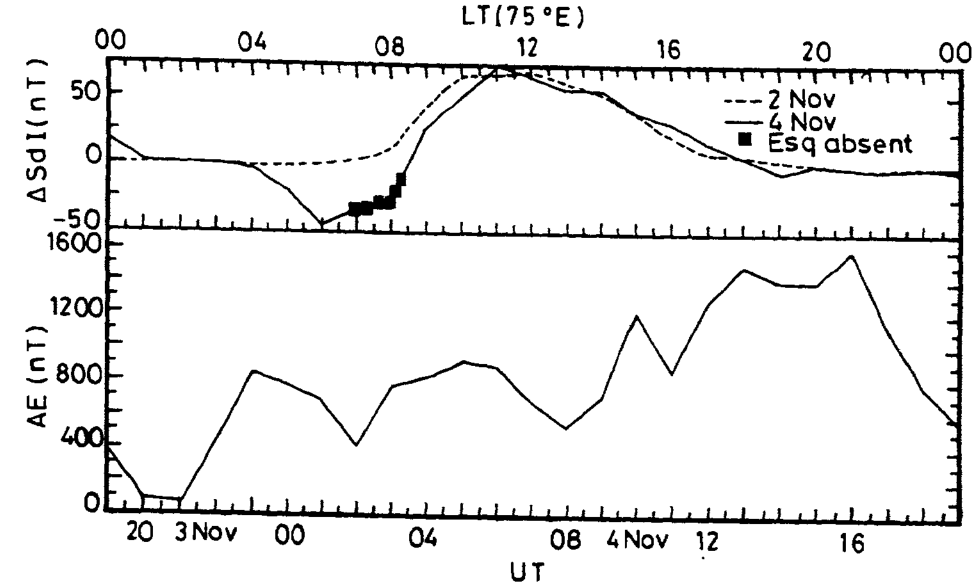

Figure 3. Time variation of the equatorial electrojet strength (ΔSdI) in the Indian sector and AE index on November 4 (Ap=77).

0600 and 0800 LT (0100-0300 UT) [see *Emery et al.*, 1999, Figure 1].

During the period of the morning CEJ, the F layer peak density (f_0F_2) exhibited an abnormal positive latitudinal gradient from Trivandrum to Ahmedabad, resembling a well developed EIA. This can be seen from Figure 4a wherein the dip angle variation of f_0F_2 is shown at 15-min interval for the period 0645-0830 LT on November 4, and also on November 2, the reference quiet day. In contrast to the negative latitudinal gradient of f_0F_2 that usually prevails in the morning hours (EIA usually starts to develop around 0900 LT and attains maximum amplitude and latitudinal extension around 1600 LT), a positive gradient started to develop from 0700 LT and reached a maximum at 0800 LT. This perturbation is characterized by a rapid depletion of plasma around the magnetic equator and accumulation of plasma far away from it. The ratio of f_0F_2 at Ahmedabad to that at Kodaikanal (no data at Trivandrum on November 2 till 0900 LT) at 0800 LT on November 4 is +1.35 as against the value of -0.75 at the same time on November 2 (see Figure 4a). It is interesting to note that this short-duration disturbance in the latitudinal distribution of f_0F_2 is associated with significant changes in hpF_2. To bring out more clearly the storm-related changes in F layer peak density and height across the equatorial region, the local time variation of of the percentage deviation of the values of the parameters on November 4 from those on November 2 is shown in Figure 5 for the four stations. It is clear from the figure that hpF_2 at Ahmedabad underwent a rapid decrease over the period 0645-0800 LT on November 4, in contrast to the normal steady increase in the morning accompanied by a substantial increase in f_0F_2 such that at 0800 LT, the percentage increase (decrease) in f_0F_2 (hpF_2) is 54.3 (14.3). A similar behavior is also evident at Sriharikota in both the F layer parameters though of a lesser magnitude as may be seen from Figure 5. The percentage deviation in f_0F_2 (hpF_2) at 0800 LT at Sriharikota is +12.6 (-13.5). On the other hand, at Kodaikanal near the magnetic equator, hpF_2 is depressed relative to the quiet day values in the morning accompanied by a reduction also in f_0F_2, such that at 0800 LT, the percentage deviation in f_0F_2 (hpF_2) is -14.0 (-11.3). An unfortunate gap in ionosonde data at Trivandrum till 0900 LT on November 2 precluded assessment of the relative changes in F layer parameters closer to the equator in the morning on November 4. The abnormal positive spatial gradient in f_0F_2 very quickly weakened and by 0830 LT the latitudinal profile recovered more or less close to the quiet day pattern (see Figure 4a).

3.3. Daytime Perturbations in F Layer Peak Height and Density and EIA

After the cessation of the morning CEJ condition, the equatorial electrojet strength, ΔSdI closely followed the course as on the reference quiet day (see Figures 1-3). This indicates the absence of any further major disturbances in the electrojet strength and hence in vertical plasma drift at F region altitudes, the main ingredient of the plasma fountain process responsible for EIA. It is therefore not unreasonable to expect the usual temporal patterns in hpF_2 and f_0F_2 at individual stations and in the development of EIA through the rest of the day. The data presented in Figures 1-2 and 5, however, reveal the presence of impressive wave-like and coherent oscillations in hpF_2 at Ahmedabad and Sriharikota away from the dip equator till local sunset (1300 UT), accompanied by remarkable short-term changes in f_0F_2 at individual stations as well as in the spatial distribution of f_0F_2. In the following we will present the temporal changes in the latitudinal distribution of f_0F_2 with reference to specific phases of the wave-like oscillations in hpF_2 at Ahmedabad and Sriharikota, i.e., epochs of an increase and decrease in hpF_2 indicative of equatorward and poleward neutral winds, respectively.

Let us now consider the interval 0900-1045 LT over which hpF_2 increased to above the quiet day values (by 11-26%) at Ahmedabad, while hpF_2 remained lower than normal at Kodaikanal (by 10-14%) and Trivandrum (8-14%) indicative of a relatively weaker upward **ExB** drift around the dip equator (see Figure 5). As mentioned earlier, the latitudinal profile of f_0F_2 returned to the quiet day form by 0830 LT, although the absolute value of f_0F_2 is lower than normal throughout the equatorial region (see Figure 4a). Profiles of the

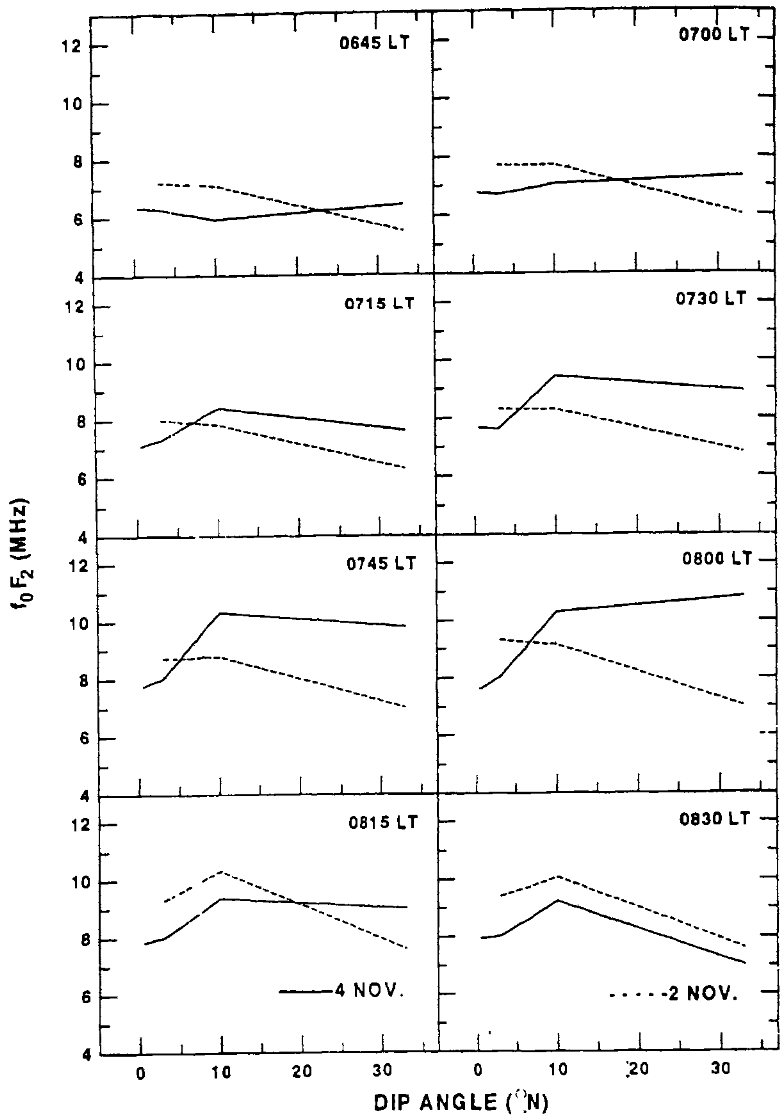

Figure 4a. Dip angle variation of f_0F_2 in the Indian sector over the time interval 0645-0830 LT (0145-0330 UT) on November 4.

dip angle variation of f_0F_2 on November 2 presented in Figure 4b demonstrate the normal pattern of the forenoon development of EIA, with the formation of a peak in f_0F_2 initially at Sriharikota and later on somewhere between Sriharikota and Ahmedabad (the exact location of the crest couldnot be determined due to lack of data poleward of Ahmedabad and between Ahmedabad and Sriharikota). The positive spatial gradient is such that the ratio of f_0F_2 at Ahmedabad to that at Trivandrum is + 1.21 by 1045 LT. In contrast to this, on November 4, the latitudinal profile of f_0F_2 assumed a rather smooth negative gradient from the dip equator right from 0915 LT and continued such that the ratio of f_0F_2 at Ahemdabad to that at Trivandrum is only 0.7 by 1030 LT (the maximum negative gradient is seen at 1015 LT when the ratio is 0.55). This striking reversal of the latitudinal gradient in f_0F_2 is brought about by a rapid depletion (accumulation) of plasma at Ahmedabad (at Trivandrum and Kodaikanal) away from dip equator (close to dip equator) as can be seen from Figure 4b. We consider the reversed profile of f_0F_2 as due to a severe inhibition of field-aligned diffusion of plasma away from the dip equator by equatorward neutral winds. The tell-tale signature of this mechanism is the anti phase relationship between the height and density of F layer peak around the crest location, which is exactly what is seen in hpF_2 and f_0F_2 at Ahmedabad over the time interval under discussion (see Figure 5). We hold the view that the inhibition of the forenoon development of EIA is also aided by the morning CEJ condition as well as by the weaker electrojet over the interval 0900-1045 LT. The CEJ condition too could be relevant because EIA responds to changes in the zonal electric field (**ExB** drift at dip equator) with a time delay of 2.5-4 hours [see *Abdu et al.*, 1990, 1993, and references therein].

Figure 4c presents the data for the interval 1115-1300 LT when hpF_2 rapidly decreased to below the quiet day values at both Sriharikota and Ahmedabad (by 20% at 1300 LT, see Figure 5). The electrojet strength is more or less the same as on the reference quiet day although hpF_2 is lower especially at Kodaikanal. The latitudinal profiles of f_0F_2 on the quiet day showed a well-developed positive gradient from the dip equator as can be expected for the interval around local noon. On November 4 the plasma bulge that is apparent at 1115 LT over Sriharikota, superposed on the overall weak negative gradient between Trivandrum and Ahmedabad, rapidly grew in strength accompanied by a gradual build up of plasma over Ahmedabad such that by 1300 LT the latitudinal profile of f_0F_2 conformed to that of the quiet day. The depth of the positive gradient, represented by the ratio of f_0F_2 at Ahmedabad to Trivandrum, in fact, is the same (1.16) on both November 4 and 2 at 1300 LT. It is instructive to note here that only after the bulge over Sriharikota attained its maximum strength by 1215 LT, the increase of f_0F_2 at Ahmedabad over quiet values took place, replacing the strong negative gradient between Sriharikota and Ahmedabad eventually by a shallower one. We interpret this delayed noon time development of EIA on November 4 as due to a renewal of the fountain process by the plasma transport due to poleward neutral winds. In other words, the reversal of neutral winds from equatorward earlier on to poleward over this interval aided by the near normal electrojet condition facilitated the establishment of a well developed EIA by 1300 LT. The anti-phase relationship between hpF_2 and f_0F_2 which prevailed at both Ahmedabad and SHAR (where it is better defined) supports the understanding, in particular the earlier strengthening of the bulge over Sriharikota as due to plasma transport by poleward winds.

The behaviour of hpF_2 at Sriharikota and Ahmedabad from 1300 to 1800 LT on November 4 is similar to that evidenced earlier in the day, namely, an increase followed by a decrease (Figure 2). This is so only in absolute values because, in comparison to November 2, hpF_2 remained higher on November 4 throughout the period 1345-1745 LT at both the locations as well as at Trivandrum close to dip equator. This feature can clearly be seen from Figure 5. The response of the spatial distribution of f_0F_2 to these height variations (not shown here) is such that the changes in f_0F_2 besides being moderate are mostly limited to Ahmedabad in absolute values as well as in comparison to values on November 2. In other words, the latitudinal profile of f_0F_2 maintained an overall positive gradient representative of a well-developed EIA. Noteworthy among the short-term variations in the spatial distribution of f_0F_2 over this time interval are (1) the highly distorted profile with negative (positive) gradient poleward (equatorward) of Sriharikota during 1430-1500 LT when hpF_2 experienced an increase both at Sriharikota and Ahmedabad and (2)

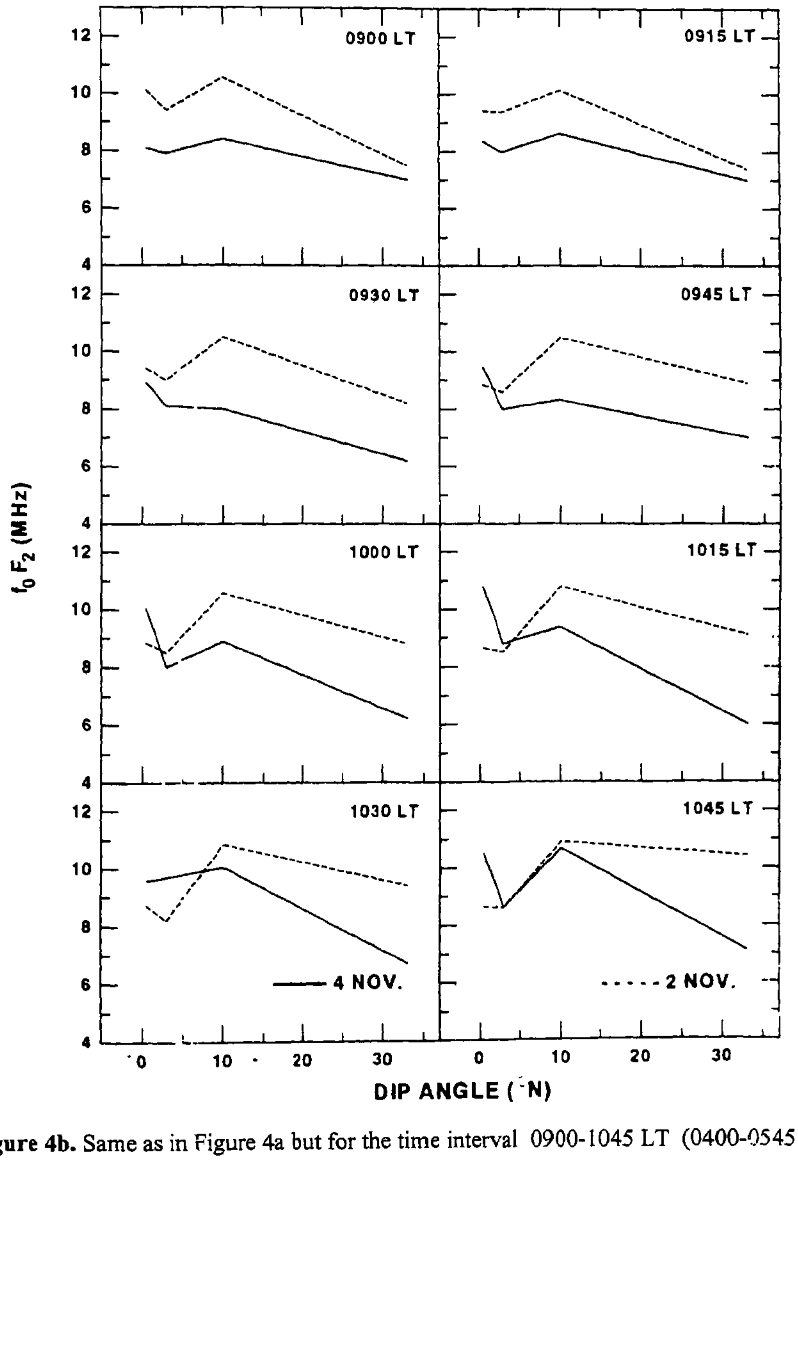

Figure 4b. Same as in Figure 4a but for the time interval 0900-1045 LT (0400-0545 UT).

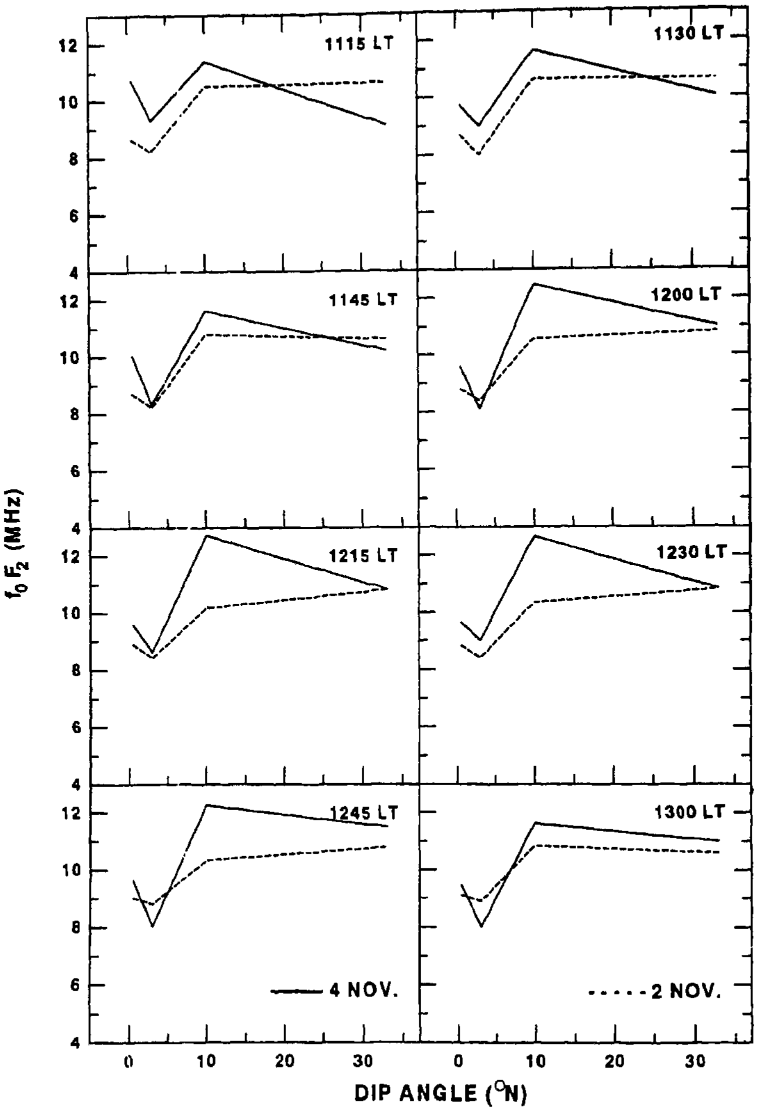

Figure 4c. Same as in Figure 4a but for the time interval 1115-1300 LT (0615-0800 UT).

development of a positive gradient between Sriharikota and Ahmedabad from 1600 to 1700 LT when hpF_2 decreased. We consider these as subtle manifestations of plasma transport due to meridional winds acting in concert with the fountain process.

3.4. Nighttime Changes in *F* Layer Height and Peak Density

Three prominent perturbations marked the behaviour of *F* layer height and density in the local sunset-sunrise period on November 4 corresponding to the early stage of the storm recovery phase which started around 1800 LT (1300 UT) (see time history of *Dst* index in Figure 1). The first one is the total absence or inhibition of the dusktime increase of *F* layer height in the immediate vicinity of dip equator. That the vertical plasma drift and hence height of *F* layer near the dip equator increases after sunset is well known from ground based as well as satellite measurements [e.g., *Batista et al.*, 1986; *Fejer*, 1991; *Sastri et al.*, 1994; *Fejer et al.*, 1995 and references therein]. This commonly observed feature, which is due to an increase of the zonal electric field through the F region dynamo effect, can be seen for example, in the time variation of hpF_2 at Trivandrum and Kodaikanal on November 2, the reference quiet day shown in Figure 2. On November 4 this normal dusk time pattern in *F* region height is absent and, in fact, what is apparent is that the bottomside *F* region ($h'F$) maintained a near-constant altitude around 240 km over the period 1800-2000 LT as may be seen from Figure 6. The postsunset suppression of *F* region height rise does not seem to bear a direct relationship to auroral activity as there is no significant change in *AE* index between 1800 and 2100 LT (1300-1600 UT) when it remained high in the range 1409-1602 nT (see Figure 6a). It is noteworthy that the inhibition of postsunset *F* layer height rise near the dip equator persisted well into the storm recovery phase and is evidenced on November 5 and 6 (see Figure 2), and the usual dusktime time behavior of *F* layer (increase of layer height) resumed only from November 7 onward.

A precipitous drop in f_0F_2 throughout the anomaly region over the interval 1915-2330 LT constitutes the second perturbation (Figure 6). At Ahmedabad f_0F_2 underwent a sharp

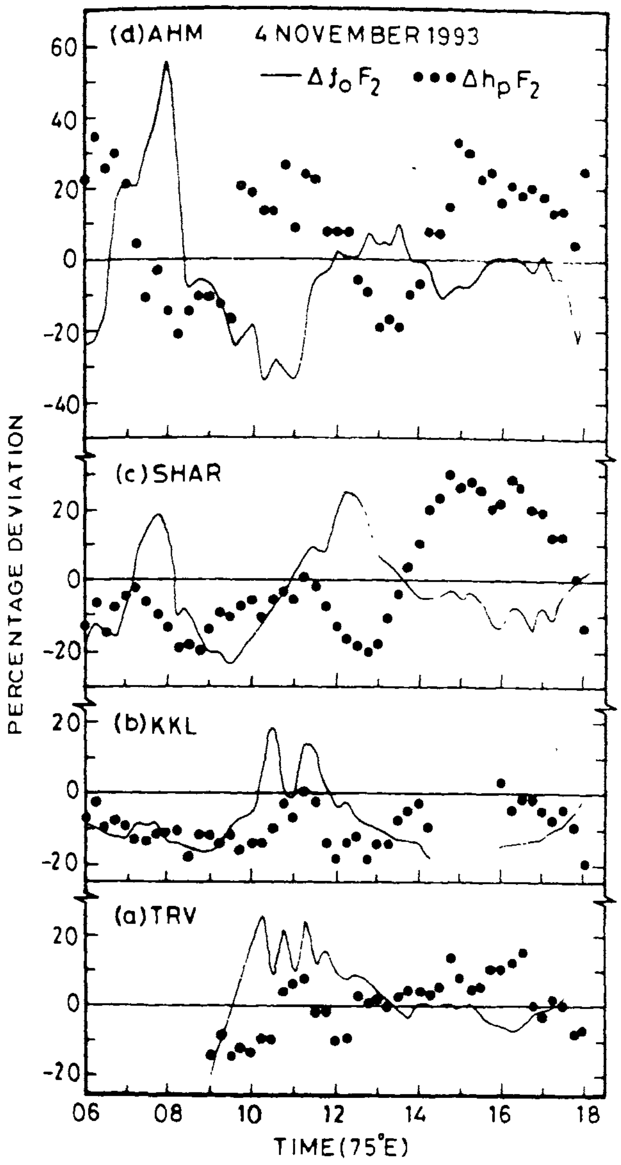

Figure 5. Time variation of the percentage deviation of f_0F_2 and hpF_2 at the four Indian stations during daytime on November 4.

decrease over the short interval 1915-2030 LT from 7.8 to 3.4 MHz, a drop of 56.4 % in 75 min. This is considered a storm time effect because normally f_0F_2 attains lowest values (diurnal minimum) in the pre sunrise hours around 0500 LT. A similar rapid reduction in F layer peak density is also seen in quick succession at Sriharikota, Kodaikanal, and Trivandrum such that by midnight the latitudinal distribution of f_0F_2 became fairly smooth and featureless. The amplitude of the decrease in f_0F_2 at Sriharikota, Kodaikanal and Trivandrum is in the range 54-57% beginning at 2015, 2030, and 2045 LT, respectively (the drop in f_0F_2 at Trivandrum is rather ill defined in comparison to other stations). It is worthwhile to note in this context that on November 4 the sunset time at 250 km over Ahmedabad, Sriharikota, Kodaikanal, and Trivandrum was at 1850, 1845, 1841, and 1840 LT, respectively (all the times refer to 75°E). The drop in f_0F_2 is associated with an increase in $h'F$ (as well as hpF_2, see Figure 2) that is latitude dependent in that it is distinctly seen at Ahmedabad and Sriharikota and not at Kodaikanal and Trivandrum. This behaviour is representative of the F layer uplift by equatorward neutral winds. The sudden and significant reduction in f_0F_2 throughout the equatorial region is therefore to be due to horizontal movement of plasma across the equator toward the opposite hemisphere by an equatorward propagating wind disturbance, rather than by changes in the fountain process. This all the more the case because, besides other things, the usual dusktime increase in F layer height near the dip equator is inhibited as detailed before and f_0F_2 maintained a near-constant value at Trivandrum and

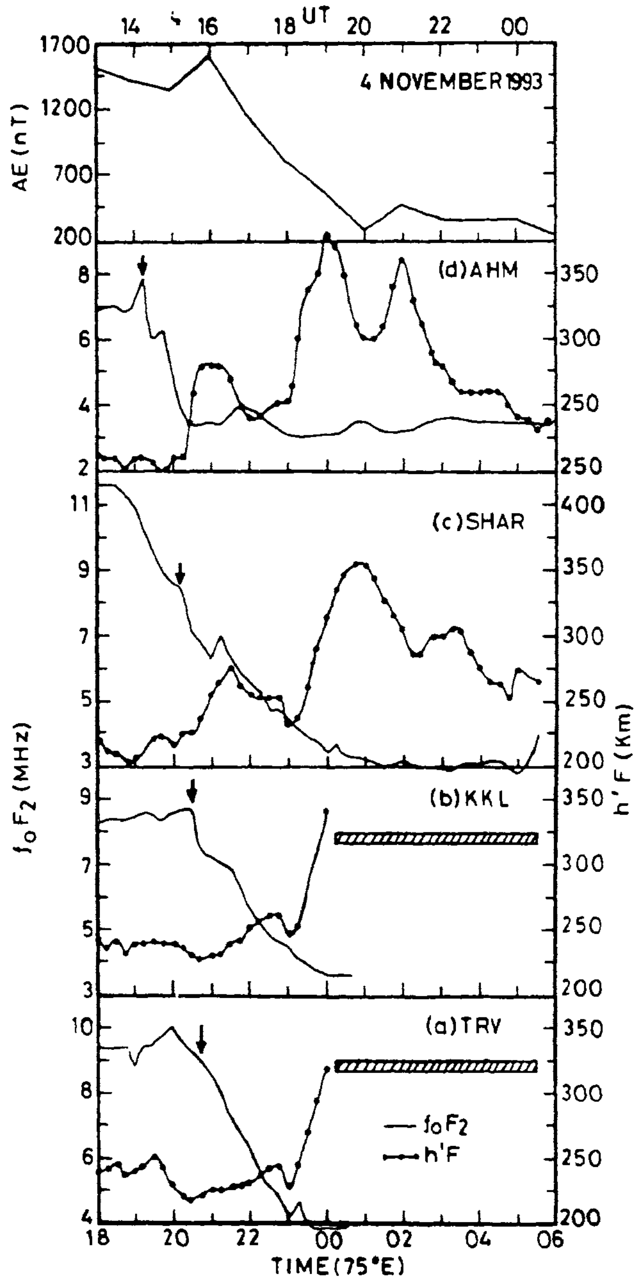

Figure 6. Time variation of f_0F_2 and $h'F$ at equatorial stations in the Indian sector on the night of November 4-5. The arrows indicate the sharp reduction in f_0F_2 in the premidnight period and the hatched rectangles spread F conditions at the various stations.

Kodaikanal till 2030 LT as may be expected for such a situation (see Figure 6). The time delays in the onset of the drop in f_0F_2 between the stations imply a phase speed of 202-404 m/sec for the causative propagating wind disturbance. The estimate is considered reasonable in view the low time resolution (15 min) of the ionosonde data coupled with the uneven separations between the stations.

We have derived nightime meridional neutral winds for the night of November 4-5, using $h'F$ data of Sriharikota and Trivandrum following the method of *Krishnamurthy et al.*, [1990] to verify the proposed role of winds. The method is based on the assumption that that the F region vertical drift at Trivandrum, very close to the dip equator is affected solely by zonal electric fields, while that at Sriharikota is determined by electric fields, meridional winds, and plasma diffusion. The winds are calculated at 15-min intervals from the time derivative of $h'F$ at the two stations, making allowance for chemical loss and diffusion effects, and are smoothed for random fluctuations (if any) with a five-point running mean filter. The overall uncertainty in the winds thus derived is 25 m/s. The outcome presented in Figure 7 clearly shows equatorward winds of 75 m/s (maximum) between 1945 and 2200 LT over Sriharikota in support of the interpretation made. *Lakshmi et al.*, [1997] recently reported on sudden postmidnight decreases in f_0F_2 at Kodaikanal during severe storms, which they attributed to vertical/horizontal plasma transport by upward vertical drift/equatorward meridional winds. To the best of our knowledge, the multistation ionosonde observations presented here of an abnormal pre-midnight reduction of F layer ionization throughout the equatorial region during the recovery phase of a major storm are the first of their kind.

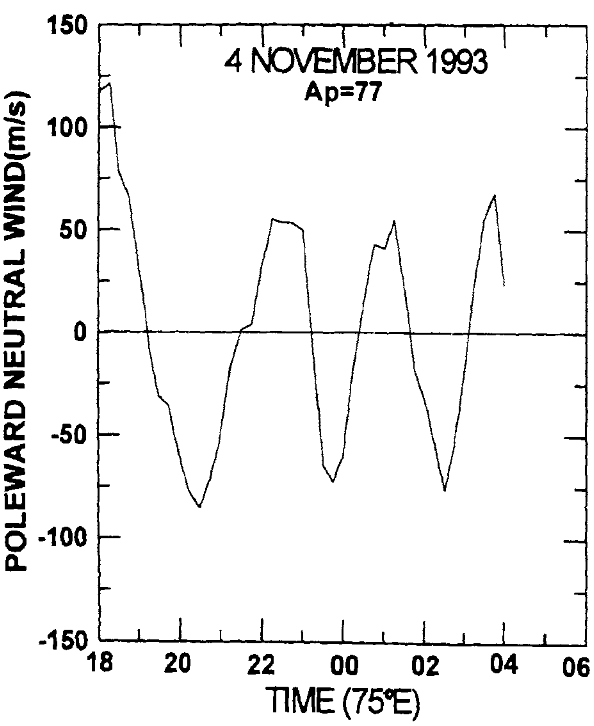

Figure 7. Temporal variation of nighttime meridional winds derived from $h'F$ data of Sriharikota and Trivandrum for the night of November 4-5, 1993, see text for details.

The third perturbation on the night of November 4-5 manifested in the form of an abrupt and significant increase in F layer height around midnight at all the stations but with subtle differences between the stations suggestive of the underlying physical mechanisms. At Ahmedabad the increase in $h'F$ started at 2300 LT and reached a maximum (380 km) by 0000 LT followed by a decrease and a second maximum (360 km) at 0200 LT. On the other hand, at Trivandrum and Kodaikanal, close to the dip equator, $h'F$ increased quite rapidly beginning at 2330 LT accompanied by spread F condition by 0015 LT when the bottomside F region reached altitudes above 310 km (Figure 6). The temporal pattern of $h'F$ at Sriharikota is a more or less similar to that Ahmedabad including the double-peak feature but delayed by 1-1.5 hours as can seen from Figure 6. We consider the height disturbance at Ahmedabad as mostly due to equatorward neutral winds while that at Trivandrum and Kodaikanal as due mainly to an eastward perturbation electric field. There is a decrease in AE index from 1144 to 297 nT over the interval 2200-0100 LT (1700-2000 UT) and the polar cap potential drop derived from the assimilative mapping of ionospheric electrodynamics (AMIE) procedure also shows a rapid decrease by ≈70 kV between 2300 and 0100 LT (1800-2000 UT) [see *Emery et al.*, 1999, Figure 1]. The eastward electric field responsible for the abnormal height rise around midnight at Trivandrum and Kodaikanal therefore seems to be of high-latitude origin. On the other hand, the height rise at Sriharikota might have contributions from both meridional winds and zonal electric fields because of its location. The meridional wind pattern over Sriharikota estimated from $h'F$ data of Sriharikota and Trivandrum presented in Figure 7 clearly shows equatorward surges centered at 0015 and 0300 LT in support of the understanding reached. The midnight onset of spread F at Trivandrum and Kodaikanal in association with the F layer height rise is consistent with earlier work which showed that such a height perturbation (eastward reversal of the electric field) is a favorable condition for the growth of Rayleigh-Taylor (RT) instability responsible for spread F [e.g., *Fejer et al.*, 1976; *Sastri*, 1979; *Kelley and Maruyama*, 1992].

4. Discussion and Conclusions

In this paper we have presented the salient features of the response of equatorial ionosphere in the Indian sector to the severe magnetic storm of November 3, 1993.The response is characterized by significant perturbations in the equatorial electrojet strength and in the density and height of F layer peak throughout the anomaly region during daytime on November 4 and on the night of November 4/5, corresponding to the main phase and early part of the recovery phase, respectively, of the magnetic storm. Let us first consider the electric field disturbances and related effects evidenced in the ionsopheric storm. The CEJ condition on the morning of November 4 seems to be due to direct electric field penetration because it is closely associated with a significant decrease in the polar cap potential and the AE index. Its westward polarity is consistent with the theoretical models which predict the penetration electric field due to a sudden decrease in polar cap potential to be westward (eastward) by day (night) at sub auroral latitudes with transitions around 0600 LT and 2100 LT [e.g., *Senior and Blanc*, 1984; *Fejer et al.*, 1990]. The prevalence of a significant positive latitudinal gradient in f_0F_2 during the morning CEJ is anomalous and interesting because the morning CEJ condition is generally found to result in a delayed onset of the development of EIA due to the reduced efficiency of the plasma fountain process responsible for EIA [e.g., *Sastri*, 1982; *Abdu et al.*, 1990, 1993]. In fact, we are aware of only one earlier report of a similar morning (0700-0930 LT) development of EIA, namely the one evidenced in the Asian (120^{0}E) sector on September 23, 1986, the most disturbed day of the SUNDIAL-86 campaign period [*Abdu et al.*, 1990]. There is an important difference though between the event on November 4, 1993 and the SUNDIAL-86 event in that in the former reported here, the positive latitudinal gradient in f_0F_2 is found for the first time under CEJ condition.

It is known that the height of F layer peak around the crest region of EIA is a sensitive indicator of the direction and magnitude of neutral meridional winds [see *Fesen et al.*, 1989, and references therein]. The significant decrease in hpF_2 at Ahmedabad in the morning on November 4 (see Figures 2 and 6), which is indicative of poleward neutral winds, strongly suggests that the abnormal positive latitudinal gradient in f_0F_2 (at the time of morning CEJ) could be due to horizontal movement of plasma by a poleward surge in transequatorial winds. Such a plasma transport leads to an anti-phase relationship between f_0F_2 and hpF_2 away from dip equator and a depletion of plasma near dip equator. The behaviour of f_0F_2 and hpF_2 at Ahmedabad and Sriharikota and of f_0F_2 at Kodaikanal detailed earlier is consistent with this line of interpretation. The poleward surge could be due to large-scale AGWs launched by auroral zone heating. The simulations of *Emery et al.* [1999] using Thermosphere Ionosphere Electrodynamics General Circulation Model (TIEGCM), in fact, predict that the auroral Joule heating around 0000 UT on November 4 is to be followed by enhanced equatorward winds from both the polar regions (source at 60^{0}N and 70^{0}S) with a phase speed of ~700 m/s in the American sector (70^{0}W). The poleward surge in transequatorial winds implied by our ionosonde data suggests that in the Indian (75^{0}E) sector winds from the Southern Hemisphere extended into the Northern Hemisphere

The CEJ condition on the morning of November 4, however, suggests the presence of a westward electric field disturbance besides a poleward surge in transequatorial winds. The reduction in hpF_2 at Kodaikanal close to the dip equator at the time of CEJ condition collaborates the inference because the height of F layer near the magnetic equator is strongly dependent on vertical **ExB** drift due to zonal electric field [see *Anderson*, 1981; *Abdu et al.*, 1991; *Preble et al.*, 1994, and references therein] . A similar physical situation was inferred to have prevailed at middle and low latitudes in different longitude zones at the time when CEJ condition is apparent in the Indian equatorial region. *Foster and Rich* [1998] found a prominent increase of F layer peak altitude during 0030-0400 UT in the region equatorward of the sharply defined midlatitude ionospheric trough from Millstone Hill incoherent scatter radar observations. They also presented results from the Japanese ionosonde network covering the low and midlatitude region to show an increase of F layer height between 0030 and 0230 UT (noon sector), with the magnitude of the effect increasing with decrease in latitude and peaking near 23^0 magnetic latitude. *Foster and Rich* [1998] attributed the changes in F layer peak height and density both in the American (premidnight) and the Japanese (noon) sectors to a penetrating eastward electric field. They did, however, opine that the north-south temporal dispersions in the F layer height perturbation across the Japanese ionosonde network are also consistent with the effect of a storm-generated equatorward neutral wind surge. Ionosonde measurements at lowlatitude and midlatitude locations in the Australia-New Zealand-Japan region (afternoon-evening sector) studied by *Richards and Wilkinson* [1996] also showed a pronounced and simultaneous uplift of F layer over most of the stations beginning at 0000 UT, which is interpreted as the effect of an equatorward surge in meridional winds due to high-latitude heating. They too invoked the presence of an eastward electric field perturbation to account for some of the intricate features of the F layer uplift. It is thus clear that the electric field structure as well as meridional wind field at subauroral latitudes got altered on a global scale during the early stage of the storm main phase. The polarity pattern of this apparently global electric field disturbance is rather intriguing because it is eastward in the noon-evening (Japanese-Australia-NewZealand) and premidnight (America) sectors at middle and low latitudes, and westward in the morning (India) sector near the dip equator. While the westward polarity in the morning dip equatorial region is consistent with theoretical models, the simultaneous eastward field at low and middle latitudes is not. It is possible that the westward field near the dip equator is due to dynamo effects of "fast" wave mode AGWs, which reach equatorial latitudes a few hours after the start of high-latitude current enhancements [e.g., *Prolss*, 1995; *Fuller-Rowell et al.*, 1994; *Balthazor and Moffett*, 1997; *Emery et al.*, 1999]. As mentioned in the previous section, such large-scale AGWs are to be present at the time of CEJ to account for the anomalous morning development of EIA. It would be worthwhile to examine the characteristics (amplitude and polarity) of this short-lived electric field disturbance in the equatorial regions of Africa (postmidnight), Brazil (around midnight), and Peru (postsunset) and their consistency with convection model predictions to gain a better understanding of its origin.

The absence of the postsunset F layer height rise close to dip equator on November 4 does not seem to be due to penetration electric field effects because of the absence of any sudden and significant change in AE index as well as polar cap potential (which varied around 90 kV) during the interval 1700-2000 LT (1200-1500 UT). It seems to be of IDD origin in view of its delayed appearance (12 hours after the start of the storm main phase) with a westward polarity to effectively suppress the dusktime increase of F layer height. It could also be the outcome of a westward disturbance zonal wind impeding the normal eastward wind that partly controls the dusktime increase of the vertical plasma drift near the dip equator through F region dynamo process [see *Abdu et al.*, 1995, and references therein]. The two mechanisms are not mutually exclusive because the westward wind disturbance is an important ingredient of the IDD process [*Blanc and Richmond*, 1980]. On the other hand, the large increase in F layer height that followed around midnight seems to be due to direct penetration electric field, because it is closely associated with a significant drop both in AE index and polar cap potential (by ≈ 70 kV) (see Figure 6). Theoretical results show the penetration electric field to be of small amplitude around midnight (≈0.3 mV/m for a decrease in polar cap potential by 70 kV, see Figure 5 of *Fejer et al.*[1990]). We consider the large amplitude of the eastward field (≈1 mV/m) at Trivandrum as the outcome of the combined *in-phase* effects of prompt penetration and IDD fields. This is plausible because model calculations show that IDD field reverses sign to eastward around 2100 LT [*Blanc and Richmond*, 1980] and could add on to the penetration field which also becomes eastward just before midnight [e.g., *Fejer et al.*, 1990]. The TIEGCM results indeed showed the presence of westward winds on November 4 from 1000 to 2000 UT in the 75^{0}W sector which is a signature of disturbed circulation that produces IDD electric fields [see *Emery et al.*, 1999, Figure 4d]. Recent case studies also provided credible evidence for the occasional prevalence of such a situation [*Fejer and Scherliess*, 1997; *Scherliess and Fejer*, 1997; *Sobral et al.*, 1997; *Abdu et al.*, 1997]. Equatorward meridional wind as a cause of F layer height rise close to dip equator can be discounted because of its inability to move plasma across the field lines at small angles of inclination, although this mechanism may be partly responsible for the large height rise with temporal structure at Sriharikota and Ahmedabad (see Figure 6) as discussed in the previous section.

The TIEGCM simulations of the neutral atmosphere response to the November 1993 storm by *Emery et al.* [1999] predicted the excitation of large-sacle AGWs by the episodes of high-latitude Joule heating on November 4 (particularly around 0000 UT) and their equatorward propagation in both the hemispheres as manifested in the neutral wind components and neutral temperature (see Figure 4 of their paper). The model results were able to reproduce the observed gravity waves in winds and hmF_2 at several Southern Hemisphere locations. The distinct quasiperiodic variations evidenced in hpF_2 at Ahmedabad and Sriharikota throughout the daytime on November 4 thus find a logical interpretation in terms of meridional wind variations associated with the large-scale AGWs. The attendant rapid temporal changes in the latitudinal profile of f_0F_2 (the repetitive sequence of development and inhibition of EIA) are to be due to plasma transport by meridional winds acting in opposition/ combination to that due to the fountain process. An equatorward wind transports plasma from the crest region of EIA toward the equator which can impede the field-aligned plasma diffusion associated with fountain effect. The outcome will be a weakening of EIA or a reversal of the latitudinal profile of f_0F_2 depending on the magnitude of the wind speed and the strength of the fountain (upward plasma drift over the equator). A poleward wind will produce the opposite effect of enhancing the fountain process if it is already operative, and renewing it if dormant. A variant of the meridional wind effect prevails in the presence of strong transequatorial winds in the form of plasma transport across the equator from one hemisphere to the other. The singnature of the wind-induced plasma transport is the anticorrelation between the height and density of F_2 layer peak around the crest region of EIA, as argued and modeled by *Fesen et al.* [1989] for the magnetic storm of March 22, 1979. Further evidence for meridional wind modulation of EIA under disturbed conditions has been reported by *Abdu et al.* [1991, 1993]. It follows that meridional neutral winds dominated the behavior of F layer peak at Ahmedabad during the daytime on November 4. This inference is substantiated by the statistically significant negative correlation (r = - 0.36) that is seen between hpF_2 and f_0F_2 over the interval 0600-1800 LT at this station (see Figure 5). At Sriharikota in comparison the correlation over the entire daytime period (r = -0.21) is not significant, although an anti-correlation is obvious during 1115-1745 LT as may be seen from Figure 5. The control of the disturbed neutral wind field continued on the night of November 4-5 in the form of an inhibition of the postsunset height rise close to dip equator (which continued on the nights of November 5-6 and 6-7 well into the storm recovery phase, see Figure 2) followed by a sudden and prominent depletion of f_0F_2 and an abnormal F layer height rise around midnight throughout the anomaly region. Numerical modeling of equatorial F region heights and densities using TIEGCM simulations specific to 75^{0}E (Indian) sector will help validate the interpretative aspects of the observations reported here.

In conclusion, the present case study showed that the equatorial thermosphere in the Indian sector did respond to the major magnetic storm of early November 1993 and significantly affected the ionospheric F region behavior through plasma-neutral coupling processes. The present results, which are an addition to the knowledge base of this upper atmosphere storm, strengthen the view that neutral atmospheric disturbances do contribute to equatorial ionospheric storms at times, if not always. The zonal electric field too is found to be perturbed by direct penetration and disturbance dynamo effects. In particular, the CEJ condition (westward electric field) on the morning of November 4, which occurred in close association with a significant decrease in polar cap potential and AE index, seems to be a prompt penetration effect and its polarity is conformity with theoretical results. However, this is not the case with the electric field signatures simultaneously evidenced at middle and low latitude locations in other local time sectors. In other words, there is a lack of mutual consistency in the polarity of the penetration electric field at subauroral latitudes of this apparently global transient electric field disturbance. Further study is required to gain a better understanding of the origin of this complex electric field perturbation.

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