CHAPTER VII

A STUDY OF EQUATORIAL IONOSPHERIC RESPONSE TO THE MAGNETIC STORM OF 3-11, NOVEMBER 1993

7. 1. Introduction

7.1.1. Geomagnetic storms: Onset and development

The impact of solar phenomena and associated geomagnetic, magnetospheric and ionospheric activity on the near-earth space environment is a central topic in geophysics. Geomagnetic storm is the indirect effect of solar-terrestrial activity which may reach several percent of its undisturbed value measured at the surface of the earth [Gonzalez et al., 1994]. During geomagnetic storms, the solar wind coming out of the sun compresses the Earth’s magnetosphere, and associated intense electric fields are mapped along geomagnetic field lines to the high latitude ionosphere. The Earth’s ionosphere responds markedly to varying solar and magnetospheric energy inputs. Solar disturbances produce prompt as well as delayed effects on Earth. The prompt effect is caused mainly due to solar flare associated bursts in solar EUV, X-rays and relativistic particles which affect the entire ionosphere. On the other hand, delayed effects are caused due to the ejection of particles along with the solar wind, which envelop the Earth’s magnetosphere. The disturbed condition of ionosphere during magnetic storms is known as ionospheric storms and was first recognized by Appleton and Ingram (1935). According to the geomagnetic storm characteristics (the initial, main and recovery phases) and their behaviour, the onset of ionospheric storms, their local characteristics, their classification and intensity can be predicted as the ionospheric disturbances are directly linked to geomagnetic activity. Geomagnetic activity is caused by the interaction of the solar wind with the earth’s magnetic field and thereby transporting energy and mass. The form of this interaction is primarily controlled by the interplanetary magnetic field (IMF). When the IMF is northward, disturbances are observed only within the polar cap. If it is southward, magnetic disturbances and aurora occur in the auroral oval. Intense southward IMFs are well documented as causing magnetic storms [Rostoker and Fälthammar, 1967]. The stronger the southward component of the IMF, the stronger the magnetic disturbance is. The
ionospheric electron density, \( N_e \) at a given location and altitude depends on the solar EUV fluxes, the neutral composition and dynamical effects of the neutral winds and electric fields. Prölss (1995) has reviewed the basic ionospheric F region storm morphology and associated mechanisms, especially those dependent upon the neutral composition associated disturbance effects, the significance of external electric fields and interaction between the protonosphere and ionosphere. In addition to this, they showed that the ionospheric F region densities and height too undergoes significant changes during geomagnetic storms. Disturbed neutral winds also cause the F region electric fields by the ionospheric disturbance dynamo mechanism [Blanc and Richmond, 1980]. They proposed that the energy input to the thermosphere during magnetic disturbances alters the global thermospheric circulation and consequently alters the generation of electric fields and currents at middle and low latitudes by ionospheric wind dynamo action. The disturbance electric fields and currents act to reduce or reverse the normal quiet-day pattern of electric fields and currents. The ionospheric disturbance dynamo (IDD) electric fields are slowly varying and persistent in nature and manifest with a time delay (>6 hrs) with reference to energy deposition at high latitudes. These disturbed electric fields redistribute the plasma, affecting their production and loss rates and sometimes even destabilize the plasma, producing irregularities.

7.1.2. Classification of magnetic storms

The magnetic storm is the severest manifestation of the disturbance of the geomagnetic field and is also known as 'geomagnetic storms'. During disturbed geomagnetic condition, the physical and dynamical state of the ionosphere-thermosphere system (ITS) deviates substantially from the average quiet-time pattern constituting the ITS. Quiet and disturbed day daily variations can be studied by using ground based magnetometer data which will provide information regarding three components of geomagnetic field viz. (i) horizontal component (\( H \)), (ii) Declination (\( D \)), and (iii) vertical component (\( Z \)). In order to give a semiquantitative measure of the level of magnetic activity, various indices were developed. The worldwide magnetic disturbance produced during magnetic storms is generally characterized through the use of magnetic indices like \( K_p \), \( a_p \), \( A_p \), \( AE \) and \( D_s \).
indices.

1. **Kp index:** For Kp index, 12 pre-selected (worldwide) stations between geomagnetic latitudes 48° and 63° are taken. Each observatory compares its H (horizontal component of earth's magnetic field F), D (declination), and Z (vertical component of earth's magnetic field) records for a given time of the day, month and solar activity phase and chooses the maximum deviation to assign a number K which ranges from 0 for negligible deviations to 9 for maximum deviation, the limit for which is different for different locations.

   **K values:**
   - 0, 1, 2 represents very quiet condition
   - 3, 4 small disturbances
   - 5, 6 represents disturbed conditions
   - 7, 8, 9 represents highly disturbed conditions

Values of K for a given station are first used to compute Ks index (s for standardized) which attempts to filter out local and seasonal variations. The Ks index (like K index) ranges from 0 to 9, but is broken into finer gradations and is quoted in terms of an integer using the symbols -, 0, +. For example, the interval from 3.5 to 4.5 is given by the Ks values 4, 4°, 4'. Therefore, Ks can have 28 different values

   $K_s: 0°, 0', 1°, 1', 2°, 2', 3°, 3', 4°, 4', 5°, 5', 6°, 6', 7°, 7', 8°, 8', 9°, 9'$.  

Finally, the Kp value for each 3-hour interval is derived from the Ks values from the 12 selected stations. Since, the 3-hour K, Ks and Kp indices are defined with a quasilogarithmic scale, they are not suitable for simple averaging to obtain a daily index.

2. **Ap index:** The Ap index is the conversion of the k index to a roughly linear scale, and similarly the aₖ index is derived from the Kp index. The average of aₖ and aₚ over eight 3-hour interval in a day are defined as the daily single station index, Aₖ and the average planetary index Aₚ, respectively. The aₚ index can be interpreted as the equivalent amplitude of a disturbance at a standard midlatitude station in units of 2nT [Rostoker, 1972]. The values of aₚ ranges from 0 to 400 and the daily average calculated in universal time is the more commonly known Aₚ index.

3. **AE index:** This is the principal magnetic index for auroral zone studies. This
index is measured from the H-component measurements from several auroral stations (at different longitudes) on the same UT scale. At each auroral station, the maximum positive displacement of $H$ defines AU (effect due to eastward electrojet) while the maximum negative displacement of $H$ defines AL (effects due to westward electrojet). The separation (AU-AL) is the AE index for any given UT. In one sense, AU and AL are local indices because they are only the amplitude of $H$ perturbations at two sites. AE index is much more often used in solar wind-magnetosphere coupling studies.

4. $D_s$ index: It is the most widely used low latitude index. $D_s$ is the hourly measure of the globally averaged low-latitude horizontal component of the Earth's magnetic field. The term short time variation was first coined by Moos (1910). Later Chapman (1919) called this variation 'D$_s$' for the average storm-time (st) presentation of field disturbances (D) with regular daily variations and baseline main field levels removed. The first magnetic activity indices of $D_s$ were developed by Vestine et al. (1947) long before Sugiura (1964) published his $D_s$ indices, which have been used since then for the description of the storm time variation.

There are three classifications of magnetic storms: minor, major and severe. This classification depends either on $K_p$ or $A_p$ indices [see table 7.1].

<table>
<thead>
<tr>
<th>Types of storms</th>
<th>Ap index</th>
<th>Kp index</th>
<th>Dst</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intense (severe)</td>
<td>100 or more</td>
<td>7, 8, or 9</td>
<td>-100 nT to -200 nT or still more</td>
</tr>
<tr>
<td>Moderate (major)</td>
<td>Between 50 and 100</td>
<td>6</td>
<td>-50 nT to -100 nT</td>
</tr>
<tr>
<td>Small (minor)</td>
<td>Between 30 and 50</td>
<td>5</td>
<td>-30 nT to -50 nT</td>
</tr>
</tbody>
</table>

7.1.3. Different phases of magnetic storms
The onset of geomagnetic storms is one of the most striking features of the geomagnetic disturbances. As discussed earlier, there are various geomagnetic indices to denote the intensity of the magnetic activity. It is commonly assumed that
the intensity of the magnetic storm can be defined by the minimum $D_n$ value, or the maximum depressed $D_n$ at the main phase. $D_n$ geomagnetic index is used to learn the interplanetary conditions, and hence the physical processes. Magnetic storms or geomagnetic storms are divided into four different phases based on the signatures in the $D_n$ index (i) sudden storm commencement, (ii) Initial phase, (iii) Main phase, and (iv) Recovery phase.

(i) *Sudden storm commencement (SSC):* Geomagnetic storms, as observed by ground based magnetometers, commonly begin with an increase in the strength of geomagnetic field. These storms are called sudden storm commencement (SSC). It shows several different patterns depending upon the latitude and local time of its observation point. The duration of SSC will be 1 to 6 minutes. The geomagnetic SSC is normally characterized by a sudden increase of the horizontal component of earth’s magnetic field due to increased solar wind ram pressure $\rho v^2$, where $\rho$ is the mass density and $v$ is the velocity of the solar wind particle. Sudden commencement often occur without storms, and storms without sudden commencements (*Akasofu*, 1964). Empirically, the size of the sudden commencement was found to be proportional to the square root of the solar wind ram pressure [*Siscoe et al., 1968; Ogilive et al., 1968*].

(ii) *Initial phase (IP):* The sudden arrival of the enhanced solar wind has the form of a shock wave and it results in a continuing compression of the magnetosphere. The corresponding increase of the horizontal component of magnetic field at the surface of the earth is called the initial phase of the storm. The initial phase of the storm lasts about 1 to 8 hrs. The initial phase is the time period of the magnetic fluctuation between the SSC and the main phase. During the IP of the storms, the solar wind pressure increases and the increase in the pressure is well correlated to the increase in the equatorial geomagnetic field represented by the $D_n$ index.

(iii) *Main phase (MP):* The main phase of the storm lasting typically 24-36 hrs, is preceded by an initial phase and is characterized by a decrease in horizontal component of earth’s magnetic field. *Schmidt* (1917) was the first to suggest that the storm-field decrease was due to a ring of westward electric current circling the Earth. This ring of westward electric current is known as 'ring current' and it essentially consists of ions (notably by protons of ~ 10MeV) and electrons in the 10-
300 keV energy range, located usually between 2 to 7 RE (Radius of Earth, RE ≈6371 km) and producing a magnetic field disturbance which, at the magnetic equator, is opposite in direction to the Earth's dipole field. There is usually an interval of few hours between the SSC and start of the main phase, which represents the delay time for the ring current to build up. The ring current obtains its maximum intensity at the time of maximum depression of the magnetic field.

![Diagram](image)

Figure 7.1. Idealized storm variation of the geomagnetic field. The initial phase is attributed to the impact of an enhanced solar wind; the main phase is attributed to an enhanced ring current.

(iv) Recovery Phase (RP): The last phase of the magnetic storm is known as 'recovery phase'. Once the main phase is over, the injection of new particles into the ring current takes place and its density decays slowly for days till the magnetic field returns to its normal value. This period is called the recovery phase of the storm. It might happen that another sudden commencement of magnetic storm might take place before the effects of the first storm are wiped out; in that case the geomagnetic field remains disturbed for several days. Typical storm time behaviour is shown in figure 7.1.

During geomagnetic storms, the prompt penetration of high latitude electric
fields and energy input modifies various equatorial phenomena like Equatorial Ionization Anomaly (EIA), Equatorial Spread F (ESF) and Equatorial Electrojet (EEJ) and causes an enhancement of the global thermosphere-ionosphere circulation [Abdu, 1997]. 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 [Rishbeth et al., 1987; Pröllss, 1995; Fuller-Rowell et al., 1996; Buonsanto et al., 1997; Knipp et al., 1998]. 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 [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 [Fesen et al., 1989; Barrage et al., 1992; Burns et al., 1995; Abdu, 1997; Fejer, 1997; Fuller-Rowell et al., 1994, 1997; Emery et al., 1999].

The primary cause of geomagnetic storm at Earth is believed to be due to the strong dawn-to-dusk electric fields associated with the passage of southward directed interplanetary magnetic fields, B_S, past the Earth for sufficiently long intervals of time. Equatorial ionospheric storms of primary concern in the present study result from modifications in zonal electric field, meridional neutral winds, and neutral gas temperature and chemical composition [Rishbeth, 1975; Sasori, 1980; Mikhailov et al., 1994; Abdu et al., 1991, 1993, 1997]. 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 [Anderson, 1981; Preble et al., 1994; Bailey et al., 1997]. Thus, it is logical to say that electric field disturbances are by far the most important contributor to the storm time behaviour of equatorial F region.
The equatorial zonal electric field changes during storm time and it can be classified 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) $B_z$, polar cap potential drop, auroral electrojets, and symmetric/asymmetric ring current activities, all of which are intricately related to each other [Fejer, 1997; Abdu, 1997; 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 [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 [Fejer, 1997; Abdu, 1997; 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].

Ionospheric storms result from large energy inputs to the Earth's upper atmosphere associated with geomagnetic storms. Also, the global scale perturbations in thermospheric density, temperature, and wind field that result from enhanced energy and momentum deposition in the regions of the high-latitude Thermosphere-Ionosphere-System (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 [Fesen et al., 1989; Hajkowicz, 1991; Burns and Killeen, 1992; Balthazar 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 also possible that large-scale AGWs of auroral origin could at times play a prominent role in the behavior of equatorial TIS under disturbed conditions [Fesen et al., 1989; Hajkowicz, 1991; Burns and Killeen, 1992; Balthazar and Moffett, 1997; Knipp et al., 1998].

7. 1. 4. A case study of the geomagnetic storm of November 3-11, 1993

The major and prolonged geomagnetic storm of November 3-11, 1993, which led to tumultuous changes in the near-Earth space environment is the subject of extensive origin-to-end studies under CEDAR (Coupling Energetic Dynamics of the Atmospheric Regions) and SOLTIP (Scientific Committee for Solar Terrestrial Physics) programs [Knipp et al., 1998; Emery et al., 1999]. Most of these studies are, however, limited to evaluation and interpretation of the perturbations in TIS at high and midlatitudes and it seems that the response of the equatorial TIS to the storm remained unassessed. To fill in this gap, a detailed study was carried out on the equatorial ionospheric effects though limited to the Indian (75°E) sector by using the data available from the ionosonde and magnetometer networks spanning the region 0.3-34.5°N dip. The present chapter on this study stems on the 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 which has brought out certain outstanding and new aspects of the storm time ionospheric behaviour.

7. 2. Database

Ionospheric storms are global phenomena, which can be studied by using a variety of experimental and modelling techniques. For the present study, the data used consist of quarter-hourly ionograms of the four Indian stations, Ahmedabad (23°01'N, 72°36'E, dip = 34.0°N), Sriharikota, SHAR (13°42'N, 80°30'E, dip = 10°N), Kodaikanal (10°14'N, 77°29'E, dip = 4°N) and Trivandrum (8°30' N, 76°54'E, dip
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'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, $f'_nF_2$, which represents the peak density of the layer, $N_mF_2$; and $h'pF_2$, which is an approximate measure of the height of peak density, $h_mF_2$. Since $h'pF_2$ 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 features of its temporal variations, which reflect in both $h'pF_2$ and $h_mF_2$. Also the ground based magnetometer data of Trivandrum ($8°30'N$, $76°54'E$, dip 0.3'N) and Alibag ($18°38'N$, $72°52'E$, dip 24.5'N) have been used to assess the changes in equatorial electrojet strength and hence in the zonal electric field that drives it. The parameter $\Delta SdI$, 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 [Rastogi and Patel, 1975; Bhargava et al., 1980; Sauri, 1989].

7.3 Results and discussions

7.3.1 Overview of Geomagnetic Storm and Associated Equatorial Ionospheric Storm

The geomagnetic storm of November 3-11, 1993 developed against a background of unusual magnetic quiescence that prevailed for most part of November 2 and 3. The sharp decrease in $D_s$ index signaling the start of storm main phase began at 2200 UT on November 3 and $D_s$ index reached the first minimum of main phase just before 0100 UT of November 4. $D_s$ 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, Kyoto University, Kyoto, Japan, Prompt Report, February 1996] underwent a precipitous drop just after 0100 UT on November 4 due to a transient northward excursion of IMF $B_z$.

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 continuous 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 $D_s$ and AE indices shown in figure 7.2. Further details of this "severe" storm, the causative solar wind features and attendant magnetospheric and high-latitude ionospheric phenomena are discussed by Knipp et al. [1998]. They presented the storm profiles of cross-polar voltage, Joule heating, integrated field-aligned currents and Hall conductance. They found that a total of ~ 137 PJ of energy was generated globally by Joule heating over the 10-day interval and more than 30% of this was generated within 24 hours of storm onset. The average joule heating as estimated during the most intense phase of this storm was >200 GW. Integrated field aligned currents for the same day were 6 MA compared to 4 MA for the moderate storm days. Further, they developed a simple energy budget for the storm whose magnetic activity input is close to balance with the estimated Joule, particle and ring current sinks. Their study reveals that early November 1993 storm was strong and had prolonged effects on the earth's environment.

Figure 7.2 presents the diurnal profiles of the electrojet parameter, $\Delta$DsI and $f_0F_2$ at the four Indian stations over the period 1200 UT of November 3 through 1200 UT of November 7. Here, November 2 is taken as the reference or control day which is one of the designated quiet days of the month ($Ap = 4$, $\Sigma Kp=8+$), and the diurnal pattern of the various parameters on this day is superposed in figure 7.2 to assess the characteristics of the ionospheric storm. The behavior of $hpF_2$ at the four stations is shown in figure 7.3 in the same format as of figure 7.2. Careful perusal of figures 7.2 and 7.3 show that significant perturbations in $\Delta$DsI, $f_0F_2$ and $hpF_2$.
Figure 7.2. Time variation of (a) equatorial $D_s$ index (b) auroral electrojet index, AE, (c) equatorial electrojet strength, $\Delta SdI$ and (d-g) $f_0F_2$ at the four Indian stations (TRV, Trivandrum: KKL, Kodaikanal: SHAR, Sriharikota: AHM, Ahmedabad) spanning the equatorial anomaly region 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 ($Ap=4$. $Kp=8+$) is superimposed to provide an overview of the ionospheric storm.
Figure 7.3. Same as figure 7.2 but for $h_p F_2$ at the four Indian stations.
prevailed in the Indian equatorial region but confined to November 4, the most disturbed day of the storm period ($A_p=77; \Sigma Kp=47$). The departure of the behaviour of the various parameters from reference day is more or less marginal on subsequent days corresponding to the recovery phase of the magnetic storm. The response on November 4 is characterized by five prominent effects which in chronological order are (a) morning counter-electrojet (CEJ) condition accompanied by an anomalous positive latitudinal gradient in $f_0F_2$, (b) remarkable quasi-periodic oscillations in $hpF_2$ and $f_0F_2$ during the daytime at Ahmedabad and Sriharikota and attendant rapid temporal changes in EIA, (c) absence of the usual dusktime increase of $F$ region height at Trivandrum and Kodaikanal close to dip equator, (d) an abnormal and rapid decrease of $f_0F_2$ at all the stations in the pre-midnight period with an apparent time delay towards the magnetic equator and finally, (e) anomalous increase of $F$ layer height at all the stations around midnight accompanied by onset of spread- $F$ conditions near the dip equator. Now, all these five aspects of the ionospheric storm on November 4 and their implications are discussed in the following section.

7.3.2. Morning Counter electrojet and EIA

Figure 7.4 shows the time variation of $\Delta SdI$ and AE index on November 4. A prominent negative perturbation (relative to the more or less constant nighttime level) in $\Delta SdI$ till 0830 LT (0330 UT) characteristic of counter electrojet (CEJ) condition is obvious in figure 7.4. Such a negative perturbation over the same time interval is also seen (not shown here) in the parameter, $\Delta H$ (Trivandrum)- $\Delta H$ (Alibag), which is also used to represent the electrojet strength ($\Delta H$ 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 $0.3^\circ$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 [Kane, 1976]. This 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 $\Delta$SdI 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 7.4 indicates that the CEJ condition is associated with a decrease in AE index and in the polar cap potential drop by (45 kV between 0600 and 0800 LT (0100-0300 UT) as shown in figure 1 of Emery et al., (1999).

![Figure 7.4. Time variation of the equatorial electrojet strength (SdI) in the Indian sector and AE index on 4 November (Ap = 77).](image)

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 7.5 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.
Figure 7.5. Dip angle variation of $f_{0F2}$ in the Indian sector over the time interval 0645-0830 LT (0145-0330 UT) on 4 November.
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 (Figure 7.5). 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 the percentage deviation of the values of the parameters on November 4 from those on November 2 is shown in figure 7.8 for the four stations. It is clear from the figure that $hpF_2$ at Ahmedabad underwent a rapid decrease over the period 0600-0800 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 behaviour is also evident at Sriharikota in both the F layer parameters though of a lesser magnitude as may be seen from figure 7.8. 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 (Figure 7.5).

7.3.3. *Daytime Perturbations in F Layer Peak Height and Density and EIA*

After the cessation of the morning CEJ condition, the equatorial electrojet strength, $\Delta SdI$ closely followed the course as on the reference quiet day (see Figures 7.2, 7.3, 7.4). 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 ingredients 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
7.2, 7.3 and 7.8, 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$_0$F$_2$ at individual stations as well as in the spatial distribution of f$_0$F$_2$. In the following is presented the temporal changes in the latitudinal distribution of f$_0$F$_2$ 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. The hpF$_2$ has increased above the quiet day values (by 11-26\%) at Ahmedabad and Trivandrum (8-14\%) during the interval 0900-1045 LT, while hpF$_2$ remained lower than normal at Kodaikanal (by 10-14\%), which may be considered as an indicative of a relatively weaker upward ExB drift around the dip equator (see Figure 7.8). As mentioned earlier, the latitudinal profile of f$_0$F$_2$ returned to the quiet day form by 0830 LT, although the absolute value of f$_0$F$_2$ is lower than normal throughout the equatorial region (Figure 7.5). Profiles of the dip angle variation of f$_0$F$_2$ on November 2 presented in figure 7.6 demonstrate the normal pattern of the forenoon development of EIA, with the formation of a peak in f$_0$F$_2$ initially at Sriharikota and later on somewhere between Sriharikota and Ahmedabad (the exact location of the crest could not 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$_0$F$_2$ at Ahmedabad to that at Trivandrum is +1.21 by 1045 LT. In contrast to this, on November 4, the latitudinal profile of f$_0$F$_2$ assumed a rather smooth negative gradient from the dip equator right from 0915 LT and continued such that the ratio of f$_0$F$_2$ at Ahmedabad 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$_0$F$_2$ is brought about by a rapid depletion (accumulation) of plasma at Ahmedabad (at Trivandrum and Kodaikanal) away from the dip equator (close to dip equator) as can be seen from Figure 7.6. The reversed profile of f$_0$F$_2$ is considered 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$_0$F$_2$ at Ahmedabad over the time interval under discussion (Figure 7.8). It
Figure 7.6. Same as figure 7.5 but for the time interval 0900-1045 LT (0400—0545 UT).
Figure 7.7. Same as figure 7.5 but for the time interval 1115-1300 LT (0615-0800 UT).
Figure 7.8. Time variation of the percentage deviation of $f_0F_2$ and $h_pF_2$ at the four Indian stations during daytime on 4 November.

is likely 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. Raghavarao et al. (1978) showed that the strength of EIA is having one to one correlation with the time integrated strength of the EEJ confirming that the
driving force for both the EIA and the EEJ is the same. It shows that the
development of EIA will be inhibited in the presence of CEJ or weak EEJ. 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 [Abdu et
al., 1990, 1993].

Figure 7.7 presents the data for the interval 1115-1300 LT when hpF₂
rapidly decreased to below the quiet day values at both Sriharikota and Ahmedabad
(by 20% at 1300 LT, see Figure 7.8). The electrojet strength is more or less the
same as on the reference quiet day although hpF₂ is lower especially at Kodaikanal.
The latitudinal profiles of f₉F₂ on the quiet day showed a well-developed positive
gradient from the dip equator as could 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 f₉F₂
conformed to that of the quiet day. The depth of the positive gradient, represented
by the ratio of f₉F₂ 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 f₉F₂ at
Ahmedabad over quiet values took place, replacing the strong negative gradient
between Sriharikota and Ahmedabad eventually by a shallower one. This delayed
noon time development of EIA on November 4 may be interpreted 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 hpF₂ and f₉F₂, 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 hpF₂ 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 7.3). This is so only in absolute values because, in
comparison to November 2, \( \text{hpF}_2 \) 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 7.8. The response of the spatial distribution of \( \text{f}_0\text{F}_2 \) to these height variations (not shown here) is such that the changes in \( \text{f}_0\text{F}_2 \) 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 \( \text{f}_0\text{F}_2 \) maintained an overall positive gradient representative of a well-developed EIA. Noteworthy among the short-term variations in the spatial distribution of \( \text{f}_0\text{F}_2 \) over this time interval are (1) the highly distorted profile with negative (positive) gradient poleward (equatorward) of Sriharikota during 1430-1500 LT when \( \text{hpF}_2 \) experienced an increase both at Sriharikota and Ahmedabad and (2) development of a positive gradient between Sriharikota and Ahmedabad from 1600 to 1700 LT when \( \text{hpF}_2 \) decreased. These can be considered as subtle manifestations of plasma transport due to meridional winds acting in concert with the fountain process.

7.3.4. Nighttime changes in F layer height and peak density

The recovery phase of the magnetic storm started around 1800 LT (1300 UT) on November 4 as indicated by the time history of \( D_n \) index in figure 7.2 and three prominent perturbations marked the behavior of F layer height and density in the local sunset-sunrise period corresponding to the early stage of the storm recovery phase. The first one is the total absence or inhibition of the dusk time 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 groundbased as well as satellite measurements [Batista et al., 1986; Fejer, 1991; Sastri et al., 1994; Fejer et al., 1995]. 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 \( \text{hpF}_2 \) at Trivandrum and Kodaikanal on November 2, the reference quiet day shown in figure 7.3. 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 (\( h'\text{F} \)) maintained a near-constant altitude around 240 km over the period 1800-2000 LT as may be seen from figure
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 7.9a). 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 (Figure 7.3), and the usual duskt ime time behavior of F layer (increase of layer height) resumed only from November 7 onwards.

A precipitous drop in $f_0F_2$ that is seen first at Ahmedabad and subsequently at lower altitudes over the interval 1915-2330 LT constitutes the second perturbation (Figure 7.9). At Ahmedabad $f_0F_2$ underwent a sharp decrease over the short interval 1915-2030 LT from 7.8 MHz to 3.4 MHz- a drop of 56.4 per cent in 75 minutes. This is considered a storm-time effect because normally $f_0F_2$ attains lowest values (diurnal mininum) 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 percent beginning at 2015 LT, 2030 LT 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 hrs, 1825 hrs, 1840 hrs and 1841 hrs, 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 hpF2, see figure 7.3) that is latitude dependent in that it is distinctly seen at Ahmedabad and Sriharikota and not at Kodaikanal and Trivandrum. This behavior 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 towards 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 duskt ime increase in F layer height near the dip equator is inhibited as detailed before and $f_0F_2$ maintained a near-constant value at
Figure 7.9. Time variation of $f_0F_2$ and $h'F$ at equatorial stations in the Indian sector on the night of 4-5 November. The arrows indicate the sharp reduction in $f_0F_2$ in the premidnight period and the filled rectangle shows spread-F conditions at the various stations.
Trivandrum and Kodaikanal till 2030 LT as may be expected for such a situation (Figure 7.9). The time delays in the onset of the drop in $\mathbf{F}_2$ 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 of the low time resolution (15 minutes) of the ionosonde data coupled with the uneven separations between the stations.

Nighttime meridional neutral winds have been derived for the night of November 4-5, using $h'$F data of Sriharikota and Trivandrum following the method of Krishna Murthy 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.

![Figure 7.10](image)

**Figure 7.10.** Temporal variation of nighttime meridional winds derived from $h'$F data of Sriharikota and Thiruvananthapuram for the night of 4-5 November 1993.

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 $\pm 25$ m/s. The outcome presented in
figure 7.10 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 post-midnight decreases in \( f_o F_2 \) at Kodaikanal during severe storms, which they attributed to vertical/horizontal plasma transport by upward vertical drift/equatorward meridional winds. It may be pointed out that the multi-station 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.

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 is 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 7.9). 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 hr as can seen from figure 7.9. The height disturbance at Ahmedabad is considered 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 nT to 297 nT over the interval 2200-0100 LT (1700-2000 UT) and the polar cap potential drop derived from the AMIE (Assimilative-Mapping of Ionospheric Electrodynamics) procedure also shows a rapid decrease by \(-70 \) kV between 2300 and 0100 LT (1800-2000 UT) according to figure 1 of Emery et al. (1999). 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 7.10 clearly shows equatorward surges centred at 0015 LT and 0300 LT in support of the
conclusions made in this study. 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 [Fejer et al., 1976; Sastri, 1979; Kelley and Maruyama, 1992].

7.4. Summary and Conclusions

The salient features of the response of equatorial ionosphere in the Indian sector to the severe magnetic storm of November 3, 1993 have been presented in this chapter. 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 4/5 November, corresponding to the main phase and early part of the recovery phase, respectively, of the magnetic storm. It is interesting to examine the electric field disturbances and related effects evidenced in the ionospheric 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 06 LT and 21 LT [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 [Sastri, 1982; Abdu et al., 1990, 1993]. In fact, it seems to be the case that there is only one earlier report of a similar morning (0700-0930 LT) development of EIA, namely the one evidenced in the Asian (120° E) sector on 23 September 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 4 November 1993 and the SUNDIAL-86 event in that, in the former reported here, the positive latitudinal
gradient in $f_nF_2$ 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 [Fesen et al., 1989]. They suggested that the magnetic storm can generate transequatorial winds which results in the transportation of ionization across the dip equator, depleting electron concentrations in the upwind hemisphere and enhancing them in the downwind hemisphere. Further, they showed that the EIA may be disrupted by the magnetic storm and the magnitude of the crests may be highly asymmetric with respect to the equator, with the latitudinal positions of the crests alternating in time. Thus, depending on the universal time of occurrence of the storm, the low latitude electron densities for a given station may be significantly enhanced or reduced over their quiet time values. The significant decrease in $h'F_2$ at Ahmedabad in the morning on November 4 (Figures 7.3 and 7.9) which is indicative of poleward neutral winds strongly suggests that the abnormal positive latitudinal gradient in $f_nF_2$ (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 $f_nF_2$ and $h'F_2$ away from dip equator and a depletion of plasma near dip equator. The behavior of $f_nF_2$ and $h'F_2$ at Ahmedabad and Sriharikota and of $f_nF_2$ 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 00 UT on November 4 is to be followed by enhanced equatorward winds from both the polar regions (source at 60° N and 70° S) with a phase speed of about 700 m/s in the American sector (70° W). The poleward surge in transequatorial winds implied by our ionosonde data suggests that in the Indian (75° 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 $h'F_2$ at Kodaikanal close to the dip equator at the time of CEJ condition corroborates the inference because the height of F layer
near the magnetic equator is strongly dependent on vertical ExB drift due to zonal electric field [Anderson, 1981; Abdu et al., 1991; Preble et al., 1994]. It has to be noted here that the ionosonde/radar observation at low and midlatitude has also inferred the presence of eastward electric field at different longitude zone at the time of CEJ condition in Indian equatorial region [Richards and Wilkinson, 1998; Foster and Rich, 1998]. 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 which showed 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° magnetic latitude, accompanied by an increase in f0F2 by 25-50 percent with the greatest increase near Yamagawa (20°N magnetic latitude). They attributed the changes in F layer peak height and density both in the American (premidnight) and the Japanese (noon) sectors in terms of 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 low and midlatitude locations in the Australia-New Zealand-Japan region (afternoon-evening sector) studied by Richards and Wilkinson (1998) also showed a daytime storm-induced increase in F2 density and the height of the peak F2 density over most of the stations beginning at 00 UT which they attributed as the combined effect of prompt electric field and aurorally generated equatorward wind surge. 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 sub-auroral 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-New Zealand) 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 [Prölls, 1995; Fuller-Rowell et al., 1994; Balthazar 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 in this context 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 17-20 LT (12-15 UT). It seems to be of IDD origin in view of its delayed appearance (12 hrs 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 [Abdu et al., 1995]. 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) [Figure 7.9]. 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, as shown in figure 5 of Fejer et al. (1990). The large amplitude of the eastward field (1 mV/m) at Trivandrum may be considered 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 21 LT [Blanc and Richmond, 1980] and could add
on to the penetration field which also becomes eastward just before midnight [Fejer et al., 1990]. 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].

The TIEGCM simulations of the neutral atmosphere response to the November 1993 storm by Emery et al. (1999) predicted the excitation of large-scale AGWs by the episodes of high latitude Joule heating on November 4 (particularly around 00 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 $h_{m}F_{2}$ at several southern hemisphere locations. The distinct quasi-periodic variations evidenced in $h_{m}F_{2}$ 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 $f_{b}F_{2}$ (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 towards 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 $f_{b}F_{2}$ 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 signature of the wind-induced plasma transport is the anti-correlation between the height and density of F2 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 \(hpF2\) and \(f_nF2\) over the interval 06-18 LT at this station (Figure 7.8). 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 7.8. 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 followed by a sudden and prominent depletion of \(f_nF2\) and an abnormal F layer height rise around midnight throughout the anomaly region. As discussed earlier, the height disturbances close to dip equator are attributable to IDD electric fields or a combination of IDD and prompt penetration electric fields. The TIEGCM results indeed showed the presence of westward winds on November 4 from 1000 UT to 2000 UT in the 75°W sector which is a signature of disturbed circulation that produces IDD electric fields (Figure 4d of Emery et al., 1999). The conspicuous drop in \(f_nF2\) in the premidnight period is due to plasma transport across the equator by an equatorward surge in meridional winds, which understanding is supported by the meridional wind pattern (Figure 7.10) derived by the ionosonde data using the method of Krishna Murthy et al. (1990). The storm recovery phase too exhibited signatures of the effects of disturbed neutral wind field in the form of continued inhibition of postsunset height rise close to dip equator on the nights of 5-6 and 6-7 November which may be due to the prevalence of IDD electric fields and/or westward disturbance zonal winds (Figure 7.3). Numerical modeling of equatorial F region heights and densities using TIGCEM simulations specific to 75° E (Indian) sector will help to validate the interpretative aspects of the observations reported here. Thus, 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 in addition to the knowledge base of this upper atmosphere storm, strengthen the view that neutral atmospheric disturbances do contribute to equatorial ionospheric storms at most of the times. 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 in conformity with theoretical results. But 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.