Impact of magnetospheric forcing on the electrodynamics of the equatorial ionosphere

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Impact of solar wind–magnetosphere–ionosphere coupling processes on the electrodynamics of the equatorial and low latitude ionosphere are seen in a variety of observations. Signatures of these processes are present in geomagnetic field variations recorded at equatorial and low latitudes, in ionospheric parameters estimated from ionosonde observations, in ionospheric drifts derived from coherent or incoherent scatter radar measurements or in the absence of such observations, from spaced receiver recording of ionospheric scintillations when present. The coupling processes that play a role in altering the neutral wind and zonal electric field in the post-sunset equatorial ionosphere, and hence the height of the post-sunset equatorial F layer, are particularly important since this height has emerged as one of the significant factors in the development of equatorial plasma bubbles, which form a major component of space weather in the low latitudes. Results derived from some of the observations mentioned above shall be reviewed in the context of disturbance dynamo and promptly penetrated electric fields, which arise in the equatorial ionosphere due to magnetospheric forcing.

1. Modification of equatorial ionospheric electric field

Electrodynamics of the equatorial ionosphere is influenced by magnetospheric forcing during geomagnetically disturbed periods through the prompt penetration of interplanetary electric fields (IEFs) to the equatorial ionosphere (Spiro et al., 1988; Peymirat et al., 2000) and through the delayed ionospheric disturbance dynamo (DD) electric fields, which are set up by the dynamo action of the disturbances in the neutral wind system caused by the energy deposited into the high latitude ionosphere-thermosphere system from the magnetosphere during magnetic storms and substorms (Blanc and Richmond, 1980, Huang et al., 2005). The collisionless solar wind flowing radially outward from the sun with velocity $\mathbf{V}_{SW}$ produces an interplanetary electric field $\mathbf{E}_{IEF} = -\mathbf{V}_{SW} \times \mathbf{B}_{IMF}$ where $\mathbf{B}_{IMF}$ is the interplanetary magnetic field (IMF) carried by the solar wind. For an IMF with a southward component, geomagnetic field lines in the polar cap region of the high latitude ionosphere are connected to the IMF and the electric field $\mathbf{E}_{IEF}$ in the magnetosphere due to the solar wind dynamo is mapped down to the polar cap ionosphere as a dawn-to-dusk electric field. The possibility of penetration of the IEF to the equatorial ionosphere was first demonstrated when it was found that fluctuations in the geomagnetic field measured at an equatorial location and at a polar station were both well correlated with changes in the angle the IMF made with respect to the ecliptic (Nishida, 1968). Later, radar data also showed the effect of penetration of magnetospheric electric fields to the equatorial ionosphere (Somayajulu et al., 1987).

A mechanism was proposed by Kikuchi et al. (1978) and Kikuchi and Araki (1979) for the instantaneous transmission of the polar electric field to the equatorial ionosphere by means of the Earth-ionosphere waveguide, which would allow prompt penetration of the IEF to the equatorial ionosphere before shielding was established. The enhanced magnetospheric convection causes the plasma sheet plasma to move earthward thus producing a partial ring current and the region-2 field-aligned currents, and shielding electric fields are built up, which shield the inner magnetosphere and low-and mid-latitude ionosphere from penetration of the dawn-to-dusk magnetospheric convection electric field (Jaggi and Wolf, 1973, Wolf et al., 2007). After the shielding electric field is established, an abrupt turning of the IMF from southward to northward leads to a sudden decrease in the magnetospheric convection electric field, and the shielding electric field now, results in over-shielding which produces in the low-latitude ionosphere, an eastward electric field on the nightside and a westward electric field on the dayside (Kelley et al., 1979). This is the currently accepted general scenario for prompt penetration of magnetospheric electric fields into the equatorial / low latitude ionosphere, although the detailed mechanisms and the time scale for shielding to set in are yet to be firmly established.

An important consequence of the modification of the post-sunset equatorial ionospheric electric field is the effect on the development of equatorial plasma bubbles (EPBs) and associated irregularities, which have an impact on satellite-based communication and navigation systems. Magnetic activity sometimes creates conditions for the development of EPBs in the nighttime equatorial ionosphere at local times when EPBs are not freshly generated during quiet times (Kakad et al., 2007). This is due to the appearance of promptly penetrated (PP) and/or DD electric fields which result in an eastward electric field in the nighttime equatorial ionosphere when during quiet times there would be a westward electric field (Chakrabarty et al., 2006). Magnetometer, ionosonde, and scintillation observations in the Indian region during magnetically disturbed periods have been used to demonstrate the changes that take place in the equatorial ionosphere caused by PP and DD electric fields, and their effects on the generation of EPBs, which give rise to ionospheric scintillations.

2. PP and DD electric fields in the equatorial ionosphere

In recent times, there has been a great deal of debate about two issues related to the PP and DD electric fields based on several studies of different types of data and modeling results. First of these is the efficiency and duration of prompt penetration of magnetospheric electric fields into the equatorial ionosphere. The second issue is the interplay between PP and DD electric fields. Magnetometer data have been used in several studies of the modification of equatorial ionospheric electric fields during daytime, as also coherent scatter radar data for 150 km echoes where available. For nighttime changes in the equatorial ionospheric electric field, ionospheric drifts derived from incoherent scatter radar measurements have been used, and in the absence of such observations, ionosonde data and spaced receiver recording of ionospheric scintillations when present, also provide some relevant although indirect information.

Ground-based observations related to the geomagnetic disturbances that occurred during July 24 - 26, 2004, provide an example of the complex response of the equatorial ionosphere to magnetospheric forcing. Solar wind and IMF parameters measured by the ACE satellite for this period are shown in the top five plots in Figure 1. These plots have been shifted in time to take into account the time taken for solar wind propagation from the satellite to the nominal location of the magnetopause. The variations, ΔH, in the horizontal component of the geomagnetic field at Tirunelveli (TIR) (8.7°N, 77.8°E, geomag. lat. 0.4°S) and Alibag (ABG) (18.6°N, 72.9°E, geomag. lat. 9.7°N), after removal of the nighttime value, are shown in the lowest plot as a function of 75°E local time. The difference ΔH(TIR) - ΔH(ABG) shown in the second lowest plot represents the magnetic field produced by the equatorial electrojet (EEJ) during daytime. The magnetic disturbances shown in Fig. 1 were preceded by a moderate magnetic storm with SYM-H remaining near - 100nT from 0 to 8 UT on July 23, 2004. There was a sudden commencement shortly after SYM-H returned to near quiet-time values at about 06 UT on July 24, which was followed by another decrease in SYM-H. When the IMF turned southward around 22 UT on July 24, there appeared a 'counter-electrojet' as seen in Fig. 1, showing the presence of a westward electric field in the equatorial ionosphere. This could be due to the prompt penetration of a dawn-to-dusk magnetospheric electric field into the ionosphere over

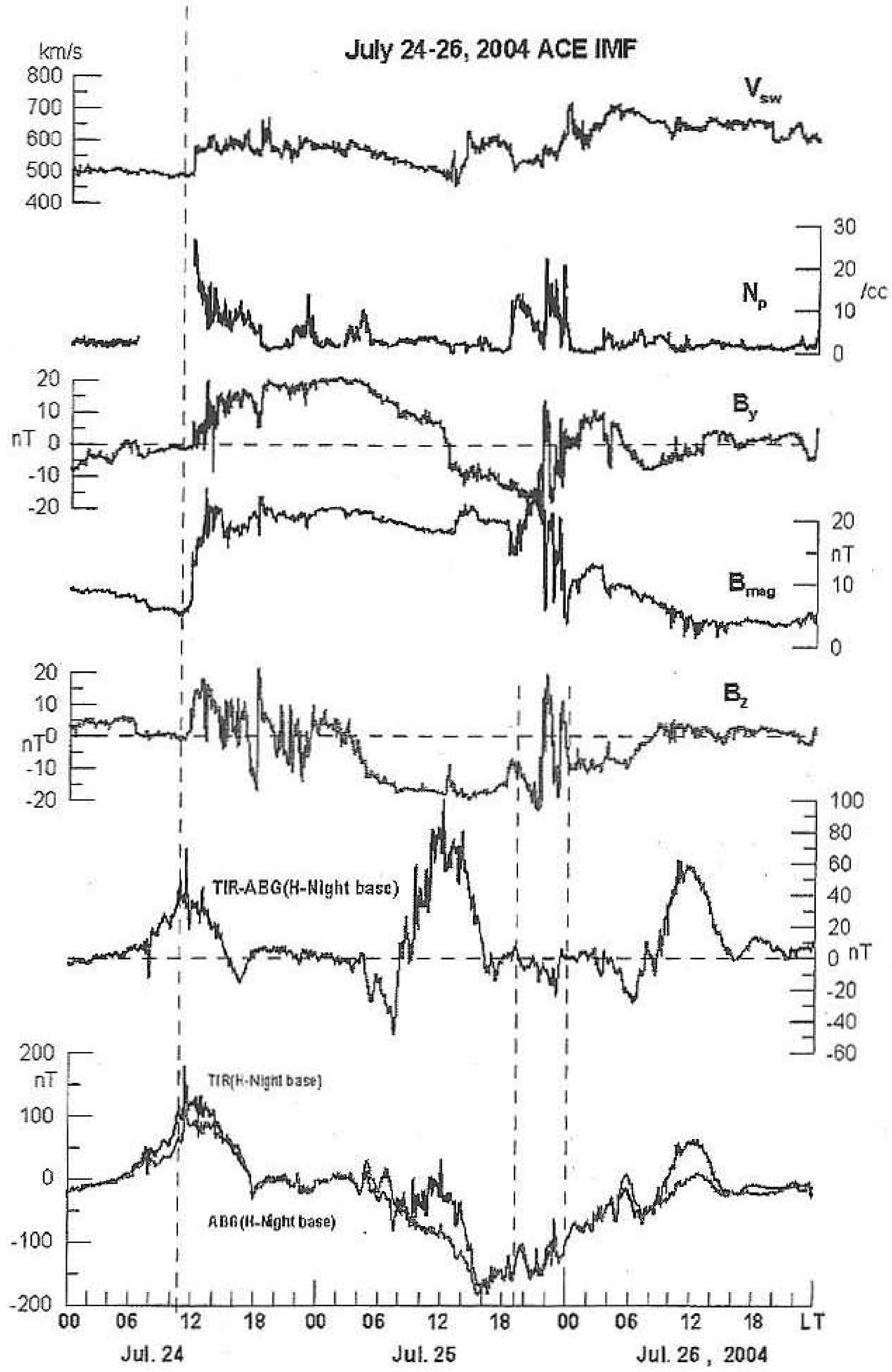

Fig. 1. *Time-shifted solar wind and IMF parameters during July 24-26, 2004, and the variations in the H-component of the geomagnetic field recorded at Tirunelveli and Alibag during the same period.*

Tirunelveli, in the pre-dawn to early morning hours. However as Tirunelveli entered the dayside, penetration of the dawn-to-dusk magnetospheric electric field to the dayside equatorial ionosphere resulted in an enhanced eastward electric field and hence stronger EEJ current, which decreased rapidly as the shielding electric field was built up at 7 UT on July 25. This could be a case of prompt penetration of the magnetospheric convection electric field into the equatorial ionosphere over a period of nearly 8 hours. To explore the possible role of DD effects resulting from earlier magnetic disturbance, ionosonde observations in this longitude sector during the period of July 24-25, 2004 is used.

During nighttime, ionosonde data from Trivandrum (8.5°N, 77.0°E, geomag. lat 0.3°S) provide information about h'F, the virtual height of the F-region, and hence indirectly about the prevailing zonal electric field. This data for the night of July 24-25, 2004 shows that a disturbance dynamo may have been set up by earlier magnetic activity, which resulted in the development of an eastward electric field in the equatorial F-region over Trivandrum starting at about 23 hrs LT (75°E) (18 UT) that raised the F layer to a much greater height compared to the average of the 5 quietest days in July 2004, as shown in Figure 2. As a result of this increase in height, an EPB grew at around midnight (75°E LT) as seen in Figure 3, where LT variation of parameters derived from scintillations produced by this bubble, on a 251 MHz signal transmitted from a geostationary satellite, and recorded by two spaced receivers at Tirunelveli, are shown. The two receivers are located along a magnetic east-west baseline, with a separation X_o = 540m. The top panel is a plot of the S_4 index, which is the standard deviation of normalized signal intensity. The middle panel is the maximum cross correlation C_I (X_o, t_m) between the signals recorded by the two receivers, which is expected to be low (< 0.5) only in the initial stage of EPB development (Bhattacharyya et al., 2001, Kakad et al., 2007). This panel shows that the moderate VHF scintillations observed around midnight are indeed due to a new EPB that came into existence because of the increase in the height of the equatorial F-region, which started about one hour before midnight, in response to an eastward electric field created by DD. Shortly after 03 hrs LT (75°E), when the IMF turned southward, there was a sharp decline in the height of the F region, and the combined effect of PP and DD electric fields rapidly brought down the equatorial ionosphere to the quiet time level by 06 LT. Maruyama et al. (2005) modeled the interaction between PP and DD electric fields in the storm-time equatorial ionosphere to find that during

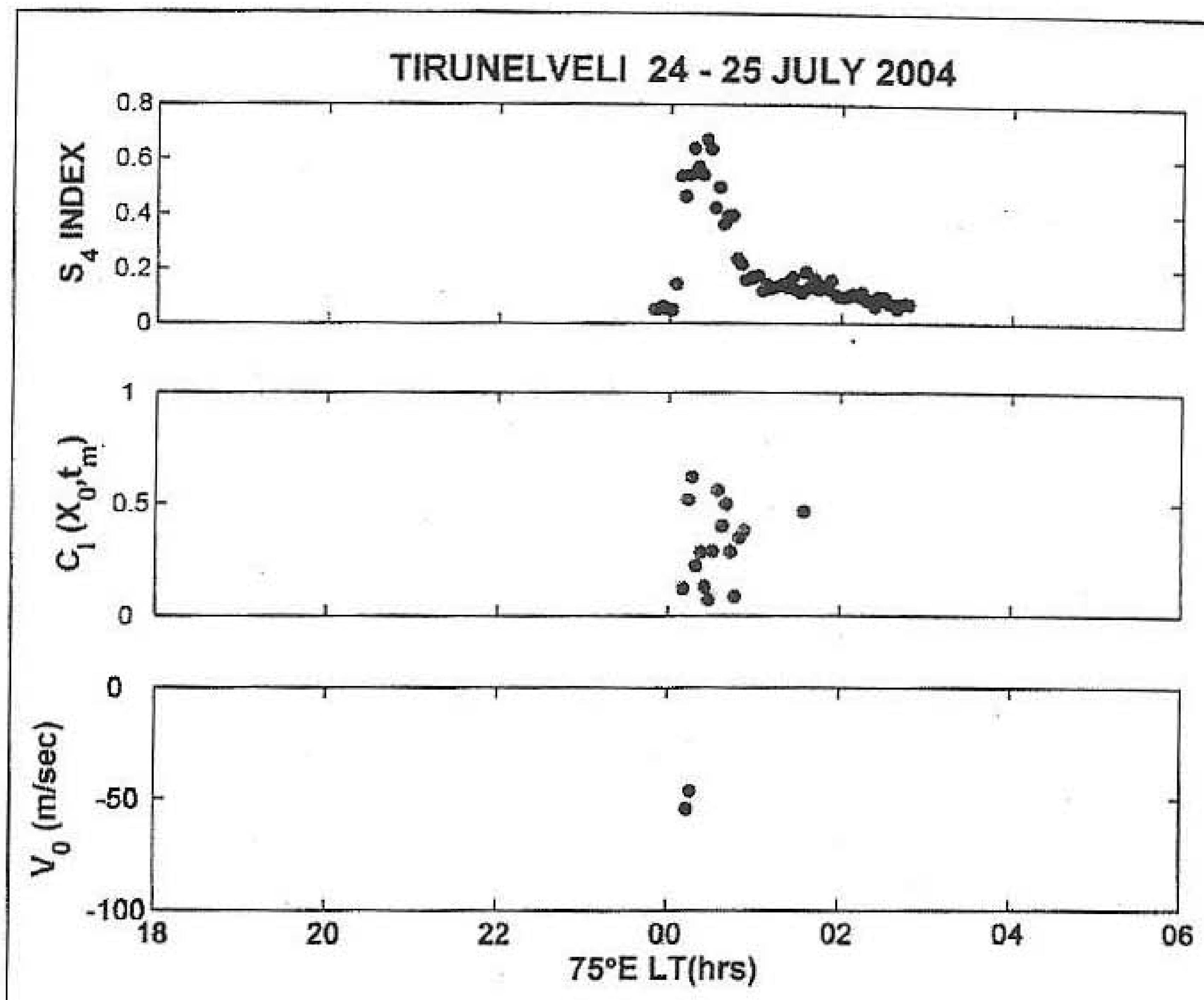

Fig. 3. *Parameters derived from scintillations on a 251 MHz signal recorded by two spaced receivers at Tirunelveli. Scintillations recorded just after local midnight were caused by a nascent equatorial plasma bubble.*

daytime and in early part of the main phase of the storm, the PP electric field dominates, while at night the PP and DD electric fields are comparable and the net result of their interaction differs substantially from simply an addition of the two effects. During daytime, the observed enhancement of the EEJ could therefore be due to PP eastward electric field, which declined rapidly when shielding became effective.

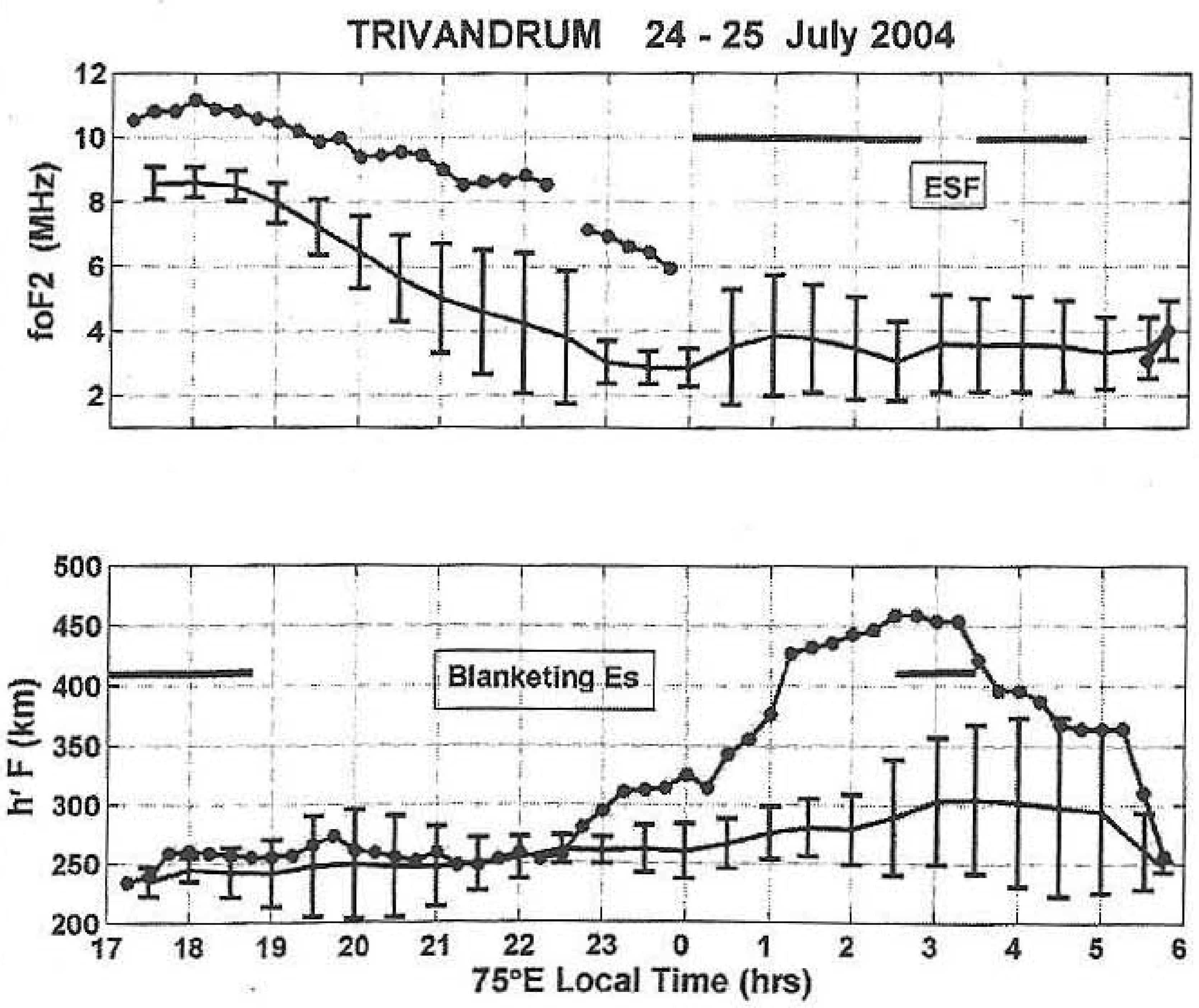

Fig. 2. *Local time variation of ionospheric parameters fOF2 and h'F estimated from Trivandrum ionosonde data for 24-25 July, 2004, and also of the averages of these parameters for the five quietest days of July 2004 along with the standard deviations.*

In order to make a quantitative comparison of the penetrated electric field (PEF) E_y with the ionospheric E_y, Huang et al. (2007) derived an empirical formula from a least squares fit of the increases of ionspheric E_y over Jicamarca during daytime with the increase of IEF dawn-to-dusk component (E_y), using a large data base of Doppler shifts of 150 km echoes, which were observed with the Jicamarca radar operating in a coherent scatter mode during the period 2001-2005. They found this formula to provide very good agreement between the predicted and observed values in some cases. One such case is a short-lived (~ 1 hr) prompt penetration event on July 25, 2004, when the eastward electric field in the dayside equatorial ionosphere over Jicamarca showed a sharp increase between 17 and 18 UT, as the IEF E_y increased, shown in Fig. 3 of Huang et al. (2007).

For the same period, h'F and vertical drift V_z obtained from Trivandrum ionograms is shown in Figure 4. The estimated V_z is meaningful only when the F layer is sufficiently high, above 300 km according to Bittencourt and Abdu (1981). Hence only the V_z values between 23 LT and 0130 LT may be considered. There is indication of the prompt penetration of an eastward electric field around 18 UT in response to northward turning of the

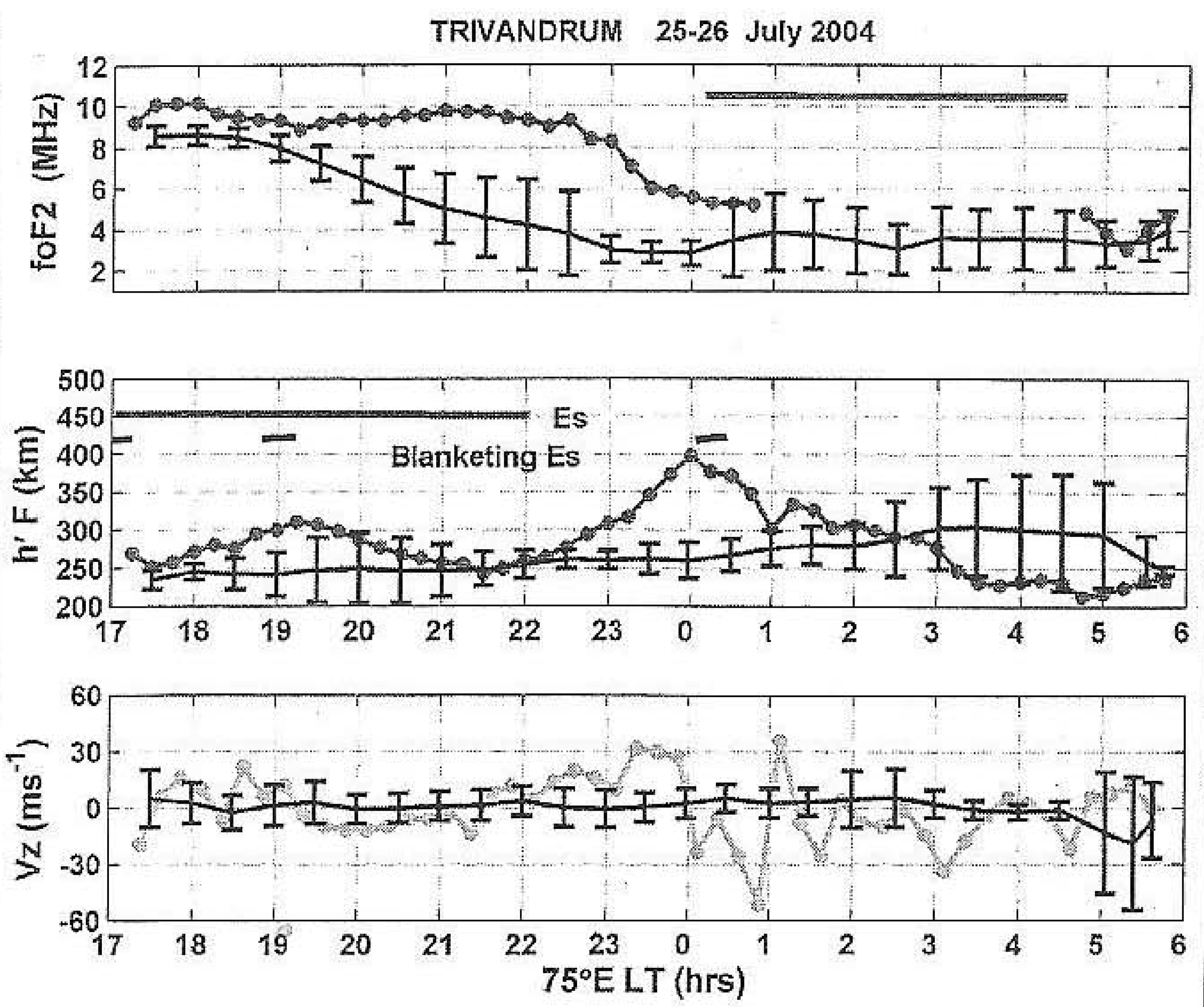

Fig. 4. *Local time variation of ionospheric parameters fOF2 and h'F estimated from Trivandrum ionosonde data for 25-26 July, 2004, averages of these parameters for the five quietest days of July 2004 and the corresponding standard deviations are shown in the top two panels. Vertical drift estimated from the time derivative of h'F is shown in the bottom panel. This estimate may be reasonable only when the F layer is above 300 km.*

IMF at that time, but the observations for the whole period are quite different from those reported for April 17, 2002, when the vertical movements of the ionospheric F region estimated from ionosonde observations at Trivandrum and incoherent scatter radar observations at Jicamarca showed a pattern of variation that would result from PP zonal electric fields in the night- and day-time equatorial ionosphere respectively, in response to variations in the IEF E_y for more than 6 hours (Kelley et al., 2007). It is possible that the DD effects were not substantial for this day since April 16, 2002 was a quiet day (all $K_p < 3$) and magnetic activity on April 17 started after 9 UT.

3. Summary

In recent years, magnetometer data has been used to estimate daytime vertical **EXB** drift in the equatorial ionospheric F region, since eastward electric fields in the daytime equatorial ionosphere drive the equatorial electrojet as well as vertical motion of the F region plasma (Anderson et al., 2002). Using this technique magnetometer data obtained during disturbed periods have been used to determine the spectral properties of daytime low latitude electric fields and to estimate an average transfer function which relates the daytime low latitude eastward electric fields with simultaneous IEF E_y values during disturbed periods (Nicolls et al., 2007). As mentioned above, an empirical formula to relate the increase in eastward component of the daytime equatorial ionospheric electric field with the increase in dawn-to-dusk component of the IEF has also been derived (Huang et al., 2007). However, using JULIA and Jicamarca incoherent scatter radar data, ground-based magnetometer data from the Pacific sector, and ionosonde data from Brazil in a study of the November 2004 geomagnetic storm, Fejer et al.(2007) have shown that the relationship of PP equatorial electric fields and solar wind electric fields could not always be reduced to a simple multiplicative factor. During nighttime, when DD effects become more prominent, if prompt penetration occurs while DD effects are also present, the resultant electric field in the equatorial ionosphere is significantly different from a simple addition of the two effects because of the altered low- and mid-latitude conductivity and neutral wind (Maruyama et al., 2005). This is evident in the statistics of EPBs generated specifically due to magnetic activity, which also indicates a seasonal dependence (Kakad et al., 2007). This aspect of seasonal differences in the appearance of an eastward electric field in the nighttime equatorial ionosphere due to magnetospheric forcing needs further investigation.

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