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Variability of total electron content near the crest of the equatorial anomaly during moderate geomagnetic storms

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ABSTRACT

The ionospheric responses to a large number (116) of moderate ($-50 \geq D_{st} > -100$ nT) geomagnetic storms distributed over the period (1980–1990) are investigated using total electron content (TEC) data recorded at Calcutta (88.38°E, 22.58°N geographic, dip: 32°N). TEC perturbations exhibit a prominent dependence on the local times of main phase occurrence (MPO). The storms with MPO during daytime hours are more effective in producing larger deviations and smaller time delays for maximum positive deviations compared to those with nighttime MPO. Though the perturbations in the equinoctial and winter solstitial months more or less follow the reported climatology, remarkable deviations are detected for the summer solstitial storms. Depending on the local times of MPO, the sunrise enhancement in TEC is greatly perturbed. The TEC variability patterns are interpreted in terms of the storm time modifications of equatorial electric field, wind system and neutral composition.

1. Introduction

Investigation of the variability of the ionospheric responses to geomagnetic disturbances is an important space weather issue in the context of the maintenance of fail-safe trans-ionospheric communication/navigation link between the earth and the satellites. Though the study may be made using various measurable *F*-layer characteristics such as f_oF_2, $h'F$, h_pF_2, N_mF_2, etc.—the parameter that has received much attention is the total electron content (TEC) which is important for time delay/scintillation of VHF/microwave ground-to-satellite navigation signals. TEC measurement can provide significant insights to ionospheric physics on both global scale and local scale. An unpredictable variation of TEC during geomagnetic disturbances necessitates more case studies as well as morphological studies for the development of an accurate model and improved forecasting capability. Ionospheric storm effects on TEC or any *F*-layer parameters are actually dependent on the time and intensity of magnetic storms (Titheridge and Buonsanto, 1988) as well as on the latitude of observing station—and its location in the summer or winter hemisphere (Essex et al., 1981; Tsurutani et al., 2004; Mannucci et al., 2005).

Geomagnetic storms are characterized by enhanced particle fluxes in the radiation belt. The enhanced fluxes can be indirectly measured by the decrease in the earth's magnetic field horizontal component caused by the diamagnetic effect generated by the ring current. Depending on the duration of storms reduction in the magnetic field may be global in nature. D_{st} index is a proxy for the magnetic ring current and it is a good quantitative measure of the intensity of the geomagnetic storms. On the basis of minimum values of D_{st} storms are categorized into intense ($D_{st} \leq -100$ nT), moderate ($-50 \geq D_{st} > -100$ nT) and weak ($-30 \geq D_{st} > -50$ nT) classes (Sugiura and Chapman, 1960).

During geomagnetic disturbances TEC has been reported to vary drastically at all latitudes (Mendillo et al., 1972; Titheridge and Buonsanto, 1988; Balan and Rao, 1990; Jakowski et al., 1999; Zhao et al., 2007). In general, enhancements (positive effects) and decreases (negative effects) in TEC during geomagnetic disturbances are prevalent in the equatorial low latitude region. In the northern hemisphere the more frequent negative effects in summer, positive in winter and neutralized effects in equinox are the reported features of TEC variability (Huang et al., 1974; Balan and Rao, 1990; Zhao et al., 2007). The perturbation of electric field plays a dominant role in the storm time modification of equatorial ionosphere. The disturbance thermospheric wind and neutral composition changes also affect the storm time variability. Though a large number of case studies on the variabilities of *F*-layer parameters are now available—these are mostly based on strong or severe magnetic storms. The morphological studies involving a large number of storm events are very few (Mendillo, 1971; Mendillo and Klobuchar, 1975, 2006; Balan and Rao, 1990; Kumar et al., 2005; Zhao et al., 2007; Wang et al., 2008) and are mostly focused on mid-latitude region. Moreover, the previous studies involve cases of both moderate and intense geomagnetic storms. The studies related to magnetic storms of moderate intensities alone are still lacking though TEC

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variability during these events near the equatorial ionization anomaly (EIA) crest region may introduce meters of errors in the measurement of position at GPS frequencies. Globally largest ionization is observed around the crest of the EIA zone. For the same percentage variations of TEC in the low latitude zone largest deviations are observed around the EIA crest region and additional range errors are introduced during magnetic disturbances (Basu et al., 2005). The latitude structure of EIA is intricately modified by the electric field disturbances that may be sensed by TEC at locations inside the EIA belt (Batista et al., 1991; Astafyeva et al., 2007). The present observing station, Calcutta (geographic: longitude 88.38°E, latitude 22.58° N, dip: 32° N), is situated near the northern crest of the EIA. It presents an excellent platform for observing electrodynamical aspect of equatorial fountain, which is mainly controlled by the $\boldsymbol{E}\times\boldsymbol{B}$ vertical drift of plasma and subsequent diffusion along the magnetic field lines. The ambient ionization level around this location is sensitive to the electric field changes at the magnetic equator as well as to the thermospheric/neutral dynamics. Depending on the occurrence time and intensity of geomagnetic storms preferential modifications of the stated components may occur. It may result in significant changes in the diurnal TEC profile—morphological studies of which are essential for development of TEC models. In the present investigation an attempt has been made to develop a climatological picture of storm time TEC variability in the context of local times of main phase occurrence (MPO) considering a large number (116) of moderate intensity geomagnetic storms distributed over a long data period (1980–1990). The results of studies from a location near the crest of the EIA may form a useful database for the development of TEC model in the context of space weather scenario.

2. Data

Total electron content (TEC) data recorded at the Ionosphere Field Station, Haringhata (geographic: longitude 88.38°E, latitude 22.58° N, dip: 32° N), University of Calcutta, by the Faraday rotation technique of a VHF (136.11 MHz) trans-ionospheric signal from geostationary satellite ETS-2 have been analyzed for the present investigation. The 400 km subionospheric point was located at 21° N, 92.7°E (geographic), dip: 27° N.

For intensity of magnetic storms D_{st} values are considered as proxy index. Only moderate intensity magnetic storms ($-50\geq D_{st}>-100$ nT) are considered for the present investigation. Total number of storms studied is 116 distributed over the period (1980–1990). The events include both the sudden commencement (46%) and gradual commencement (54%) types. Though actual number of moderate storms is around 300 in the stated period, the number of events investigated is less due to: (i) non-availability of simultaneous TEC data owing to satellite eclipse period and other instrumental errors, (ii) the consecutive moderate storm events separated with a time gap of about one/two days are neglected as the effects of independent events are only considered and (iii) the storm events with isolated and pronounced substorm activities are not considered for the development of morphological pattern.

Case as well as statistical studies (Titheridge and Buonsanto, 1988, and references therein; Balan and Rao, 1990; Kutiev et al., 2005; Zhao et al., 2007) during storm events have revealed dependence of ionospheric responses to the local times of storm commencement. To study the temporal evolution of magnetic storm related variability in TEC, local times of MPO are suggested to be more appropriate (Thomas and Venables, 1966; Zhao et al., 2007). Accordingly the storm events have been categorized on the basis of onset times of main phase (MPO) marked by (in absence of proper database of IMF B_z) the initiation of a negative trend after enhancement from the normal diurnal variation of D_{st}. Altogether five classes are obtained. These are storms with MPO at the (i) early morning sector (0530–0730 h IST), (ii) prenoon sector (0830–1130 h IST), (iii) noon to afternoon sector (1230–1630 h IST), (iv) sunset to post-sunset sector (1730–2130 h IST) and (v) premidnight to postmidnight sector (2230–0430 h IST) (IST (h)=UT+0530 h). It may be mentioned that MPO time is determined from the diurnal plot of D_{st} index available at 1 h resolution—there should not be any MPO in between the consecutive time sectors. The number distribution of storm events with MPO at different local time sectors is shown in Fig. 1. The finer classification of storm events according to the occurrences of MPO at different local time sectors is motivated by the fact that diurnal TEC profile under quiet geomagnetic conditions is the resultant of several processes, relative contributions of which may be different at different local time sectors. Simultaneous superposition of several storm induced mechanisms – depending on strength, time delay, local time sector – may strengthen or inhibit the prevailing processes to affect the TEC variability pattern.

To relate the variability of TEC with the electrodynamics at the magnetic equator, $h'F/f_oF_2$ data of Kodaikanal (geographic: latitude 10.25°N, longitude 77.5°E, dip 4°N), an equatorial station, are used for the present study. Magnetometer horizontal intensity data of Trivandrum (geographic: latitude 8.29°N, longitude 76.57°E; dip: 1.2°S) and Alibag (geographic: latitude 18.63°N, longitude 72.87°E; dip: 23°N) obtained from Indian Institute of Geomagnetism, Mumbai are considered for equatorial electrojet (EEJ) index. Data of interplanetary magnetic field component IMF B_z are downloaded from the website of the NOAA's National Geophysical Data Centre, Boulder. The asymmetric ring current index (ASY-H) and auroral electrojet index (AE) data available with the website of the World Data Centre for Geomagnetism, Kyoto are also used.

3. Results

3.1. Seasonal and solar cycle distribution of moderate storms

Fig. 2 shows the contour plot of percentage occurrence of moderate geomagnetic storms for the entire period of observation

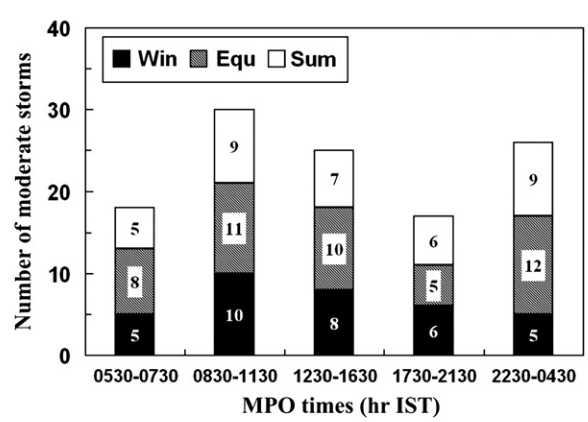

Fig. 1. Number distribution of studied moderate ($-50\geq D_{st}>-100$ nT) geomagnetic storms during the period (1980–1990). The storms are categorized on the basis of local times (IST=UT+0530 h) of main phase occurrence (MPO). The numbers within the histograms stand for the number of storms considered in the specific season at the stated MPO intervals. "Sum" indicates local summer months (May, June and July), "Equ" represents equinoctial months (February, March, April, August, September and October) and "Win" indicates local winter solstitial months (November, December and January).

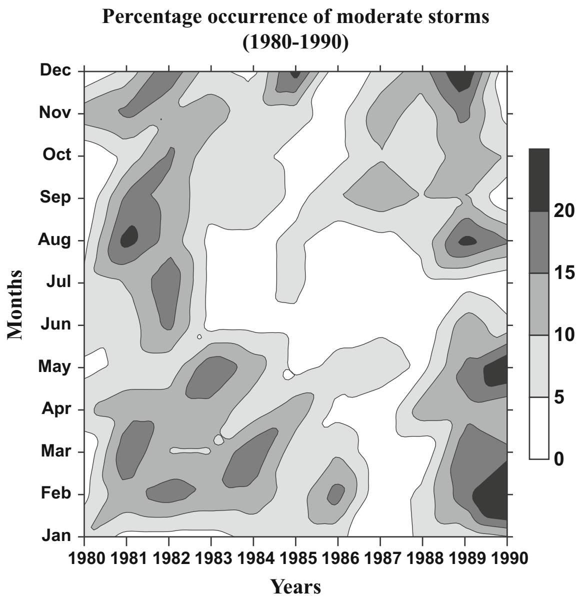

Fig. 2. Contour plot showing the percentage occurrence of moderate geomagnetic storms for the entire period of observation (1980–1990).

(1980–1990). A larger percentage occurrence during equinoxes compared to other seasons and an asymmetric nature between the two equinoxes – with vernal equinoctial months exhibiting larger occurrence compared to autumnal ones – are evident. The variation in the percentage occurrences between summer and equinox is about 5–20%, which is much smaller compared to that reported for intense storms (Gonzalez and Tsurutani, 1992; Clua de Gonzalez et al., 1993). No clear explanation of seasonal distribution of geomagnetic storms is yet available (Gonzalez et al., 1993; Taylor et al., 1996).

A solar epoch dependent feature of occurrence of the magnetic storm is also evident. The moderate and low solar activity years of the descending phase (1980–1985) are found to be more susceptible to trigger the moderate geomagnetic storms while the high solar activity years of the ascending epoch (1986–1990) exhibit higher percentage occurrence of the same. The solar activity distribution of geomagnetic storms is in good agreement with the earlier observations (Sugiura, 1980; Legrand and Simon, 1991; Ramesh, 1996). Just after the maximum and during the descending epoch of solar cycle, the solar sources of geomagnetic storms are reported to be shifted to "Geoeffective" low heliographic latitudes ($\sim\pm 20^\circ$) and the solar wind streams thus generated may be more effective in producing geomagnetic storms on the earth's environment (Ramesh, 1996).

Geomagnetic storms modify the earth's ionosphere in a complicated way the signatures of which may be reflected in the TEC variability pattern. Before studying the morphological features of ionospheric variability, a few case studies are made in the following subsections to demonstrate the TEC response pattern to geomagnetic storms around the present location.

3.2. *Case studies of some moderate storms*

3.2.1. *Storm during May 2–4, 1986*

The geomagnetic storm event on May 2, 1986 initiated with sudden commencement (SSC) at 0714 h IST (Fig. 3). The main phase of the storm primarily started, as indicated by abrupt decrease in D_{st}, around 0930 h IST. The maximum negative excursion in D_{st} of -79 nT occurred around postmidnight hours (0330 h IST) of the same day (May 2). The southward turning of IMF B_z occurred more than 2 h earlier than the time of storm onset. A southward directed IMF B_z is essential for coupling of solar wind energy into the magnetosphere and occurrence of geomagnetic storms (Gonzalez and Tsurutani, 1987).

The general features of TEC variability in the daytime period of May 2 is observed to be enhancement although most of the diurnal TEC values fall within the standard deviation of quiet days' mean. The prominent departures are, however, observed in the period 1800–0530 h IST. From about 1600 h IST on May 2 a sharp rise in AE index reaching the maximum value of >1300 nT around 1930 h IST is observed. In the main phase of storm and around local sunset hours (1918 h IST being the subionospheric sunset time) an abrupt increase in AE index is supposed to be a proxy of prompt penetration (PP) eastward electric field at the equatorial latitude (Fejer and Scherliess, 1995, 1997; Abdu et al., 2007) in the "undershielding" condition. The same period is also marked by a sharp increase in the variation of ASY-H. Sastri et al. (1997) reported a prompt upward perturbation of plasma drift at an equatorial station, Kodaikanal (geographic: latitude 10.25°N, longitude 77.5°E, dip 4°N), in the dusk sector in association with the asymmetric ring current development for which ASY-H is a proxy index. The changes in AE and ASY-H indices observed under present investigation support the idea of PP electric field in the specified local time sector. It may intensify the normally prevalent prereversal enhancement (PRE) of eastward electric field to lift the *F*-layer to higher altitudes via $\boldsymbol{E}\times\boldsymbol{B}$ drift. A sharp increase in h'F (Fig. 3a) at Kodaikanal around the period of increase in AE index may be the signature of the same. The resulting enhanced fountain leads to the resurgence of equatorial anomaly and consequent increase in TEC around the anomaly crest location. A high value of AE is found to persist throughout the night on May 2. The sustenance of high value is the signature of continuous energy deposition in the high latitude thermosphere–ionosphere system (Fejer and Scherliess, 1995) that modifies the global thermospheric circulation resulting strong electric field of disturbance dynamo (DD) origin. The said field is normally effective at the equatorial latitudes within a few hours – even less than 1 h (Huang, 2008) – of the increase in magnetic activity and persists for longer periods due to the neutral-air inertia (Blanc and Richmond, 1980). The polarity of electric field related to DD is westward during daytime and eastward at night. The TEC enhancement throughout the night may signify the dominance of DD related eastward electric over the normally prevalent nighttime S_q field of opposite polarity. The maximum enhancement excluding the day-to-day variability around the midnight period is observed to be more than 10 TEC units, which might lead to a range error of about 1.80 m at GPS L1 frequency (1.57542 GHz).

The severe effect on diurnal TEC is, however, observed on the second day (May 3) of storm commencement while on the third day (May 4), though a positive deviation is recorded, most of the diurnal TEC values fall within the day-to-day variability limit. On May 3 a remarkable negative phase persists throughout the day extending up to post-sunset period with a maximum deviation of 30 TEC units. An inspection of AE index profile indicates sustenance of high values (>800 nT) up to 1030 h IST on May 3. The persistence of high values of AE imply, as stated earlier, intense thermospheric wind/disturbance dynamo. The morphology of DD is such that it generates westward electric field during daytime. Depending upon its intensity compared to normally prevailing eastward S_q field, the fountain effect may be weakened or inhibited, which may lead to decreases in TEC values near the anomaly crest location. An indication of presence of westward electric field during daytime at the equatorial latitude may be obtained from diurnal variation of EEJ. The inset figure in panel (b) shows the diurnal variation of EEJ for the same day (May

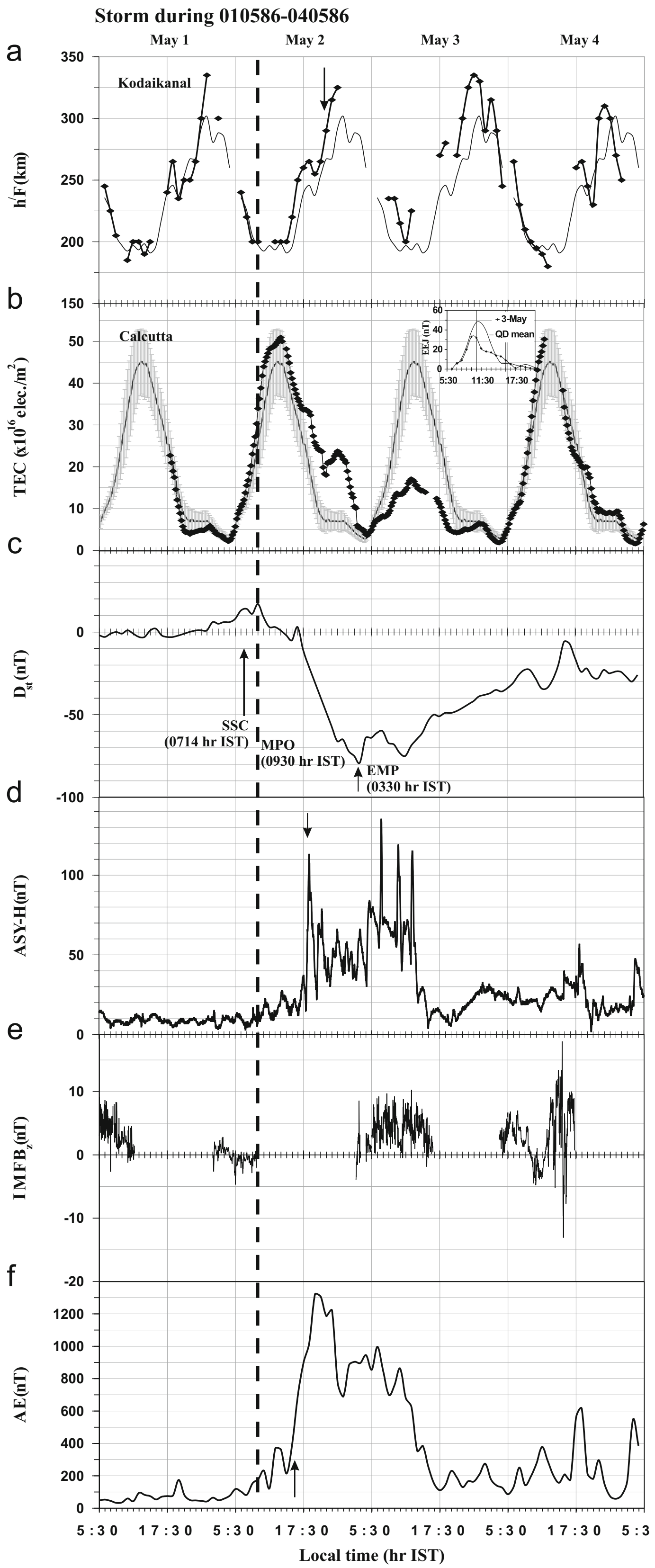

Fig. 3. Plots of the diurnal variations of: (a) $h'F$ recorded at Kodaikanal (geographic: latitude 10.25°N, longitude 77.5°E, dip 4°N), (b) TEC at Calcutta (geographic: longitude 88.38°E, latitude 22.58°N, dip: 32°N), (c) D_{st}, (d) ASY-H, (e) IMF B_z and (f) AE for the days 010586–040586. The vertical dotted line indicates the time of MPO while the vertical arrow in panel (c) indicates the time of sudden storm commencement (SSC). In panels (a) and (b) the daily values (bold line with boxes) along with quiet days' mean (thin line) are shown. In panel (b) the vertical bars pertain to the standard deviations of quiet days' mean of TEC. Inset figure in panel (b) shows the diurnal variation of EEJ (bold line with boxes) for May 3, 1986 along with the quiet days' mean (QD mean). EMP in D_{st} plot indicates end of main phase. The corresponding local time is also shown in the figure.

3) along with the diurnal variation of quiet days' mean. The lower diurnal values of EEJ compared to quiet days' mean may signify the superposition of westward electric field on the prevailing eastward S_q field. Another possible cause of negative storm effect in the summer is the changes in neutral composition (Fuller-Rowell et al., 1996). The strong ambient equatorward wind during this season (Burge et al., 1973) aids the storm induced equatorward circulation carrying ''composition bulge'' enriched with molecular nitrogen (N_2) (or low [O]/[N_2]) to reach the lower latitude. It results in increased loss rate and consequent negative perturbation in the ambient level. The MSIS-E-90 model values reflect maximum decrease of 17% in the ratio of [O]/[N_2] values as compared with the quiet days' mean on May 3 during the daytime period. The model value of the decreasing ratio of [O]/[N_2], though small, may indicate that composition change is also an important driver to reflect negative storm effects.

3.2.2. Storm during September 10–12, 1987

The equinoctial storm on September 10, 1987 initiated with SSC at 1704 h IST (Fig. 4). Main phase started around 1730 h IST on September 10 and the recovery phase initiated in the postmidnight hour (around 0430 h IST) on September 10. The maximum negative excursion of D_{st} is -83 nT. The MPO is marked by sudden increase in AE index with simultaneous southward turning of IMF B_z. The signature of the intensification of asymmetric ring current is also reflected in the ASY-H plot. A positive TEC deviation from the quiet days' mean values is observed around 2030 h IST on September 10 and continues up to 0130 h IST. The maximum deviation (greater than quiet time day-to-day variability as dictated by standard deviation) of $\sim$8 TEC units is recorded around the midnight time sector (0030 h IST). The southward turning of IMF B_z facilitates coupling of solar wind energy to the earth's magnetosphere. The sharp increases in AE and ASY-H indices in association with southward turning of IMF B_z signify penetration of eastward electric field at post-sunset period (Fejer and Scherliess, 1995, 1997; Abdu et al., 2007) when presence of same polarity electric field of DD origin may also be feasible. The disturbed time field components may strengthen the PRE leading to resurgence of equatorial fountain effect. The measurement of $h'F$ at the equatorial station (Kodaikanal) is disturbed due to evolution of equatorial spread-F (ESF) for which height rise of the equatorial F-layer over a threshold value/high vertical drift velocity is essential (Farley et al., 1970). All these observations signify intensification of post-sunset PRE by the eastward directed PP and DD electric fields. It leads to a stronger height rise over the equator and subsequent redistribution of ionization increases TEC near the anomaly crest location.

A further intensification of AE index occurs around 0100 h IST with peak value ($\sim$1150 nT) around 0230 h IST on September 10 and southward IMF B_z continues for several hours. In this case no appreciable perturbation is detected in ambient ionization level. Possibly, the competitive effects of DD (eastward) and PP (westward) electric fields, if at all emerged, may lead to this null result. The recovery phase starts around 0430 h IST on September 10 and continues up to next 24 h. Although both positive and negative deviations are recorded in diurnal TEC profile during this interval (September 11), these are mostly within the quiet time day-to-day variability limit. An appreciable deviation in TEC around the local prenoon to afternoon period (1100–1400 h IST) is, however, detected during the recovery phase on September 12. The long-term component of DD electric field and increase in mean molecular mass (N_2) associated with residual composition bulge or wind variation may be taken as the probable causes for this long-term negative effect. Inspection of the diurnal variation of EEJ data on September 12 in relation to the quiet days' mean values (inset figure of panel (b)) reveals comparatively lower diurnal values for the day. It may signify the dominance of DD related westward electric field to perturb the equatorial fountain that is reflected in TEC measurement around the anomaly crest location.

3.2.3. Storm during November 2–5, 1985

The main phase of the winter solstitial storm (Fig. 5) started around 0630 h IST on November 2, 1985. D_{st} variation in the main phase occurs slowly and multi-step intensification of ring current characterizes the storm development. It is a low intensity (minimum $D_{st}=-52$ nT) moderate storm. In the diurnal variation of TEC on November 2 prominent effect is observed around the sunset to postmidnight time sector (1830–0200 h IST) with a mild enhancement around the morning hours (0730–0930 h IST). IMF B_z turns southward around 1745 h IST. An increase in the variation of AE index reaching a value greater than 850 nT is observed around the period of sunset (1830 h IST) of the same day. All these features may signify favorable condition for PP of high latitude electric field of eastward polarity to the equatorial latitude. This may strengthen the PRE to enhance the fountain mechanism leading to resurgence of anomaly. It is documented through enhancement in TEC with peak value around 2015 h IST at the anomaly crest location. It may be noted that there is another simultaneous increases in AE ($\sim$1000 nT), ASY-H and southward turning of IMF B_z around midnight hours (0030 h IST) on November 2. The situation is feasible for prompt penetration of westward electric field (Fejer and Scherliess, 1997; Abdu et al., 2007) and if the effect of DD (eastward electric field) exceeds that due to PP (westward electric field) the fountain effect may be strengthened. A decreasing trend in f_oF_2 at the equatorial station and secondary enhancement in TEC around the anomaly crest may signify the dominance of DD.

The recovery of AE simultaneously with sharp drop in ASY-H is noted around 0130 h IST on November 2 when IMF B_z fluctuates with negative values up to 0200 h IST. The drop of AE may be related to the penetration of eastward electric field to the equatorial latitudes (Sastri et al., 2002; Abdu et al., 2007). A sharp rise in $h'F$ at Kodaikanal (not shown in figure) during the stated time period is recorded. It may be the signature of in phase contributions of PP and DD related eastward electric fields. But in TEC no perceptible changes are detected. It may be noted that in spite of sharp increase in $h'F$ its ultimate value is recorded to be too low ($\sim$265 km) to expect a large eastward electric field that enhances the fountain effect.

The recovery phase starts around 0730 h IST on the next day (November 3). No prominent deviation is detected in diurnal TEC variation except mild increase around 0930 h IST to prenoon hours. The TEC deviations in the consecutive days mostly fall within the day-to-day variability ranges.

The above three case studies pertain to the storms in the summer, equinox and winter solstitial months, respectively. The similar type of study is made on the large number (116) of moderate geomagnetic storm events distributed over a long data period (1980–1990). Since no two ionospheric storms are quite the same, it is usual to combine a number of observations to an average pattern which would emphasize the essentials of the storm behavior as observed from a particular location. In fact many workers (Matsushita, 1959; Hargreaves and Bagenal, 1977; Mendillo, 2006) have emphasized the statistical studies on storm induced perturbations as there are some common elements to all ionospheric responses, revealed through observations on various

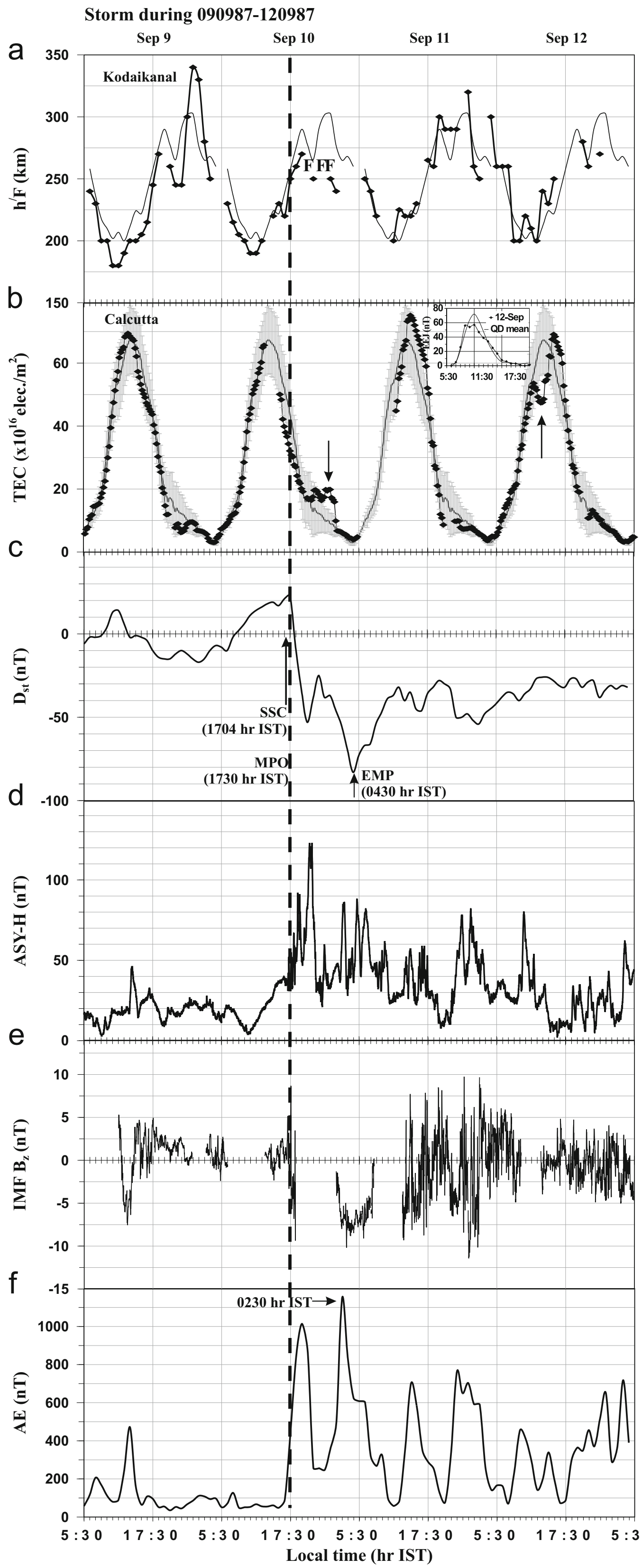

Fig. 4. Same as Fig. 3 for moderate storm occurring on September 10, 1987. In panel (a) "*F*" indicates presence of equatorial spread-*F* (ESF).

ionospheric parameters. In the statistical analysis only independent, not multiple, storm events are considered. The occurrences of storm events are not evenly distributed over all the local time sectors and seasons. Further all the storms are not of equal durations. Thus the statistical analysis does not pertain to equal number of data points in all specified local time sectors.

3.3. Analysis of storm time morphological variation in TEC for MPO at different local times

The storm time morphology of TEC variation may be discussed with reference to Fig. 6. It illustrates the mass plots of local time variation of the diurnal TEC deviations from the quiet days' mean during moderate geomagnetic storms occurring at different local time sectors along with an estimated average pattern of diurnal variation (bold line). The quiet days' mean level is estimated by considering about seven magnetically quiet days preceding and succeeding the disturbed days. TEC deviations exhibit remarkable dependences on the local times of MPO as well as on the seasons.

For storm events occurring in local winter months (November, December and January) and for MPO in early morning to prenoon hours (0530–0730 and 0830–1130 h IST) prominent enhancements with amplitudes varying in the range of 10–30 TEC units are observed. The daytime period is found to be more susceptible to exhibit storm induced TEC variations. For MPO in the noon to afternoon sector (1230–1630 h IST) a fluctuating response in the average pattern – more prominent with respect to both amplitude and duration in the later two time sectors of MPO – characterizes the storm time deviation pattern.

TEC variability pattern for local summer solstitial (May, June and July) storms with MPO around early morning period (0530–0730 h IST) is marked by prominent decreases ($\sim$40 TEC units) from quiet days' mean in the first 24 h interval. A reverse picture, i.e., positive deviations in majority of cases, is noted for storms with MPO during 0830–1130 h IST. Though a reduction in the enhancement amplitude is reflected for storms with MPO during 1230–1630 h IST, the positive storm effect dominates the average response pattern. The negative deviations of comparatively less amplitudes ($\sim$10 TEC units) followed by enhancements ($\sim$20 TEC units) characterize the same time interval for MPOs during 1730–2130 h IST and 2230–0430 h IST. In majority of the cases the daytime period is found to be more susceptible to exhibit positive deviations than the nighttime ones. The reported climatology of dominating negative storm effect in summer months (Huang et al., 1974; Balan and Rao, 1990; Zhao et al., 2007) is not consistent with the present investigation pertaining to moderate geomagnetic storm events.

The average response pattern in the initial state (within 6–7 h) of the equinoctial (February, March, April, August, September and October) storms with MPO in the daytime hours (0530–1630 h IST) is dominated by enhancements in the range of 10–40 TEC units. The following 12 h interval is largely populated by negative effects. The reverse features are reflected for storms with MPO around sunset to nighttime hours (1730–0430 h IST). In general, the mass as well as average plots of diurnal TEC perturbations for MPO at different local time sectors exhibit oscillation between positive and negative effects with variable amplitude and duration. The daytime period for all the sectors of MPO is mainly populated by positive deviations while the negative deviations are noted to be much susceptible to the dusk sector.

The percentage occurrence of maximum response features during daytime hours and in the main phase of the storms for different local time sectors of MPO is presented in Table 1. When all the storm events are considered the maximum TEC deviations are noted during the daytime period for about 80% cases of all the storm events studied. If the maximum TEC deviations are considered in the context of their occurrences in main or recovery phases, it is found that in 57% cases they occur in the main phase of the storms. The sector-wise analysis reveals that (Table 1) for storms with MPO during sunset to premidnight hours the maximum TEC deviations preferentially occur in the recovery phase.

A statistical analysis is made on the time delays of maximum responses estimated from the initiation times of main phase (MPO). Fig. 7 shows the distribution of time delays of maximum positive and negative responses against the local times of corresponding MPOs. For storms with MPO during daytime period (0530–1630 h IST) the

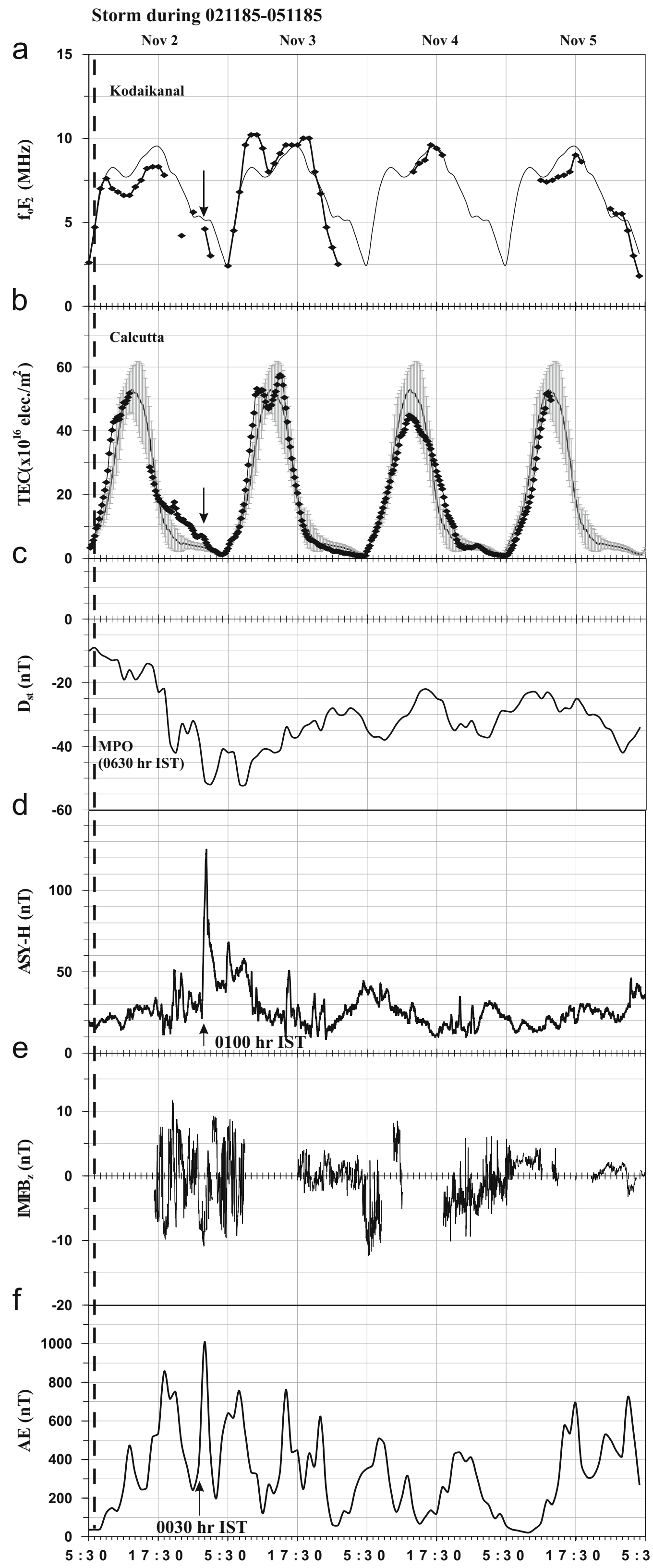

Fig. 5. Same as Fig. 3 for moderate storm occurring on November 2, 1985, except that diurnal plot of $h'F$ in panel (a) is replaced by that of f_oF_2.

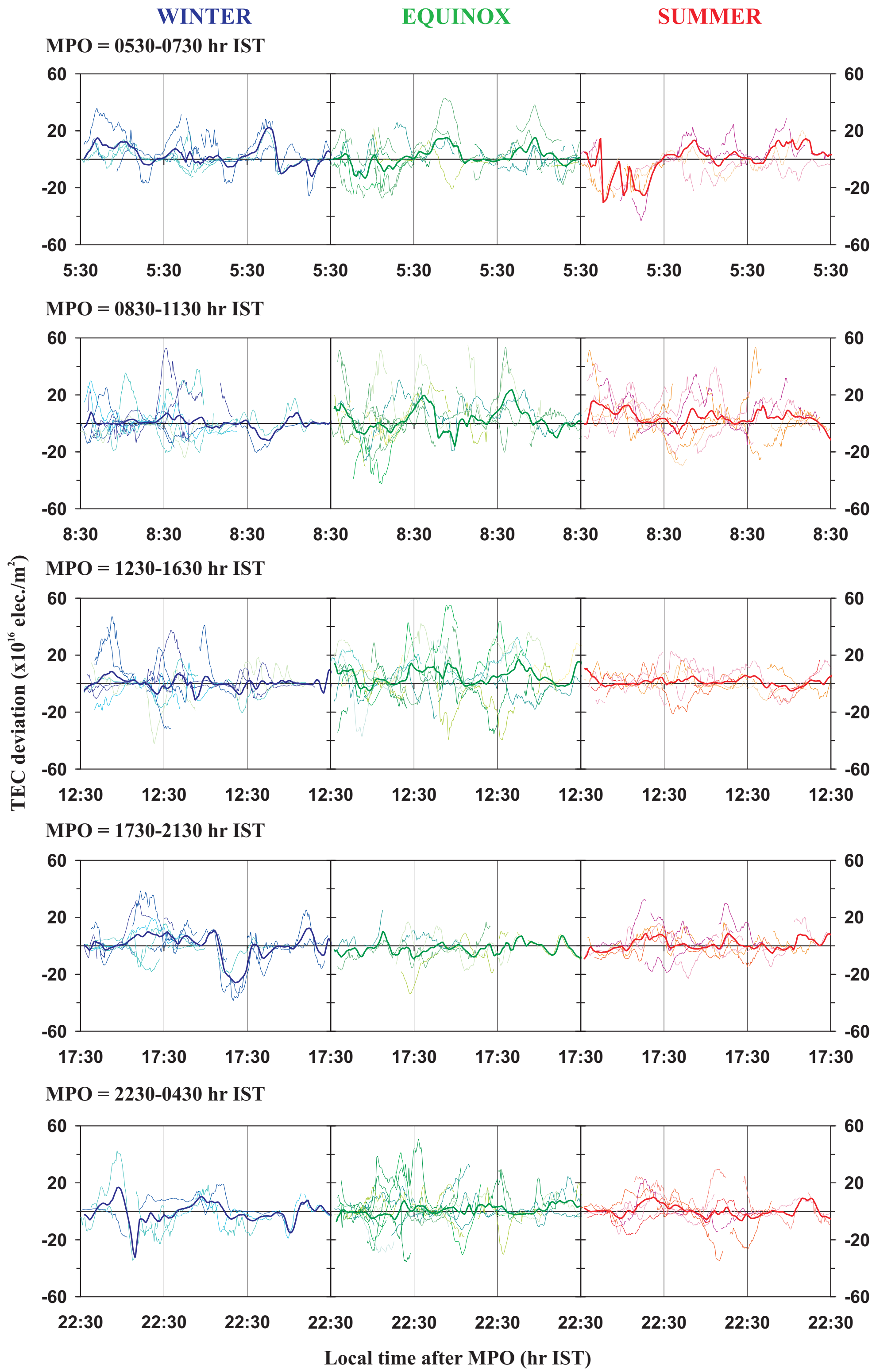

Fig. 6. Mass plots of TEC deviations from quiet days' mean values along with average deviations (bold thick lines) for different seasons at specific local time (hour IST) sectors of MPO as mentioned. Initial time of each plot indicates the corresponding initiation time of MPO.

maximum positive responses in about 70% cases occur within 7 h of MPO while negative responses are mostly (74% cases) distributed beyond that interval. The result is found to be statistically significant. For storms with nighttime MPO longer time delays (greater than 7 h) are reflected for positive responses compared to the negative ones.

The standard deviation of the quiet days' mean value may be approximated as a measure of day-to-day variability. On magnetically disturbed days TEC deviations in excess of day-to-day variability may be quantized as ΔTEC_{dev}=diurnal TEC–(quiet days' mean$\pm$standard deviation). When storm effects are analyzed in terms of ΔTEC_{dev}, average response patterns stated above are found to be modified with respect to duration and amplitudes of deviations but the morphology remains more or less the same.

Table 1
Percentage occurrences of maximum TEC deviations for different local time sectors of MPO.

Local tome sectors of MPO (hour IST)	Occurrences of maximum TEC deviations (%) during	
	Daytime hours	Main phase
0530–0730	90	70
0830–1130	90	70
1230–1630	67	56
1730–2130	75	25
2230–0430	75	58

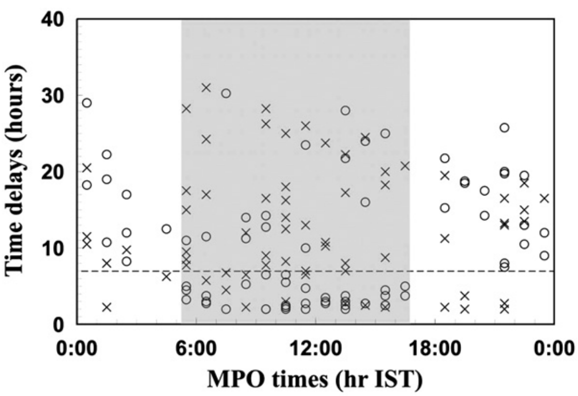

Fig. 7. Time delays of maximum positive (indicated by circles) and negative deviations (indicated by crosses) in TEC as estimated from the initiation times of main phase (MPO) against the local times of corresponding MPO. The dashed horizontal line corresponds to time delay of 7 h. The shaded region pertains to storm events with daytime MPOs.

One important feature of magnetic storm induced ionospheric responses is the perturbation in the TEC profile around the local dawn to early morning hours (0400–0745 h IST). The period is pertinent to observe the sunrise effect in the diurnal TEC profile. The two time sectors namely the periods around sunrise and sunset are most susceptible to reflect changes in ionospheric conductivity, dictated by the ionization density. The time sectors are very important in the context of studying ionospheric variability. Simultaneous superposition of magnetic disturbance effects may strongly modulate the sunrise variability pattern. It is interesting to study how the local time of MPO affects the sunrise pattern in TEC. The recent observation (Zhao et al., 2007) using global GPS data reported a cent percent sunrise enhancement (SE) from 27 days' median values around the equatorial latitudes for 200 storms of moderate and severe intensities. Observations from present location, however, reflect some deviations from the reported results. Instead of cent percent enhancement during the stated period a changeover from positive to negative deviations and vice versa from the quiet day pattern are reflected in the present analysis. Fig. 8 shows three sample cases of TEC response patterns in the stated period (shown by shaded region). Out of total events studied 51% cases exhibit flip-over from negative to positive deviations (SE), i.e., prominent enhancement from the mean (Fig. 8a), while a reverse picture, i.e., changeover from positive to negative deviations is noted in 31% cases (Fig. 8b). The positive phases in the former case and the negative phases in the latter case may be assumed to emerge in the sunrise period. For rest of the cases presunrise status, either positive or negative, is maintained (Fig. 8c). The distribution of median values of initiation times of SE (Fig. 9) exhibits the earliest SE for the storms with MPO in the early morning hours and the corresponding time is delayed as MPO shifts from morning to noon time hours. The longest delay is recorded for storms with

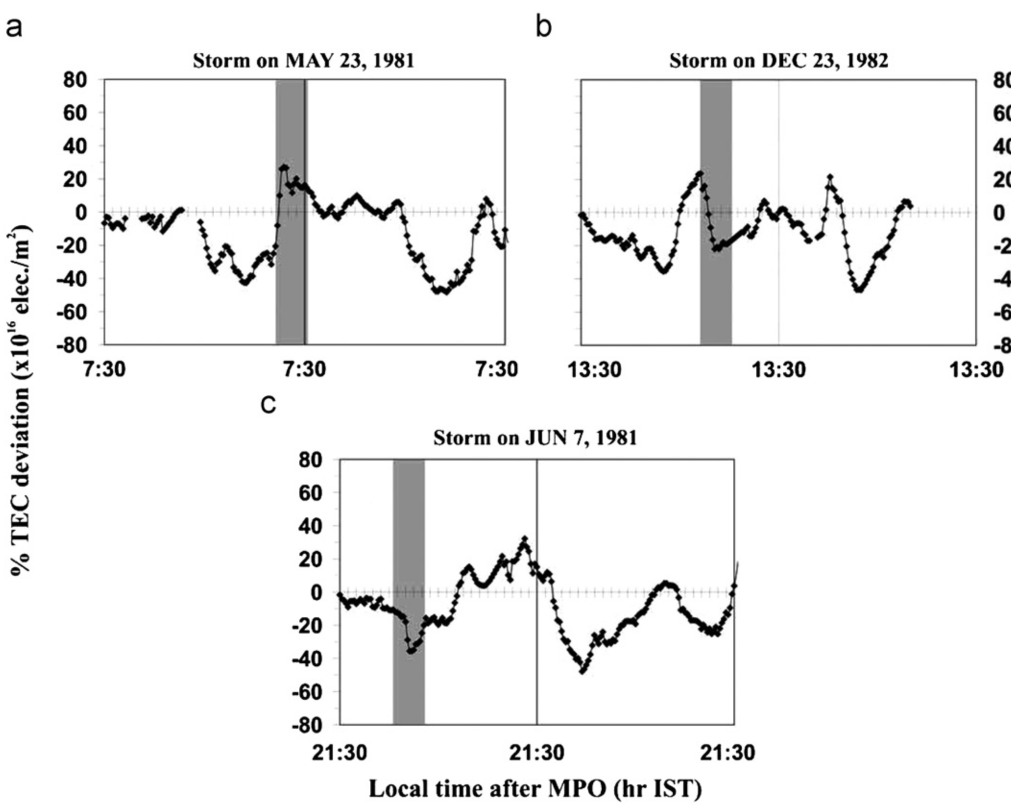

Fig. 8. Diurnal variations of percentage deviations in TEC from the quiet days' mean values after the onset of main phases of the specified storm events. The shaded region in each plot indicates TEC deviation status at the early morning period (0400–0745 h IST). In plot (a) TEC deviation changes from negative to positive values, in plot (b) it changes from positive to negative values while in plot (c) presunrise deviation status persists in the stated interval.

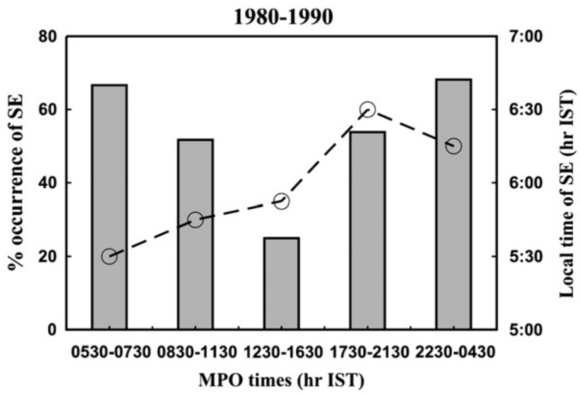

Fig. 9. Distribution (histograms) of percentage occurrence of sunrise enhancement (SE) in TEC for different local time sectors of MPO. The median values of initiation times of SE in each case are also shown by circles connected by dashed lines.

MPO around sunset hours. A somewhat reverse picture of dependence of SE time on MPO – with low latitude SE first for MPO in sunset hours, later for MPOs during noon and early morning and last for midnight events – was reported by Zhao et al. (2007).

An investigation of TEC data pertaining to the individual time sectors of MPO reveals the highest percentage occurrence (68%) of SE for storms with MPO during premidnight to postmidnight hours (2230–0430 h IST) while the lowest (25%) occurrence probability is recorded for MPOs in the noon to afternoon time sector (1230–1630 h IST) (Fig. 9). It may be noted that in the former cases the sunrise period mostly falls within about 4 h of MPO, i.e., well inside the main phase of the storm, and for the later cases it occurs during the end of main phase or at the initial part of recovery phase. The probability of SE is observed to decrease as the sunrise period approaches the end of main phase. The reverse feature is, however, reflected as the said time approaches the end of recovery phase.

The regular increase in TEC around the sunrise period during geomagnetically quiet days is mainly attributed to the solar flux effect (Garriott and Smith, 1965; Iyer and Rastogi, 1978). During the period of magnetic disturbances the sunrise enhancement or depression with respect to the quite time mean values may be the manifestations of storm time variations in electric field, neutral wind and composition changes. The storm time disturbance wind is reported to drive upward equatorial plasma drifts (i.e., eastward equatorial electric field) during the night with largest amplitudes in the 0200–0500 LT sector having time delays of about 2–4 h between the high latitude current enhancements and the equatorial perturbations (Fejer and Scherliess, 1995). The short-term DD related variability may accentuate the prevailing sunrise effect to reflect higher percentage occurrence of SE for MPO in the premidnight to postmidnight sector.

During the end of main phase appreciably large upward plasma drift was suggested (Fejer and Scherliess, 1995, 1997) in the postmidnight to sunrise sector due to equatorial DD electric field. Also a larger upward drift is expected during the same local time sector in course of initial part of recovery phase which may be attributed to the combined effects of PP and DD electric field components. Though the sunrise periods for the storms with MPO around 1230–1630 h IST are mostly distributed around the stated phases of the storm, the result of present analysis, showing least probability of SE, is found not to comply with the electric field model.

The initial storm time perturbations of the equatorial *F*-region are controlled mainly by the electric fields, the importance of neutral composition changes is appreciable in the later part of main and recovery phases of the storms. During the end of main phase or early stage of recovery phase Mansilla (2006) reported significant drop of electron density at low latitudes simultaneously with a relative increase in concentration of molecular nitrogen ($[N_2]$) over that of atomic oxygen ($[O]$). It ensures greater loss rate of ionization than the production rate thereby reducing the probability of SE for storms with MPO around 1230–1630 h IST.

For the storm events with MPO during 0530–1130 h IST the stipulated time of SE falls in most cases at the end or post-recovery phases of the storms. The increased probability of SE for this case may be attributed to the maintenance of enhanced electron density at low latitudes by the combined effects of decrease of mean molecular mass due to enhanced equatorward winds and upward plasma drift instigated by long-term DD component modulated by composition changes (Fuller-Rowell et al., 1996; Scherliess and Fejer, 1997; Mansilla, 2006).

4. Summary and discussions

The results of morphological studies on the variation of diurnal TEC from Calcutta during the period of moderate geomagnetic storms, categorized on the basis of local times of MPO and seasons, may be summarized as follows:

(i) The TEC responses to geomagnetic storms are largely dependent on the local times of MPO. The storm events with MPO during daytime sectors are found to be more effective in producing larger perturbations in TEC compared to those with MPO at the nighttime sectors. The maximum positive deviations in the former cases are mostly recorded within 7 h of MPO while longer time delays (more than 7 h) are reflected for storms with nighttime MPO. A reverse picture is, however, revealed for occurrence of maximum negative deviations.
(ii) The maximum TEC deviations are recoded mostly during daylight hours.
(iii) The perturbation maxima in TEC are largely populated in the main phases of the storms occurring in any local time sectors, except around sunset to premidnight hours. The maximum perturbations in the later case are, however, recorded in the recovery phases.
(iv) The reported seasonal response patterns of ionospheric storms – i.e., the dominant positive effect during local winter months, negative effect during local summer and oscillation between the two effects during equinoxes – are found to be largely modulated by local times of MPO, which is more prominent for summer solstitial storms.
(v) The sunrise enhancement (SE) in TEC is observed to be greatly perturbed with respect to its occurrence time as well as occurrence probability depending on the local times of MPO vis-à-vis on the phase of the geomagnetic storm in which the sunrise time falls. The earliest SE time is noted for storms with MPO in the early morning hours and the corresponding time is delayed as MPO shifts to the latter part of the day. The occurrence probability of SE is found to be remarkably less for the storm events with MPO in the local noon to afternoon sector.

The morphological features of diurnal TEC variabilities during moderate geomagnetic storms, thus emerged, may be discussed in the light of contemporary ideas of variations in the driving mechanisms namely the electric field changes, thermospheric winds, and neutral composition changes. The competitive interaction among the ionospheric drivers and their relative dominance at a particular time may lead to the storm induced ionospheric perturbations. At Calcutta, situated virtually below the northern crest of EIA, transport of ionization by the equatorial fountain plays a dominant role in dictating TEC profile under quite geomagnetic conditions (DasGupta and Basu, 1973). It was also reported that (Fuller-Rowell et al., 2002) the low latitude ionospheric responses to storm is dominated by electrodynamics where changes develop very rapidly in response to the high latitude forces. The equatorial electrodynamics or equatorial plasma fountain is mainly controlled by the electric field, the storm induced modification of which can drastically modulate the EIA latitude structure thereby affecting the diurnal TEC profile near the anomaly crest. TEC deviations recorded under present investigation at the early stage of main phase may be attributed to the disturbed fountain prompted mainly by penetration electric field (PP) of magnetospheric origin. The effects of ionospheric disturbance dynamo (DD) at the magnetic equator become perceptible after a delay of few hours (Huang, 2008). This (DD) field in association with PP component, having climatologically different polarities and efficiencies at different local time sectors (Fejer and Scherliess, 1995, 1997; Scherliess and Fejer, 1997; Manoj et al., 2008), may dictate the local time dependent TEC perturbations in the main phase and during initial stage of recovery phase (mostly on day 1 and day 2) of the storms. Further, the thermospheric disturbance wind whose strengths are reduced towards lower latitudes under moderately disturbed conditions (Maruyama et al., 2004) may have some contribution to TEC perturbations in the daytime extending up to post-sunset hours (Abdu et al., 2007). The storm induced thermospheric wind, with an appropriate time delay at low latitude, normally accentuates the prevailing transequatorial wind in summer while during equinox and winter solstitial months the normal daytime wind may even be reversed to affect the development of anomaly (Burge et al., 1973). For negative perturbation observed with longer time delays (24 h or more) advected composition bulge (characterized by reduced [O]/[N_2] ratio) particularly at nighttime, which is further modulated by sunrise effect in the succeeding day, may act as stimulating agent (Dabas and Jain, 1985; Fuller-Rowell et al., 1996; Liou et al., 2005). TEC perturbations during geomagnetic disturbances are actually the manifestation of complex interaction of the several processes.

The morphology of TEC responses to winter solstitial storms with MPO during daytime to premidnight sector more or less follow the climatology of thermospheric wind dynamics and neutral composition changes (Burge et al., 1973; Prolss, 1977; Fuller-Rowell et al., 1996). The prominent negative deviations during daytime period for MPO around sunset to nighttime hours (1730–0430 h IST) may be attributed to the combined effect of disturbed fountain due to DD electric field (westward) and thermospheric equatorward wind, which restricts the anomaly expansion. Though for MPO around early morning hours of summer solstitial months the negative deviation is the main feature in conformity with the climatological pattern (Duncan, 1969; Prolss, 1977), the formation of positive phases for MPO in the later local time sectors, particularly in the daytime, and persistence of the same phase in majority of the events may signify the dominant role played by the disturbed electric field in dictating TEC perturbations from the present location.

For all the categories of MPO maximum responses are recorded mostly in the daytime period when both the production and transport of ionization by equatorial fountain primarily control the quiet time TEC profile. The equatorial plasma fountain is highly responsive to disturbance electric filed (Tsurutani et al., 2004). Also the daytime *F* region is sensitive to composition changes and wind dynamics (Mikhailov and Marin, 2001). For maximum positive deviations occurring within 7 h of MPO disturbed fountain instigated by perturbed electric field may be assumed to be the contributing factor while for maximum responses with longer time delay not only the electric field but the effects of equatorward thermospheric disturbance wind and composition changes are also to be taken into account.

The fluctuations between positive and negative variabilities in the equinoctial months may be attributed to variation in several stimulating components such as electric field, wind and tidal modes, and composition bulge. As no data, other than proxies of electric field, are available only possible causes may be suggested but are not verifiable.

5. Conclusions

The morphological studies on storm time variations in TEC from Calcutta reveal that ambient ionization around the present location may deviate appreciably from the quiet time mean values during moderate intensity geomagnetic storms. The polarity of TEC deviations and the corresponding amplitudes are found to be largely affected by local times of occurrence of the storm main phase as well as by the seasons. In the sunrise period the regular features of TEC profile are also disturbed. The perturbations depend on the local times of MPO as well as on the phases of storms on which the sunrise time falls. The maximum amplitudes of deviations are mostly recorded during the daytime period. TEC perturbations are found to be much susceptible to storms with daytime MPO as well as to the main phase of storms. TEC deviations during the moderate geomagnetic storm period may be sufficient to introduce range error of the order of 7–10 m at the GPS L1 frequency (1.57542 GHz). For precise measurement of position modeling of TEC during geomagnetic storms is an important ensuing space weather problem. The results of present investigation may form a useful database for the same.

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