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On the response of the equatorial and low latitude ionospheric regions in the Indian sector to the large magnetic disturbance of 29 October 2003

G. Manju, T. Kumar Pant, S. Ravindran, and R. Sridharan

Space Physics Laboratory, Vikram Sarabhai Space Centre, Trivandrum – 695 022, Kerala, India

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Abstract. The present paper investigates the response of the equatorial and low latitude ionosphere over the Indian longitudes to the events on 29 October 2003 using ionosonde data at Trivandrum (8.5° N (0.5° N geomagnetic), 77° E) and SHAR (13.7° N (5.7° N geomagnetic), 80.2° E), ground-based magnetometer data from Trivandrum and Total Electron Content (TEC) derived from GPS data at the locations of Ahmedabad (23° N (15° N geomagnetic), 72° E), Jodhpur (26.3° N (18.3° N geomagnetic), 73° E) and Delhi (28° N (20° N geomagnetic), 77° E). Following the storm sudden commencement, the TEC at all the three stations showed an overall enhancement in association with episodes of interplanetary electric field penetration. Interestingly, real ionospheric height profiles derived using the ionosonde data at both Trivandrum and SHAR showed significant short-term excursions and recoveries. In the post noon sector, these features are more pronounced over SHAR, an off equatorial station, than those over Trivandrum indicating the increased effects of neutral winds.

Keywords. Ionosphere (Equatorial ionosphere; Ionospheric disturbances; Mid-latitude ionosphere)

1 Introduction

Earth's magnetosphere, thermosphere and ionosphere are driven by a multitude of non-local energy sources. Nonetheless, sun is the ultimate source of energy that controls the near earth space and drives its weather and climate. The disturbances on the Sun produce dramatic effects in near space environment surrounding the earth and also within the earth's upper atmosphere. Though most dramatic manifestations of space weather changes are observed in the thermosphere-ionosphere (TI) over polar latitudes, the energetics of the low latitude TI also gets significantly altered. In this context, the response of the ionosphere over low latitudes has been the matter of intense research across the globe. The severe space weather event of October 2003, was one such geomagnetic storm event when very prominent changes in the ionosphere were observed over the low and equatorial latitudes. Very large enhancements in the TEC, even at low and mid latitudes, were reported during this event.

Previous studies of storm-time dynamics have shown the presence of large winds, electric fields and currents in the ionosphere during the geomagnetic storms (Fejer, 2002; Mannucci et al., 2005). Significant changes in TEC have also been observed following interplanetary events that are generally attributed to intense disturbance-related electric fields resulting from the magnetosphere-ionosphere interaction processes. The electric fields during geomagnetic disturbances at low latitudes have been attributed to prompt penetration zonal electric fields (Abdu et al., 1995; Sastri et al., 2002; Dabas et al., 2006) and/or delayed disturbance dynamo electric fields (Blanc and Richmond, 1980; Fejer and Scherliess, 1997; Richmond and Lu, 2000; Sobral et al., 2001). It has been shown that these electric fields, depending on their polarity and duration, could produce very significant enhancements or decreases of the vertical TEC.

The extreme events of October 2003 have been extensively investigated using a variety of ground and satellite based data (Mannucci et al., 2005; Tsurutani et al., 2005). Most of these investigations demonstrate an extreme ionospheric response to the large interplanetary electric fields during the "Halloween" storms that occurred on 29 and 30 October 2003. In fact, dayside total electron content increases of ∼40% and ∼250% were reported for the 29 and 30 October events within a few (2–5) h of the onset of the interplanetary events (Mannucci et al., 2005). A factor contributing to the observed TEC increases during these events has been

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Correspondence to: G. Manju
(manju_spl@vssc.gov.in)

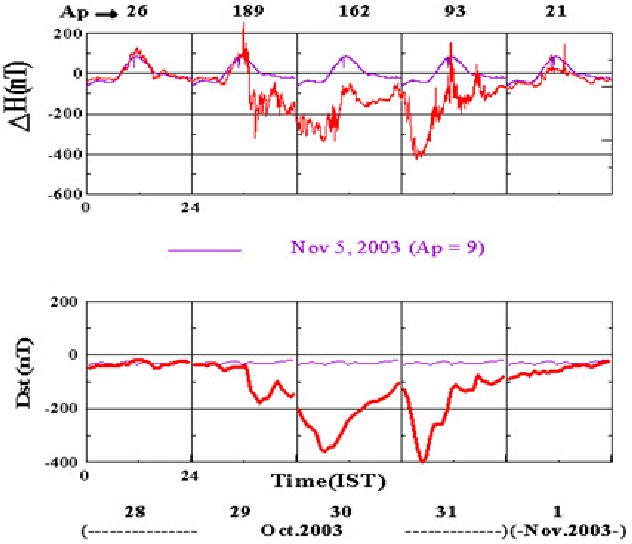

Fig. 1. The temporal variations of ΔH and Dst from 28 October 2003 to 1 November 2003.

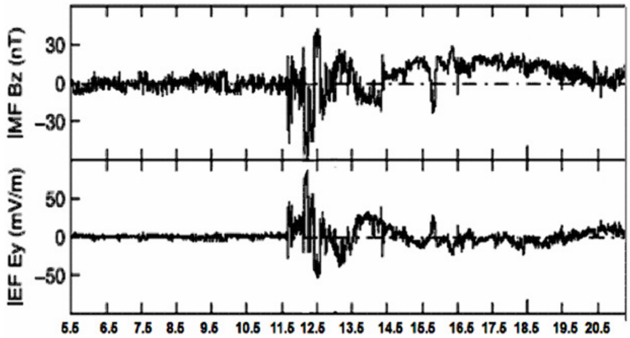

Fig. 2. The time variations of IMF B_z (top panel) and the interplanetary electric field (bottom panel) on 29 October 2003.

ascribed to daytime eastward-directed electric fields penetrating promptly from high to low latitudes. The same field has been reported to have produced “daytime super fountain” in the ionosphere over the low and equatorial latitudes (Tsurutani et al., 2005).

In the light of the above, in the present study, we investigate the response of the ionosphere to the interplanetary events of 29 October 2003 and the observed changes in the TEC over the Indian longitudes.

2 Data and method of analysis

The present study has been carried out using : i) TEC values derived from GPS data at the locations of Ahmedabad (23° N, 72° E), Jodhpur (26.3° N, 73° E) and Delhi (28° N, 77° E).

The Absolute Slant GPS-TEC values are derived from the carrier phase delays and pseudoranges of the GPS signals at L1 and L2 frequencies. The STEC are then converted to Absolute Vertical TEC (VTEC) following the standard procedure using the mapping function as given below.

$$\mathrm{VTEC} = \mathrm{STEC} \cos(\chi),$$

where, χ is the zenith angle at ionospheric pierce point (IPP) which is estimated from the satellite elevation angle. The shell height is taken as 350 km. Here, only those ray paths with elevation angles greater than 50° are used. It has been shown by Ramarao et al. (2006) that an elevation angle cut off of $>50°$ is ideally suited to represent the TEC over the Indian sector. IPP is the point where the line joining the satellite and the receiver cuts the ionosphere at an altitude where the entire ionisation is assumed to be concentrated (single shell model). Average VTEC values are obtained by averaging every 15 min values of VTEC from satellites with elevation angle above 50°.

ΔH values (the deviation of the horizontal component of the earth’s magnetic field H from its mean night time level) were obtained using a ground based Proton Precession magnetometer. The ionospheric real height profiles were estimated using ionogram data from KEL ionosondes operated at Trivandrum (8.5° N, 77° E) and SHAR (13.7° N; 80.2° E). The real height profiles are obtained from the manually scaled ionogram data using POLAN software.

3 Observations

Figure 1 shows the temporal variation of ΔH (the deviation of the horizontal component of the earth’s magnetic field from the mean night time level) for the period 28 October 2003 to 1 November 2003. The control quiet day (5 November 2003) variations are also shown in each panel. The storm sudden commencement was seen around 11:45 IST on 29 October 2003 with field increasing to above 200 nT. Thereafter, within ~90 min the field decreased to ~ -300 nT. This is followed by a recovery phase. Recurrent storm activity is observed in the following days and the disturbances persist beyond 31 October 2003.

Figure 2 shows the time variations of IMF B_z (top panel) and the interplanetary electric field (bottom panel) on 29 October 2003. After the storm sudden commencement at ~11:45 IST, a number of episodes of southward IMF B_z are clearly discernible from the figure. Episodes of south ward IMF and penetration electric field are indicated at ~11:45 IST, ~12:15 IST, ~12:45 IST and ~14:30 IST while northward IMF is seen to be manifested at ~12:30 IST and ~13:15 IST. During these episodes of southward IMF B_z, the prompt penetration of interplanetary electric fields into the ionosphere over the low and equatorial latitudes occur, thereby modulating the quiet time ionospheric zonal electric field. The rapid fluctuations in the polarity of the interplanetary electric field shown in the Fig. 2 would therefore give

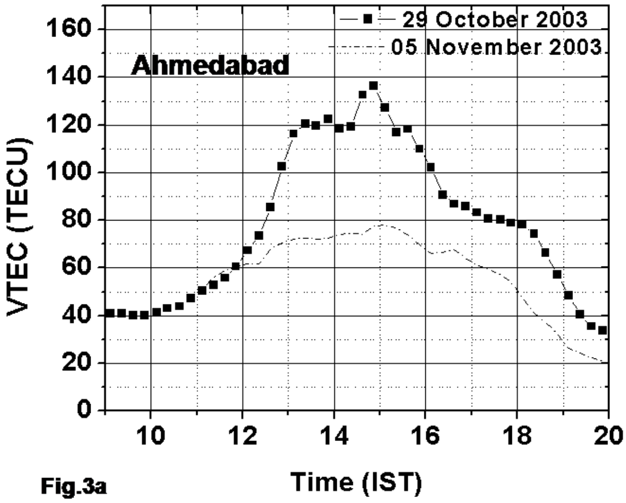

Fig.3a

Fig. 3a. The temporal variation of average VTEC for 29 October 2003 (solid lines) at the station of Delhi (28° N, 77° E. The corresponding average VTEC values for the control day of 5 November 2003 (dashed line) are also shown.

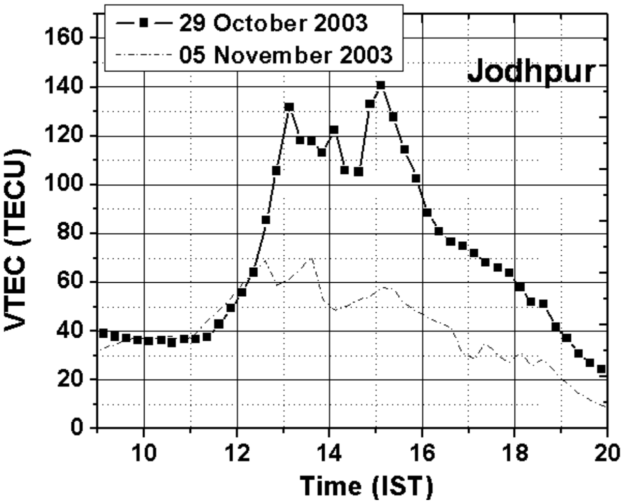

Fig. 3b. The temporal variation ofaverage VTEC for 29 October 2003 (solid lines) at the station of Jodhpur (26° N, 73° E). The corresponding average VTEC values for the control day of 5 November 2003 (dashed line) are also shown.

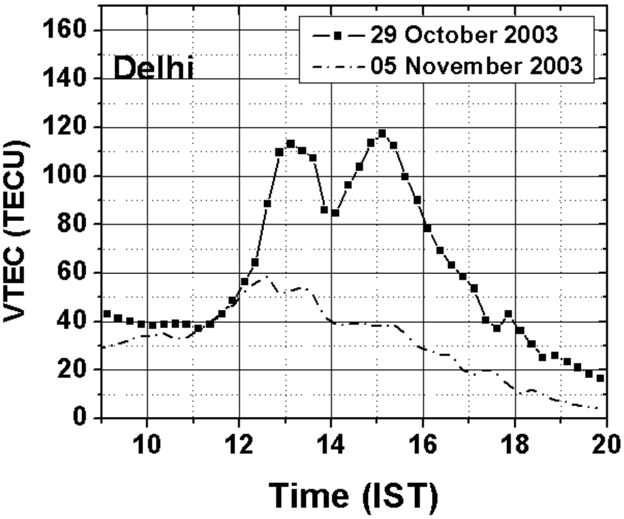

Fig. 3c. The temporal variation of average VTEC for 29 October 2003 (solid lines) at the station of Ahmedanad (23° N, 72° E). The corresponding average VTEC values for the control day of 5 November 2003 (dashed line) are also shown.

rise to rapid fluctuations in the vertical drift of the F layer (discussed in Fig. 5). The presence of these intense interplanetary electric fields during the event being presented here had been shown earlier (Huang et al., 2007).

The temporal variations of average VTEC for 29 October 2003 at the low latitude stations of Ahmedabad (23° N, 72° E), Jodhpur (26.3° N, 73° E) and Delhi (28° N, 77° E) are shown by solid lines in the Fig. 3a, b and c, respectively. The corresponding average VTEC values for the control quiet day are also shown by dashed lines in each figure. It is clear from these figures that for the control day, the VTEC at all the three stations shows a variation with time typically representing the solar zenith angle dependence (and consequent diurnal variation of VTEC). The diurnal maximum VTEC values are seen to be 80, 70 and 60 TECU, respectively, at Ahmedabad, Jodhpur and Delhi. This indicates that the anomaly crest does not extend beyond the latitude of Ahmedabad. On the contrary, for the event day of 29 October 2003, after the storm sudden commencement at 11:45 IST, the VTEC at all three stations show very large increase from around 60 TECU to above 100 TECU. At 13:00 IST, the VTEC is 120, 130 and 115 TECU, respectively, at Ahmedabad, Jodhpur and Delhi, the maximum being over Jodhpur. Between ∼13:30 IST and ∼14:15 IST a reduction in TEC is seen over Jodhpur and Delhi while no such reduction is observed over Ahmedabad. After ∼14:30 IST, TEC enhancements are seen again over all three stations with the maximum being observed over Jodhpur at 15:00 IST. The clear dramatic TEC enhancement over low to mid latitudes (maximum ∼120–140 TECU) in the Indian EIA region is brought out by the figures in contrast to the relatively low VTEC values (maximum∼60–80 TECU) observed on the control day. The anomaly crests on the event day have evidently gone beyond ∼18° geomagnetic latitude (Jodhpur) which is very high for low solar activity period.

Figure 4 illustrates the response of ionosphere at the magnetic equatorial station, Trivandrum (TRV) (top panel) and the low latitude station, SHAR (bottom panel) on 5 November 2003, the control day. The color bar and the lines in the figure represent the electron density and iso-electron density contours respectively. In the morning as the equatorial ExB drift increases in conjunction with the global dynamo generated electric field in the E-region of the ionosphere,

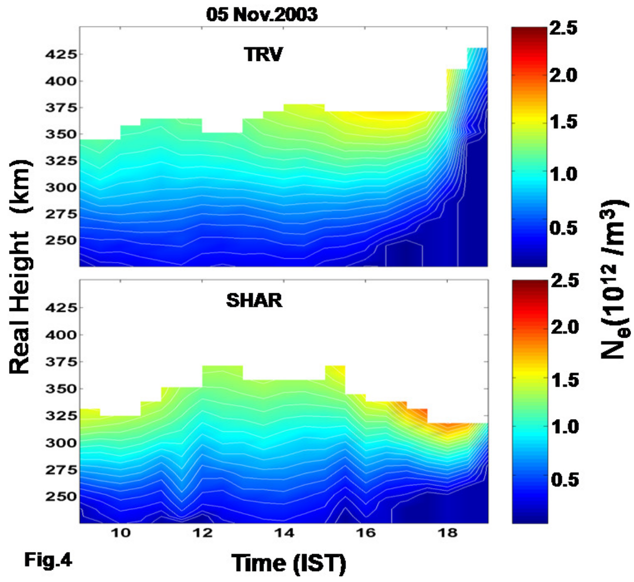

Fig. 4. The time variations of real height at the magnetic equatorial location, TRV (top panel) and the low latitude station, SHAR(bottom panel) on 5 November 2003.

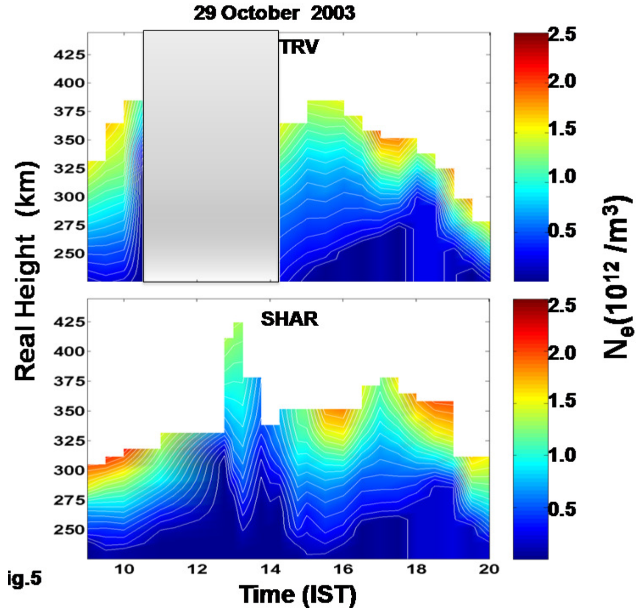

Fig. 5. The time variations of real height at the magnetic equatorial location, TRV (top panel) and the low latitude station, SHAR(bottom panel) on 29 October 2003.

the equatorial ionization anomaly starts developing. As a consequence of this anomaly development is seen at SHAR from 09:00 IST itself. The presence of the crest at SHAR is discernible from a comparison of the top and bottom panels. Later on (beyond 11:00 IST) the anomaly crest further develops and moves beyond SHAR. With the reduction in EXB drift in the post noon period, the crest comes back towards SHAR and then Trivandrum. But later in the evening ∼18:00 IST, due to the prereversal enhancement of the ionospheric electric field, the height of the F layer goes up dramatically with consequent increased vertical drift. As a result of this a further enhancement in the ionization is observed over SHAR. On the magnetically disturbed, the real height analysis reveals a different temporal pattern.

Figure 5 illustrates the temporal variation of real height for 29 October 2003, at TRV (top panel) and SHAR (bottom panel). It is clear from the figure that when compared with the control day, significantly large upward excursion is seen right from morning at TRV and SHAR. The anomaly is also seen to be more strongly developed on this day over SHAR right from morning in relation to that on control day. This observation even before storm commencement is probably indicative of the disturbances building up in the ionosphere in the last part October 2003, with solar flares occurring on 26 October 2003 and 28 October 2003(large X17 solar flare in the evening). The F10.7 cm flux is increases during this period. The F10.7 cm flux values on the control day and the event day are 112 and 274, respectively indicating the enhanced level of solar activity during the disturbed day. On 29 October 2003 there is a data gap between 11:00 and 14:15 IST at Trivandrum. The plasma over SHAR continues to exhibit a gradual upward excursion till ∼12:00 IST. However, after 12:00 IST the plasma undergoes a large upward excursion. After this upward excursion it recovers by around 13:15 IST. Another upward excursion begins around this time, with the enhancement persisting upto around 14:15 IST. After 14:15 IST the plasma gradually moves down till ∼15:00 IST after which a brief and small upward excursion is seen at most altitudes. At TRV, the layer is seen to be moving upwards from ∼14:15 IST to 15:00 IST and corresponding plasma density enhancement is also seen at SHAR. Interestingly, around 17:00 IST when plasma over SHAR shows a large upward movement, the same over TRV exhibits a large downward movement. After 17:00 IST till evening, a gradual downward movement of the plasma is seen over SHAR. However, the plasma over TRV shows another, small upward excursion around 17:30 IST followed by a gradual recovery beginning about half hour later. In the post 16:00 IST period we can see large fluctuations in the vertical drift over SHAR which are not showing correspondence with the variations over TRV. This probably indicates the important role of meridional winds at the low latitude station SHAR. In the period upto 16:00 IST, from the available data over TRV and SHAR it seems that the electrodynamical effects are playing a dominant role in controlling the ionization density. Another interesting aspect is the inhibition of the post sunset enhancement in vertical drift over the two stations on 29 October 2003 due to disturbance effects.

4 Results and discussion

As is known, during daytime the global eastward electric field over the low latitudes causes the ionospheric plasma to move upwards over the dip equator only to let it diffuse along the geomagnetic lines to higher latitudes resulting in the formation of regions of enhanced ionisation density at off-equatorial latitudes and an ionisation trough right over the dip-equator, a phenomenon known as EIA. In other words, the variability in the ionisation density over the low latitudes at any time during the day can arise due to two factors. One, due to the modulations in the direct solar insolation which causes the ionisation; and the other due to the transport of additional plasma from the equatorial latitudes towards low latitudes along the magnetic field lines. These ionisation crests manifest as enhanced TEC over low latitudes. Yet another factor that can modulate the ionization density is the effect of neutral winds.

It has been reported that during low solar activity the EIA crests over the Indian longitudes do not extend beyond 12–15 geomagnetic latitudes. Nevertheless, it has been found that during certain space weather events in the low solar activity epochs, the equatorial ionospheric electric field gets enhanced due to penetration of an electric field of magnetospheric origin causing enhanced ionisation crests at locations far beyond 12–15 latitudes (Abdu et al., 1995; Sastri et al., 2002; Tsurutani et al., 2004). Further, large changes in TEC can also be produced a few hours after the event onset by intense disturbance dynamo electric fields originating from the magnetosphere-ionosphere interaction (Blanc and Richmond, 1980; Richmond and Lu, 2000; Fejer and Scherliess, 1997).

In this context, as mentioned earlier the period of 28–30 October 2003 was marked by an overall enhancement in the TEC over the low latitudes on a global scale. Mannucci et al. (2005) attributed this enhancement in EIA to the so called super fountain. Tsurutani et al. (2005) explained the so called “super-fountain” as uplift caused by an unusually large electric field, induced by interactions of the IMF with the earth’s magnetic field. In fact, it has been shown for this period that this higher uplift takes plasma to a higher L-shell such that recombination happens very slowly and the plasma drifts north and south along field lines to produce TEC enhancements at mid-latitudes. Mannucci et al. (2005) have shown observations similar to those reported here for the interplanetary events of 30 October 2003 using CHAMP satellite data. All these observations indicated that the EIA during this period was able to extend beyond 20 geomagnetic latitude.

The TEC enhancement seen at Indian longitudes during the disturbed period of 29 October 2003 is the largest such enhancement observed so far using GPS data over the Indian region. The interesting observations are made corresponding to the initial phase of the storm immediately following the sudden commencement as can be seen from the ΔH and Dst temporal variations. After the storm sudden commencement, the fluctuating nature of the interplanetary electric field which is anticorrelated with the polarity of IMF B_z, produces fluctuations in the ionospheric electric field and thereby modulates the $\boldsymbol{E} \times \boldsymbol{B}$ drift. Large upliftment of ionization is evidenced at SHAR corresponding to the effect of interplanetary electric field penetration. The large upliftment is in evidence at TRV also wherever data is available. Two strong episodes of enhanced vertical drift are seen in the SHAR plot with a reduction in vertical drift in between at ∼13:15 IST. This seems to agree with the pattern of TEC variation over Delhi, Jodhpur and Ahmedabad.

As mentioned earlier, the anomaly crests move towards higher latitudes away from Ahmedabad corresponding to the times of enhanced vertical plasma drift as seen from ionogram real height profiles. In between the two strong bursts, the anomaly crest as seen in TEC appears over Ahmedabad in agreement with the real height profiles. These observations indicate the effect of prompt penetration electric fields and consequent enhanced vertical drift as being causative mechanisms for the observed large TEC over Delhi and Jodhpur stations. The increased effects of meridional winds on the plasma density become evident from ∼16:00 h with the vertical plasma motions at TRV and SHAR showing significant differences. It has been shown that the intensity of a TEC storm over low to mid latitudes produced by prompt penetration electric fields can be enhanced by the presence of equatorward winds under daytime conditions. (Abdu et al., 2007). Similar effects seem to be present on 29 October 2003 over Indian sector in the post 16:00 h period.

It is well known that the position accuracy achievable from navigation satellites (e.g. Global Positioning System (GPS) is largely affected by the intervening ionosphere which is the single biggest factor contributing to the error in positioning. The range error is directly proportional to the total electron content (TEC) along the ray path. In the context of the increased use of GPS based systems for positioning and navigation purposes, measurement accuracies of better than 3 TECU are ideally required. 1 TECU contributes to a range error of 16 cm. Hence a disturbance induced TEC enhancement of ∼80 TECU (as observed in the present study) will increase the range error by ∼13 m which can have devastating effects on navigation systems. This study, therefore, highlights the intense threat to GPS based navigation systems from space weather events. It also underlines the need to quantify the effects of magnetic disturbances on the equatorial and low latitude ionosphere so that these aspects can also be incorporated in the regional ionospheric models.

5 Conclusions

1. The study highlights the threat to GPS based navigation systems from severe magnetic disturbances.

2. It indicates the manifestation of the super fountain effect over Indian longitudes during interplanetary events of 29 October 2003.

3. The potentially significant effect of meridional winds in the late afternoon hours of 29 October 2003 is brought out by the real height analysis of TRV and SHAR.

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