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Key Points:
- Observational evidence for the westward DD electric field affecting the daytime low-latitude ionosphere
- EIA is suppressed due to the westward electric field prevailing from morning hours
- GITM model simulations agree with the observations

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Direct observational evidence for disturbance dynamo on the daytime low-latitude ionosphere: A case study based on the 28 June 2013 space weather event

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Abstract A case of the westward disturbance dynamo (DD) electric field, influencing the daytime equatorial and low-latitude ionosphere, during a geomagnetic storm that occurred on 28–29 June 2013 is presented. The GPS total electron content (TEC) observations from a network of stations in the Indian equatorial, low and middle latitude regions along with the radio beacon TEC, ionosonde, and magnetic field observations are used to study the storm time behavior of the ionosphere. Negative ionospheric storm effects were seen over the low and middle latitudes during the storm time due to the presence of a westward DD electric field. Observations show that the suppression of the equatorial ionization anomaly (EIA) from the morning hours itself on 29 June 2013 took place due to the prevailing westward DD electric field, providing evidence for the model calculations by Balan et al. (2013). Simulations using the GITM model also agree well with our results. The present study gains importance as the direct observational evidences for disturbance dynamo effects on the daytime low-latitude ionosphere and the EIA are sparse, as it has been difficult to delineate it from the compositional disturbances.

1. Introduction

During a geomagnetic storm, two components of electric fields are generated in the terrestrial ionosphere. The first one is the prompt penetration (PP) electric field which is often eastward in the day sector and westward in the night sector [*Sastri et al.*, 2002]. The second component of electric field generated during space weather events is the disturbance dynamo (DD) electric field [*Blanc and Richmond*, 1980]. The energy input to the high-latitude ionosphere generates westward and equatorward neutral disturbances, which modifies the quiet time ionospheric dynamo electric field. Studies have shown that after the storm commencement, a few hours are required for the disturbance winds and DD electric field to set up [*Huang*, 2013; *Fuller-Rowell et al.*, 1994]. Once set up, they can persist for many hours [*Huang*, 2013; *Fuller-Rowell et al.*, 1994]. In the studies of the low-latitude ionospheric response to geomagnetic storms, the PP is inferred using interplanetary magnetic field (IMF) B_z or IEF$_y$ data and has clear signatures in ground magnetic field data [*Kelley et al.*, 1979; *Fejer et al.*, 1979; *Huang et al.*, 2005; *Simi et al.*, 2012; *Shreedevi et al.*, 2016]. In contrast, the identification of DD electric field is mostly based on inferences from the ionospheric observations and modeling [*Sastri*, 1988; *Fejer et al.*, 2008; *Huang*, 2013].

The DD electric field results from the neutral winds developed due to joule heating associated with the auroral particle precipitation during a geomagnetic storm [*Blanc and Richmond*, 1980]. Over low latitudes, the DD effects are seen prominently in the zonal and vertical drifts during afternoon and nighttime [*Fejer and Emmert*, 2003]. In one of the recent studies by *Tulasiram et al.* [2015], the duskside enhancement of equatorial electric field was shown to be in response to the eastward prompt penetration electric field (PPEF) despite the existence of background westward disturbance dynamo fields. Many times, it is seen that although DD currents develop in the daytime, the resulting dynamo electric fields are shorted out by the large *E* region conductivities [*Huang*, 2013]. However, model simulations have shown that DD tends to reduce the daytime upward drifts [*Maruyama et al.*, 2005]. The intensity of the DD electric field is also seen to be highly dependent on solar activity, season, UT, etc. [*Huang*, 2013]. The major challenge in identifying the DD electric field from

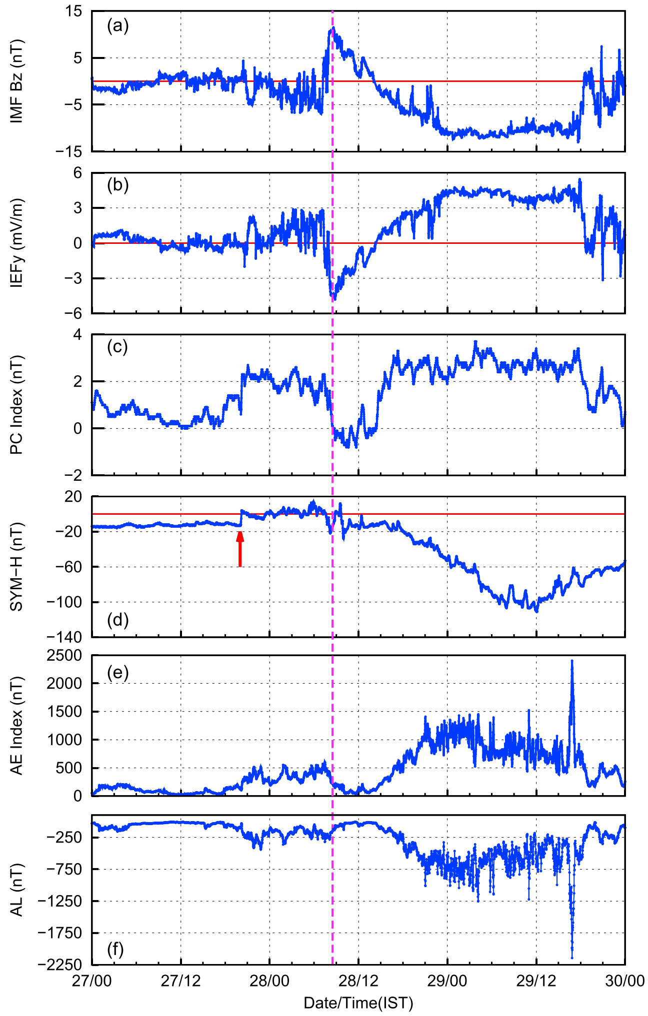

Figure 1. Geomagnetic conditions during the period 27 – 29 June 2013.

ionospheric observations lies in delineating the effects of DD electric field from those due to composition changes. We present a case study that clearly shows that the presence of DD electric fields can alter the electrodynamics which in turn decides the low-latitude plasma distribution. For this we have used simultaneous total electron content (TEC) measurements from several stations along the Indian longitude, and latitudinal distribution of TEC derived from radio beacon data along with other observations, during a space weather event that occurred during 28 – 29 June 2013.

2. Data and Methodology

The ionospheric response to the geomagnetic storm that occurred between 28 – 29 June 2013 ($Ap = 50$ on 29 June) is analyzed. The basic interplanetary and geomagnetic parameters are obtained from the CDAWeb and World Data Center, Kyoto University. The propagation lag of the IEF_y up to the ionosphere is calculated based on *Chakrabarty et al.* [2005]. To understand the middle, low, and equatorial ionospheric response, the GPS data from the midlatitude station Shimla (31.08°N, 77.06°E geographic, dip latitude 22.35°N), low-latitude stations, Bangalore (12.95°N, 77.68°E geographic, dip latitude 04.33°N), Bhopal (23.28°N, 77.34°E geographic, dip latitude 14.59°N) and Delhi (28.56°N, 77.22°E geographic, dip latitude 19.84°N) and the equatorial station, Trivandrum (8.47°N, 76.92°E geographic, dip latitude 0.05°N) are used. The details of the vertical TEC estimation are provided elsewhere [*Shreedevi et al.*, 2016]. The digisonde data from Trivandrum are used to understand the variation of h_mF_2 and f_oF_2 during the event.

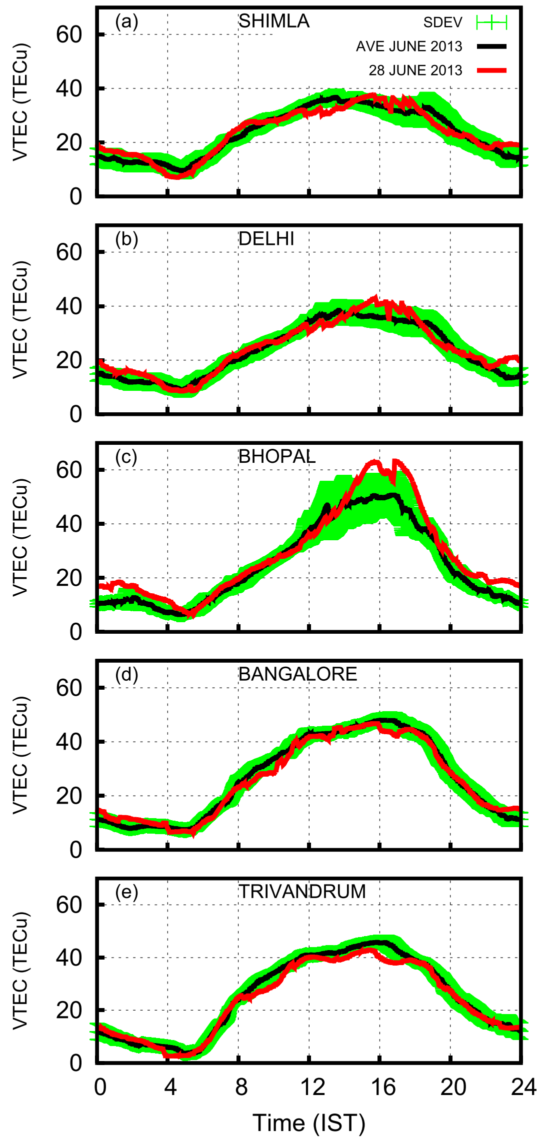

Figure 2. TEC variation at the GPS stations during 28 June 2013 is shown in red. The black line represents the quiet day mean variation of TEC for *Ap* < 4 days along with the standard deviation shown in green.

Apart from this, the radio beacon observations from Ahmedabad (23.04°N, 72.54°E geographic, dip latitude 17°N) are used to understand the response of the equatorial ionization anomaly (EIA). These data are obtained from the GNU Radio Beacon Receiver (GRBR), which tracks the 150 and 400 MHz transmissions from low-Earth orbiting satellites to get the latitude variation of ionospheric TEC. An ensemble average method developed by *Thampi et al.* [2014] is used to estimate the latitudinal variation absolute TEC using radio beacon-based differential phase measurements.

The equatorial electrojet (EEJ) strength, which is a proxy for equatorial electric field changes, is calculated using the magnetic field data from Tirunelveli (8.3°N, 77.8°E, dip latitude 0.6°N) and Alibag (18.64° N, 72.9° E, dip latitude 5.2°N). We have also used data from the GUVI (Global Ultraviolet Imager) instrument aboard Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) satellite for obtaining the thermospheric composition changes during the storm [*Christensen*, 2003]. We have also used the Global-Ionosphere-Thermosphere Model (GITM) [*Ridley et al.*, 2006] to simulate the global ionospheric electron density distribution during the storm time. Earlier studies using the GITM model have highlighted the

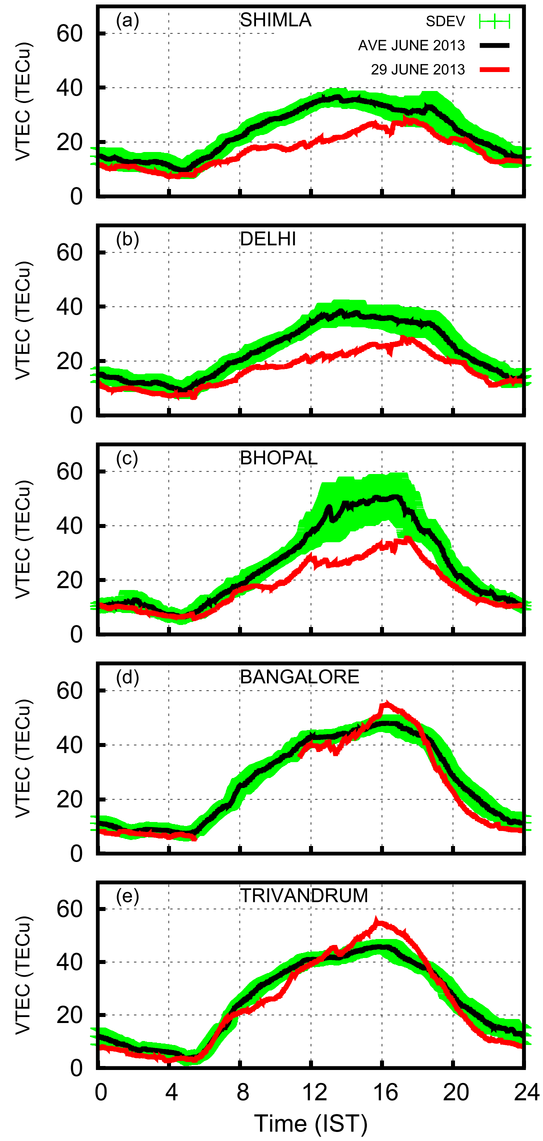

Figure 3. Same as Figure 2 but for low-latitude stations on 29 June 2013.

capability of the model to produce the quiet time and storm time responses [*Vichare et al.*, 2012; *Yigit et al.*, 2016]. The GITM model also specifies the high-latitude electrodynamics using many models and can be accessed at http://ccmc.gsfc.nasa.gov/requests/requests.php.

3. Results

The variation of IMF B_z, IEF$_Y$, polar cap (PC) index, *SYM-H*, *AE*, and *AL* indices during 27–29 June 2013 is shown in Figures 1a–1f. The IEF$_y$ reversed its polarity at around 08:00 IST on 28 June. It remained eastward while fluctuating up to ~3 mV and then became suddenly westward again. Later in ~5 h, the IMF B_z and IEF$_y$ slowly changed their polarities to southward and eastward, respectively. The ionospheric storm actually started with the second southward turning of IMF B_z on 28 June. The pink vertical line marks this time. The PC index showed corresponding enhancements in association with the southward turning of the IMF B_z. Figure 1d shows the variation in the *SYM-H* values. *SYM-H* increased abruptly with the southward turning of the IMF B_z revealing the Sudden Storm Commencement (SSC) on 27 June. However, the main phase of a geomagnetic storm ensued much later, after the second southward turning of the IMF B_z at ~11:55 IST on 28 June. Significant substorm activities were also found to occur after this, as evident from the *AL* variation. The auroral electrojet (*AE*) index

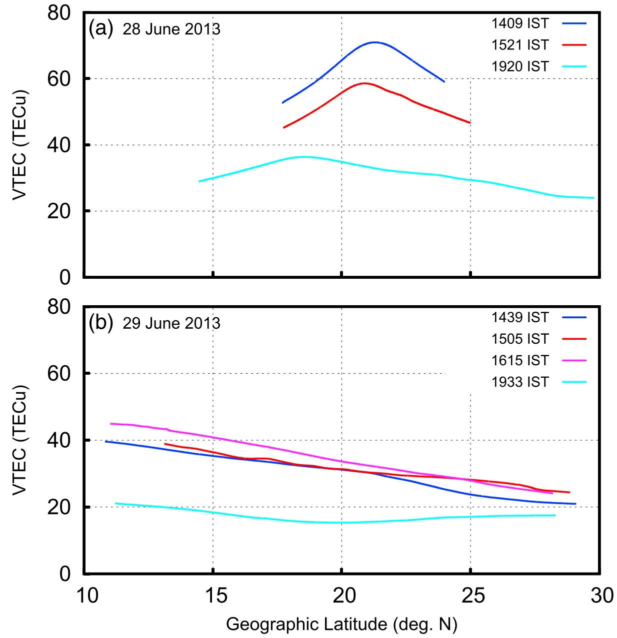

Figure 4. The latitudinal variation in TEC as observed by radio beacon.

variation shown in Figure 1e indicates an enhanced joule heating of the polar thermosphere few hours after the southward turning of IMF B_z on 28 June.

In order to see the response of the ionosphere over the middle, low, and equatorial latitudes, the TEC data from a network of stations over the Northern Hemisphere along the Indian longitude sector are used. Figures 2a–2e show the TEC variation over Shimla, Delhi, Bhopal, Bangalore, and Trivandrum on 28 June 2013. It can be seen that on 28 June, there was hardly any change in the TEC over Shimla and Delhi from the quiet day mean behavior in response to the eastward turning of IEF_y. The TEC over Bhopal (anomaly crest region) shows only a marginal increase in the afternoon hours, which also is close to the standard deviation for the quiet period, while the TEC over Trivandrum does not register any significant change. (Figure 2e corresponds to EIA trough region.) Nonetheless, the bottomside electron density did respond to the PPEF, as evident from ionosonde data (described later in this section). The possible reasons for the apparently different degree of responses as seen in TEC and ionosonde data are discussed in the subsequent section.

Figures 3a–3e show the TEC variation over these stations on 29 June 2013. The TEC over Shimla, Delhi, and Bhopal remained substantially low from morning till evening. There is no data from Bangalore during the morning hours; however, the change from quiet time variation was a marginal increase in the afternoon hours. The TEC over Trivandrum on this day increased as compared to the quiet time during afternoon hours.

To see the degree to which the EIA is affected by the storm time electric fields, we need the latitude variation of TEC, which is provided by the low-Earth orbit (LEO) beacon-based observations. Figures 4a and 3b show the latitude variation of TEC obtained using several beacon passes on 28 and 29 June. The start time of the satellite pass over the location is given in the legend. On both these days, unfortunately, we do not have any satellite passes in the morning sector. The presence of an EIA crest on 28 June can be seen clearly from the satellite passes that commenced at 14:09 IST and 15:21 IST, respectively. In contrast, on 29 June (Figure 4b), the EIA is completely suppressed as evident from the TEC variation at 14:39 IST, 15:05 IST, and 16:15 IST. Compared to the previous day, on 29 June the EIA is not developed at all. The latitudinal variation of TEC shows a maximum over equator decreasing northward. This is a direct evidence for the presence of westward DD electric field.

Further evidences of the changes in the low-latitude plasma distribution under the storm time electric fields can be found in the temporal variation of equatorial f_oF_2 and h_mF_2, as observed by ionosonde. The temporal variation of h_mF_2 and f_oF_2 during 28–29 June 2013 are shown in Figures 5a–5b. The diurnal variation of h_mF_2 and f_oF_2 on a quiet day closest to the storm period is represented using the blue line. There is a reduction in f_oF_2 and a corresponding overall increase in h_mF_2 during daytime on 28 June, indicating enhanced vertical drifts

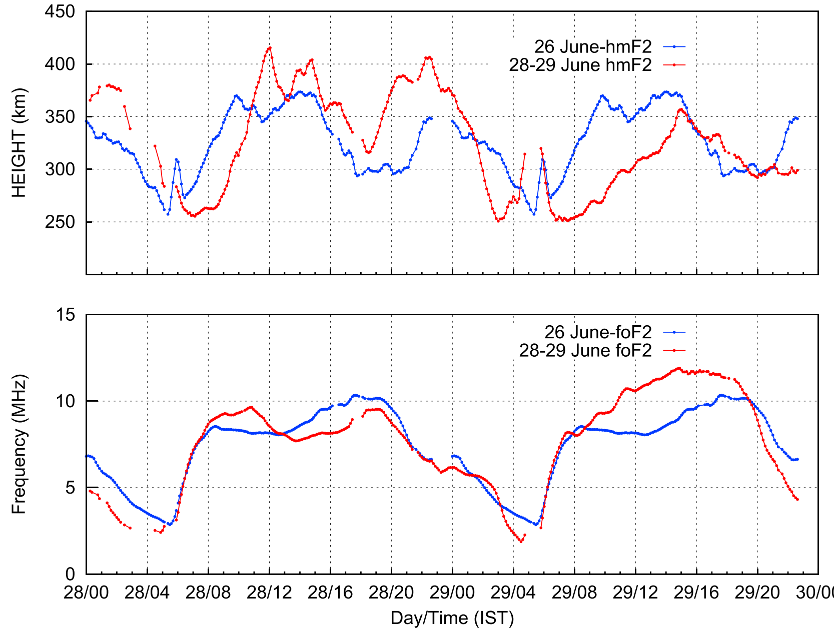

Figure 5. Digisonde measurements from Trivandrum during 28–29 June 2013. The red line represents the diurnal variation during the period 28–29 June 2013. The blue line represents the variations on a quiet day (26 June 2013) and is shown here to facilitate comparison of the disturbed day variation with that of the quiet day.

(compared to the quiet time value), resulting in an enhanced fountain. Hence, the presence of the enhanced fountain due to PPEF can be confirmed. In contrast, there is an increase in f_oF_2 and a corresponding overall decrease in h_mF_2 during daytime on 29 June, indicating westward and downward drifts and a decreased fountain effect.

On the night of 29 June, there is a marginal increase in h_mF_2 over Trivandrum from 18:00 to 20:00 h and f_oF_2 remained high compared to the quiet time value. This may indicate the presence of an enhanced electric field and the corresponding increase in electron density (because the recombination rates are lower at higher altitudes). However, we do not see any indication for the presence of a DD eastward electric field in TEC (Figure 3). By 20:00 IST, the DD effect almost ceases. This corroborates with the model simulations by *Huang* [2013], wherein they show that in the nighttime, during the summer months, the equatorward and westward neutral disturbances in the Northern Hemisphere can penetrate into the southern hemisphere. In such cases the DD electric field effects in the Northern Hemisphere become small and most of the DD currents become poleward in the Southern Hemisphere [*Huang*, 2013]. By ∼18:00 IST on 29 June, the IMF B_z also starts to turn

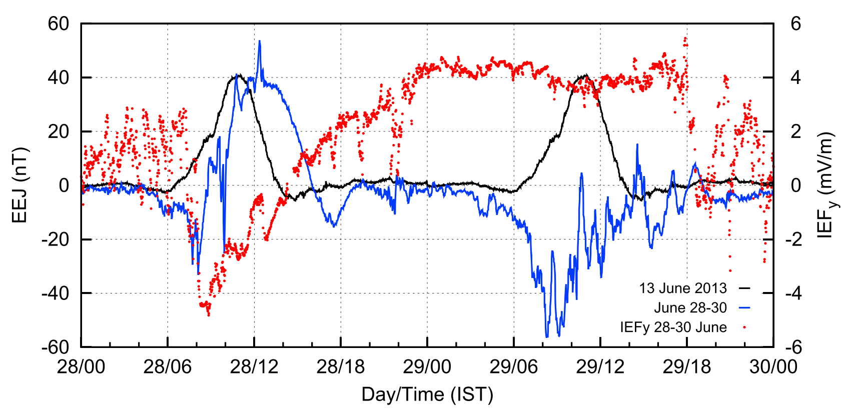

Figure 6. EEJ variation during 28–29 June 2013 (blue line) along with variation in IEF$_Y$ (red dots). The black line represents the typical quiet day variation of EEJ on 13 June 2013 which is a quiet day. The variation of EEJ on the quiet day is shown with both 28 and 29 June to facilitate comparison.

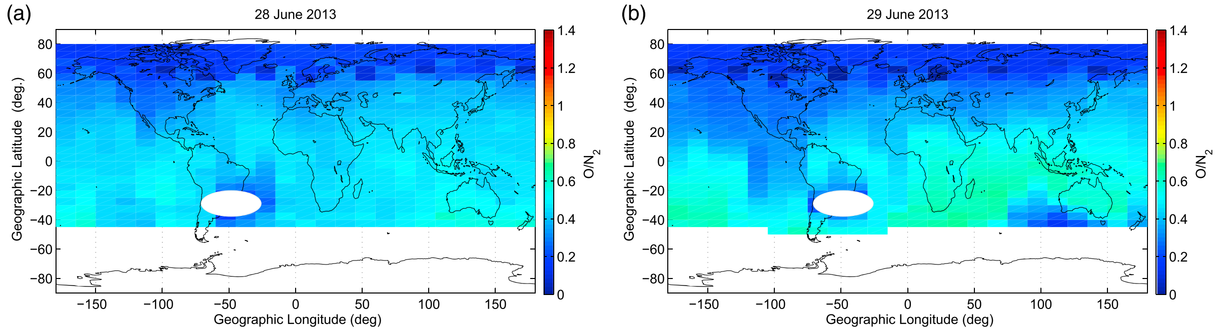

Figure 7. O/N_2 maps obtained from TIMED/GUVI satellite measurements to show the composition changes in the thermosphere. The measurements were made at ~1400 LT on both 28 and 29 June 2013.

northward, indicating the beginning of recovery to normal state. The signature of a clear prereversal enhancement is absent both during quiet and disturbed day, and this corroborates with the typical drift variation during moderate solar activity summer [*Scherliess and Fejer*, 1999].

Signatures of the PPEF (DD) currents also get reflected in magnetometer observations, as enhanced Equatorial electrojet (EEJ) (CEJ (counter electrojet)) conditions. The EEJ strength is plotted for the period 28–29 June, along with the quiet day mean and standard deviation, in Figure 6. In order to facilitate comparison, the variation in IEF_Y is also shown. It can be seen that the EEJ responds promptly to the changes in the IEF_Y on 28 June. The enhanced eastward electric field during daytime is evident from the enhanced EEJ current on 28 June. On 29 June, the EEJ is completely suppressed and does not show any correspondence with IEF_Y, confirming the presence of a westward electric field during daytime.

To understand the thermospheric composition changes associated with the geomagnetic disturbance, the GUVI observations are used. This is to delineate the effects of composition changes, if any, from the DD effects. Figure 7 shows the GUVI maps of the O/N_2 ratio, for 28 and 29 June 2013. Both the maps are shown for the same time of the day, i.e., 14:00 IST when the EIA is supposed to be significant. There is a substantial increase in O/N_2 ratio in the southern low-middle latitudes on 29 June. Compared to this, the degree of enhancement in O/N_2 is much less over northern middle and low latitudes. This indicates that the effect of composition disturbances was less over the northern middle and low latitudes on 29 June compared to the Southern Hemisphere. However, the O/N_2 ratio shows a moderate increase in the Northern Hemisphere low-middle latitudes, which favors a positive storm over low-middle latitudes. However, the TEC data showed the presence of a negative storm associated with the daytime westward electric field. Hence, it is apparent that the effect of the composition disturbance, if any, is offsetted by the presence of the DD electric field. The O/N_2 change is most prominent in the Southern (winter) Hemisphere compared to summer hemisphere, which is expected [*Huang*, 2013].

4. Discussion

The first interesting observation is that though the magnetic field and ionosonde data showed the presence of PPEF clearly on 28 June 2013, the TEC variation over the equatorial and low-latitude region remained more or less close to the quiet time values. Over the equatorial region, such events are reported previously as well [*Tsurutani et al.*, 2008; *Lei et al.*, 2015; *Shreedevi et al.*, 2016] wherein the TEC over equator does not reflect the enhanced fountain effect during daytime. It is suggested that this is probably because of the enhancement/replenishment of ionization in the equatorial ionosphere [*Tsurutani et al.*, 2008; *Lei et al.*, 2015]. This can also happen when the TEC is dominated by the electron density of the topside ionosphere. However, the TEC variation over Bhopal on 28 June indicates that at the crest location also, the TEC does not show a clear enhancement.

The TEC over the anomaly crest region would have also been much higher if the replenishment of ionization by production was the only mechanism that was responsible for the TEC to remain unchanged over the equator even when the fountain effect was taking place in the background. The TEC over both equatorial and low-latitude regions can remain unchanged only during two scenarios: (1) when the TEC is dominated by the density of the topside ionosphere and (2) when the signature of the PPEF is not clearly seen in the summer crest which is more influenced by the transhemispheric winds. However, if the TEC over the crest region was dominated by the topside electron density (unlike in the case of a typical quiet day), we would have expected significant increase in TEC compared to a typical quiet day. This is (1) because chemical recombination rates are low in the topside ionosphere, and hence, if there is considerable accumulation of plasma at those altitudes, it should manifest in TEC, and (2) because the effective scale height of the plasma at the topside ionosphere is also higher, the TEC should show an increase compared to a quiet day as TEC is more weighted to the *F* region peak [*Lei et al.*, 2015]. Hence, we conjecture that the transhemispheric winds play an important role in deciding the TEC variation on this day.

It is understood from the Formosa Satellite Mission 3/Constellation Observing System for Meteorology, Ionosphere, and Climate (Formosat-3/COSMIC) observations that the winter EIA crest forms earlier than the summer crest, due to summer-to-winter neutral wind effect. The summer crest starts to develop after the fountain effect becomes dominant, i.e., around 12:00 LT, and the winter EIA crest becomes stronger than the southern crest around 15:00 LT [*Lin et al.*, 2007]. In the observations that we present here, the effect of PPEF is not discernable from TEC even at 14:00 – 15:00 LT, i.e., even when the fountain effect maximizes. This indicates either the presence of strong meridional winds to the winter hemisphere or the enhanced contribution of topside electron density in TEC, which we may not be able to demarcate. The summer EIA crest is indeed present in the afternoon hours as evident from the radio beacon observations. This corroborates with the earlier results by *Lin et al.* [2007].

On the next day, i.e., 29 June 2013, there is a reduction in the TEC over low-latitude stations due to the suppression of fountain effect, because of the existing westward DD electric field. In the presence of a DD electric field, the resultant suppression of fountain would cause an enhancement in TEC over the dip equatorial region (compared to the normal day, wherein the plasma from the equator would be transported to low latitudes due to the fountain). This means, the effect of DD would be manifested as a positive ionospheric storm over Trivandrum, which is a dip equatorial station. Consequently, due to the suppression of the fountain, the plasma density over low-latitude regions would be lower (compared to the normal day, wherein the plasma from the equator would be transported to low latitudes due to fountain). As mentioned earlier, several observations showed that over the low latitudes, the DD electric field effects are seen prominently in the afternoon and nighttime zonal and vertical drifts [*Fejer and Emmert*, 2003], and not during the morning-noon hours. The development of EIA may also take place during weak CEJ conditions as the typical response time of the EIA to zonal electric field is 1 – 2 h [*Stolle et al.*, 2008]. *Sastri* [1988] have even shown that some geomagnetic storms do not generate detectable patterns of equatorial DD electric fields for the entire day. In contrast, the case presented here shows a clear presence of DD electric field effect during entire daytime, continuing at lesser extent over nighttime and ceasing by 20:00 IST. In this case, the DD electric field has become active from the main phase of the storm and continues for the whole day while the recovery phase is in progress.

Simulations by *Balan et al.* [2013] have shown that the zonal electric fields during daytime recovery phases can be zero or westward, and hence, the fountain can cease and the latitude variation of N_{max} and TEC can peak over the equator, especially when the zero or westward electric field in the morning hours. If the electric field becomes westward only in the afternoon hours (after the development of EIA), it may not be able to completely alter the latitudinal structure but only can cause positive ionospheric storm over equator. To obtain further evidence for this, we have performed simulations using Global-Ionosphere-Thermosphere Model (GITM) using the space weather conditions that prevailed during this event. Simulated electron density distribution of the ionosphere at 08:00 IST, 10:00 IST, 12:00 IST, 14:00 IST, 16:00 IST, and 18:00 IST on 29 June 2013 is presented in Figure 8. A notable feature in Figure 8 is the suppression of the EIA over the Indian low-middle latitudes on 29 June 2013 (Figure 3). The enhancement in electron density seen in the daytime winter hemisphere (evident in all the figures) could be a result of the summer-to-winter hemispheric transport of plasma. As mentioned earlier, during quiet times,the summer – to – winter neutral wind effect causes as pile up of the electron density at the winter hemisphere, even before the equatorial fountain sets up, and this feature gets diminished after 17:00 LT [*Lin et al.*, 2007].

In the GTIM simulations, the pileup of electron density in the winter hemisphere due to transhemispheric wind is clearly seen for the entire day. The feature appears even before the commencement of the fountain process. As mentioned earlier, a lag of 2 h is expected for a change in the electric field to be manifested in the EIA crest densities [*Rush and Richmond*, 1973; *Raghavarao et al.*, 1977; *Stolle et al.*, 2008], and hence, we can conclusively say that the pileup of electron density observed in the winter hemisphere is related to transequatorial winds,

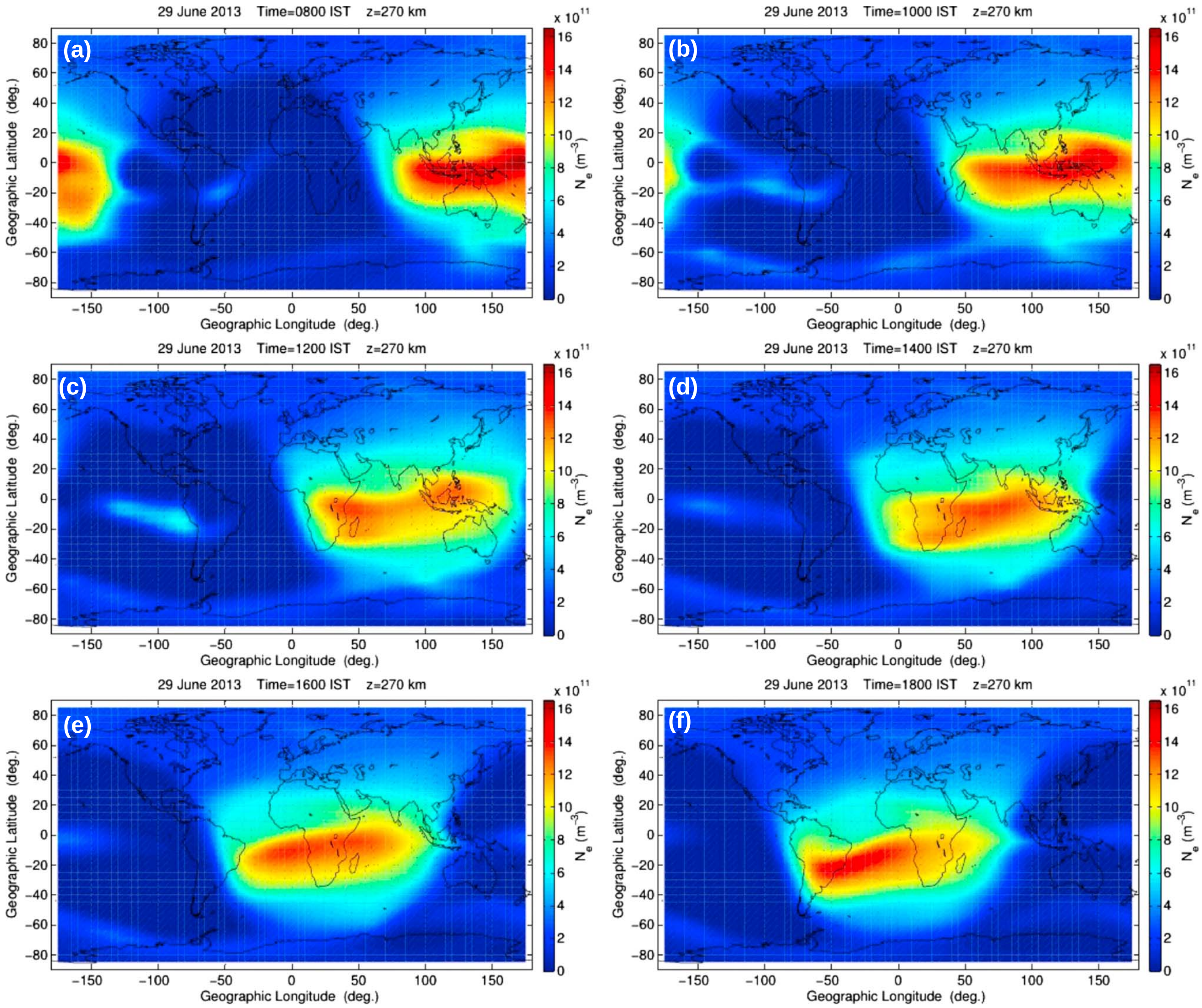

Figure 8. Simulation of the electron density distribution of the ionosphere on 29 June 2013 using the GITM model. Panels (a)–(f) represent the electron density maps at 08:00 IST, 10:00 IST, 12:00 IST, 14:00 IST, 16:00 IST and 18:00 IST respectively. The electron density maps are shown in IST as we are referring to the Indian longitudes in this study.

and not related to fountain. This is further evident from the fact that northern crest is not at all developed for the entire day. Previous studies have shown that the summer EIA crest due to fountain effect forms near 1200 LT and becomes stronger (than the southern winter crest) near 15:00 LT [*Lin et al.*, 2007]. In contrast, the simulation results for the disturbed day show suppression of northern EIA crest during 10:00–18:00 IST, which indicates the absence of a fountain process. With the support of the evidences from the model and observations, it is clear that the presence of the westward electric field (DDEF) from the morning time on 29 June 2013 has inhibited the fountain effect. This is in contrast to the observations by *Fejer and Emmert* [2003] and *Huang* [2013] that over low latitudes, the DD effects are only seen significantly in the equatorial plasma drifts during afternoon and nighttime.

In a study of the climatology of zonal plasma drifts over Jicamarca by *Fejer et al.* [2005], the DD electric field was shown to act with a time delay of about 3–15 h after a period of increased magnetic activity. The intensity of the geomagnetic activity was defined in terms of the *Kp* indices (quiet time conditions defined by an average *Kp* 3.0 over the preceding 9 h). They suggested that the DD electric field largely accounts for the disturbed time zonal plasma drifts. The short-term DD effects were attributed to traveling atmospheric disturbances which can reach equatorial latitudes a few hours after enhancement in the high-latitude disturbance current.

The study of DD effects on the nocturnal equatorial *F* region over Indian longitudes also showed short-term DD effects with a time delay of 4 h or even less [*Kakad et al.*, 2011]. However, they have not studied the DD effects on the daytime *F* region. The case study presented here gives clear evidence for the complete alteration of the latitudinal pattern of TEC in the presence of the westward zonal electric field. In this event, the storm time response is dominated by the electrodynamical forcing and hence the composition changes or chemistry plays a secondary role highlighting the relative importance of ionospheric electrodynamics over chemistry (composition changes). This is in contrast to the case of the 18–21 February 2014 storm, during which no significant changes were seen in the TEC over the crest region due to the competing effects of the DDEF with the changes caused by the composition disturbances [*Shreedevi et al.*, 2016].

The evidences for DD electric fields over the low-latitude region are sparse, especially during daytime. Apart from this, it is always difficult to delineate the DD effect from the compositional disturbances based on ionospheric observations (like GPS-based diurnal variation of TEC) alone, and this investigation makes a definite progress on this account, because of the availability of other simultaneous data like latitudinal variation of TEC from beacon satellites along with magnetic field and ionospheric observations from equatorial stations.

5. Conclusion

In this work, we have studied the impact of a geomagnetic storm that occurred during 28–29 June 2013 using GPS-TEC measurements over northern midlatitude station Shimla, low-latitude stations Bhopal and Ahmedabad, magnetic equatorial station Trivandrum, along with latitudinal variation of TEC derived using radio beacon observations. The northern hemispheric low-middle latidues shows a clear response to the disturbance dynamo electric field. It is seen that as a result of the westward DD electric field the EIA is completely suppressed. This is an interesting event which shows that daytime zonal electric fields can become westward during the late main phase to recovery phase of a storm, and because this happens from the morning hours, the fountain can completely cease and the latitude variation of TEC can peak over the equator. The present study using both GPS-TEC and LEO satellite-based beacon TEC data, from the Indian region demonstrating the complete suppression of EIA under the influence of DD electric field provides a clear example of the effect of storm time electrodynamical forcing on the low-latitude plasma density distribution. The study also demonstrates the usefulness of LEO satellite-based radio beacon observations to investigate the storm time low-latitude ionosphere.

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References

Balan, N., Y. Otsuka, M. Nishioka, J. Y. Liu, and G. J. Bailey (2013), Physical mechanisms of the ionospheric storms at equatorial and higher latitudes during the recovery phase of geomagnetic storms, *J. Geophys. Res. Space Physics*, *118*, 2660–2669, doi:10.1002/jgra.50275.

Blanc, M., and A. D. Richmond (1980), The ionospheric disturbance dynamo, *J. Geophys. Res.*, *85*(16), 925.

Chakrabarty, D., R. Sekar, R. Narayanan, and C. V. Devasia (2005), Evidence for interplanetary electric field effect on the OI 630.0 nm airglow over low latitudes, *J. Geophys. Res.*, *110*(A11301), doi:10.1029/2005JA011221.

Christensen, A. B. (2003), Initial observations with the Global Ultraviolet Imager (GUVI) in the NASA TIMED satellite mission, *J. Geophys. Res.*, *108*(A12), 1451, doi:10.1029/2003JA009918.

Fejer, B. G., and J. T. Emmert (2003), Low-latitude ionospheric disturbance electric field effects during the recovery phase of the 19–21 October 1998 magnetic storm, *J. Geophys. Res.*, *108*(A12), 1454, doi:10.1029/2003JA010190.

Fejer, B. G., C. A. Gonzales, D. T. Farley, M. C. Kelley, and R. F. Woodman (1979), Equatorial electric fields during magnetically disturned conditions: 1. The effect of the interplanetary magnetic field, *J. Geophys. Res.*, *84*(13), 5797–5802.

Fejer, B. G., J. R. Souza, A. S. Santos, and A. E. C. Pereira (2005), Climatology of *F*-region zonal plasma drifts over Jicamarca, *J. Geophys. Res.*, *110*, A12310, doi:10.1029/2005JA011324.

Fejer, B. G., J. W. Jensen, and S.-Y. Su (2008), Seasonal and longitudinal dependence of equatorial disturbance vertical plasma drifts, *Geophys. Res. Lett.*, *35*, L20106, doi:10.1029/2008GL035584.

Fuller-Rowell, T. J., M. V. Codrescu, R. J. Moffett, and S. Quegan (1994), Response of the thermosphere and ionosphere to geomagnetic storms, *J. Geophys. Res.*, *99*(A3), 3893–3914, doi:10.1029/93JA02015.

Huang, C. M. (2013), Disturbance dynamo electric fields in response to geomagnetic storms at different universal times, *J. Geophys. Res. Space Physics*, *118*, 496–501, doi:10.1029/2012JA018118.

Huang, C.-S., J. C. Foster, and M. C. Kelley (2005), Long-duration penetration of the interplanetary electric field to the low-latitude ionosphere during the main phase of magnetic storms, *J. Geophys. Res.*, *110*, A11309, doi:10.1029/2005JA011202.

Kakad, B., D. Tiwari, and T. K. Pant (2011), Study of disturbance dynamo effects at nighttime equatorial *F* region in Indian longitude, *J. Geophys. Res.*, *116*, A12318, doi:10.1029/2011JA016626.

Kelley, M. C., B. G. Fejer, and C. A. Gonzales (1979), An explanation for anomalous equatorial ionospheric electric fields associated with a northward turning of the interplanetary magnetic field, *Geophys. Res. Lett.*, *6*, 301.

Lei, J., Q. Zhu, W. Wang, A. G. Burns, B. Zhao, X. Luan, J. Zhong, and X. Dou (2015), Response of the topside and bottomside ionosphere at low and middle latitudes to the October 2003 superstorms, *J. Geophys. Res. Space Physics*, *120*, 6974–6986, doi:10.1002/2015JA021310.

Lin, C., J. Y. Liu, T. W. Fang, P. Y. Chang, H. F. Tsai, C. H. Chen, and C. C. Hsiao (2007), Motions of the equatorial ionization anomaly crests imaged by FORMOSAT-3/COSMIC, *Geophys. Res. Lett.*, *34*, L19101, doi:10.1029/2007GL030741.

Maruyama, N., A. D. Richmond, T. J. Fuller-Rowell, M. V. Codrescu, S. Sazykin, F. R. Toffoletto, R. W. Spiro, and G. H. Millward (2005), Interaction between direct penetration and disturbance dynamo electric fields in the storm-time equatorial ionosphere, *Geophys. Res. Lett.*, *32*, L17105, doi:10.1029/2005GL023763.

Raghavarao, R., P. Sharma, and M. R. Sivaraman (1977), Correlation of the ionisation anomaly with the intensity of the electrojet, *Proceedings of the Open Meetings of the Working Groups on Physical Sciences*, 7–18.

Ridley, A. J., Y. Deng, and G. Toth (2006), The Global Ionosphere-Thermosphere Model (GITM), *J. Atmos. Solar-Terrestr. Phys.*, *68*, 839–864.

Rush, C. M., and A. D. Richmond (1973), The relationship between the structure of the equatorial anomaly and the strength of the equatorial electrojet, *J. Atmos. Terr. Phys.*, *35*, 1171.

Sastri, J. H. (1988), Equatorial electric fields of ionospheric disturbance dynamo origin, *Ann. Geophys.*, *6*, 635–642.

Sastri, J. H., K. Niranjan, and K. S. V. Subbarao (2002), Response of the equatorial ionosphere in the Indian (midnight) sector to the severe magnetic storm of July 15, 2000, *Geophys. Res. Lett.*, *29*(13), 1651, doi:10.1029/2002GL015133.

Scherliess, L., and B. G. Fejer (1999), Radar and satellite global equatorial F-region vertical drift model, *J. Geophys. Res.*, *104*(A4), 6829–6842, doi:10.1029/1999JA900025.

Shreedevi, P. R., S. V. Thampi, D. Chakrabarty, R. K. Choudhary, T. K. Pant, A. Bhardwaj, and S. Mukherjee (2016), On the latitudinal changes in ionospheric electrodynamics and composition based on observations over the 76–77°E meridian from both hemispheres during a geomagnetic storm, *J. Geophys. Res. Space Physics*, *121*, 1557–1568, doi:10.1002/2015JA021841.

Simi, K. G., S. V. Thampi, D. Chakrabarty, D. M. Pathan, S. R. Prabhakaran Nayar, and T. K. Pant (2012), Extreme changes in the equatorial electrojet under the influence of interplanetary electric field and the associated modification in the low-latitude F region plasma distribution, *J. Geophys. Res.*, *117*(A03331), doi:10.1029/2011JA01732.

Stolle, C., C. Manoj, H. Luhr, S. Maus, and P. Alken (2008), Estimating the daytime equatorial ionization anomaly strength from electric field proxies, *J. Geophys. Res.*, *113*, A09310, doi:10.1029/2007JA012781.

Thampi, S. V., M. S. Bagiya, D. Chakrabarty, Y. B. Acharya, and M. Yamamoto (2014), An ensemble average method to estimate absolute TEC using radio beacon-based differential phase measurements: Applicability to regions of large latitudinal gradients in plasma density, *Radio Sci.*, *49*, 1153–1161, doi:10.1002/2014RS005372.

Tsurutani, B. T., et al. (2008), Prompt penetration electric fields (PPEFs) and their ionospheric effects during the great magnetic storm of 30–31 October 2003., *J. Geophys. Res.*, *113*, A5311, doi:10.1029/2007JA012879.

Tulasiram, S., et al. (2015), Duskside enhancement of equatorial zonal electric field response to convection electric fields during the St. Patrick's day storm on 17 March 2015, *J. Geophys. Res. Space Physics*, *121*, 538–548, doi:10.1002/2015JA021932.

Vichare, G., A. Ridley, E. Yigit (2012), Quiet time low latitude ionospheric electrodynamics in the non-hydrostatic global ionosphere-thermosphere model, *J. Atmos. Sol. Terr. Phys.*, *80*, 161–172.

Yigit, E., H. U. Frey, M. B. Moldwin, T. J. Immel, A. J. Ridley (2016), Hemispheric differences in the response of the upper atmosphere to the August 2011 geomagnetic storm: A simulation study, *J. Atmos. Sol. Terr. Phys.*, *141*, 13–26.