Response of the Earth’s equatorial ionosphere during the severe G4-class geomagnetic storm of 8th September 2017

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Abstract. Equatorial and low latitude ionospheric response of the 8th September 2017 severe G4-class geomagnetic storm is investigated using the total electron content (TEC) data from a longitudinal chain of global positioning system (GPS) receivers over Asian, African and American sectors. During the main phase, a positive storm effect is observed over Asian sector, a complete negative storm effect over African sector and both are observed over American sector. A sharp increase in peak TEC is observed over the complete longitudinal chain during the recovery phase. The results show the decisive contribution of prompt penetration electric fields (PPEFs) and disturbance dynamo electric fields (DDEFs), storm time disturbed meridional (equatorward) wind as well as the neutral compositional changes over equatorial and low latitudes in the observed ionospheric storm effects.

1. Introduction
The ionized region of the earth’s atmosphere i.e. the ionosphere is perturbed by different meteorological disturbances like tropical cyclones, lightning [1], solar and space weather disturbances like solar flares, geomagnetic storms [2]. These in terns perturb radio wave propagation through the ionosphere [3]. The composition, temperature, circulation and electric fields of the whole thermosphere-ionosphere (T-I) system change considerably during geomagnetic storms due to the enhanced coupling between the solar wind and the ionosphere. A geomagnetic storm is a disturbance in the earth’s magnetic field due to the enhanced injection of solar energy into the earth’s magnetosphere-ionosphere-thermosphere system [4]. These in turn significantly changes the TEC during the storm period [2]. In low latitude and equatorial regions, the storm-time ionospheric disturbed electric fields can effectively redistribute the ionospheric plasma to create ionospheric storm effects [5].

In low latitude and equatorial regions, the storm-time ionospheric disturbed electric fields can affectively redistribute the ionospheric plasma to create ionospheric storm effects. Due to the almost instantaneous response of (a) prompt penetration electric field or PPEF [6] and the delayed response of the (b) disturbance dynamo electric field or DDEF, the ionospheric electrodynamics over the middle to low latitudes get modulated [7]. With the starting of the storm’s main phase, the interplanetary electric field (IEF) penetrates instantaneously (as PPEF) from high-latitude to mid and low-latitudes which are perturbed within few minutes and up to an hour after commencement of storm. The electric field perturbations associated with the PPEF are usually directed eastward during the daytime, thus enhancing the ionospheric electric field, and westward during nighttime causing the opposite effect. On the other hand, the slowly varying electric field perturbations i.e. the DDEF are due to over shielding effects of the interplanetary electric field and are associated with the meridional circulation from polar to
equatorial latitudes. In dayside, the DDEF is directed westward thus reducing the ambient ionospheric electric field, and its direction is eastward in nightside with the opposite effect [8]. It perturbs the low-latitude ionosphere during and up to about a day or two after the onset of a geomagnetic storm. At equatorial and low latitudes, the ionospheric plasma is redistributed by the storm-induced ionospheric electric field perturbations which in turn affect the occurrence of plasma density irregularities [5,9].

A significant theoretical development explaining the space weather effect on earth ionosphere has been possible due to the past 400 years of scientific research on the sun, space weather and its effect on earth’s magnetosphere and ionosphere. With the advent of space era, the studies of geomagnetic storms and their solar and interplanetary causes have come to the prime focus of the atmospheric physicists [10]. The 1071 operational satellites (as of May 2017 according to www.universetoday.com) on orbit has different types of scientific, commercial and lifesaving applications like meteorology, earth observation, communications, global navigation, security and defence. Space weather, especially geomagnetic storms can affect these orbiting satellites by several different ways like (i) increase in satellite drag by Joule heating of the atmosphere, (ii) uncontrolled re-entry of satellites, (iii) satellite damage, (iv) navigation problems, (v) communication failures, (vi) life-threatening power outages [2,10,11].

The complete understanding of the geomagnetic storms is still lacking and most importantly the accurate prediction method of storm occurrence is still in developing stage due to which the effects of the intense geomagnetic storms in earth’s atmosphere are still examined. The principal motivation behind this research is to study the impact of the severe G4-class geomagnetic storm of 8 September 2017 on the equatorial ionosphere of the globe and to investigate the responsible physical mechanisms i.e. how the solar driven background winds and global thermospheric neutral compositions contribute to the ionospheric responses.

2. Data Sources and Processing Methods
Black triangles of figure 1 show the location of a longitudinal chain of 7 GPS receivers, located in the equatorial region of Asian, African and American sectors whose data is used to study the ionospheric response of the G4 class geomagnetic storm of 8 September 2017. The name of the receiver stations with their sectors, country, geographic locations, magnetic dip latitudes and local time (LT) conversion with respect to UT is tabulated in table 1. To portray the variations of storm-time interplanetary and geomagnetic conditions solar indices viz. solar wind speed, solar wind pressure (ram pressure); geomagnetic activity indices viz. AE index, AL/AU index, SYM-H, and interplanetary indices viz. interplanetary magnetic field (IMF Bz), interplanetary electric field (IEF) data are used.

![Figure 1. Locations of IGS GPS receivers NAUR, PNGM situated in Asian sector; MAL2, MBAR, NKLG in African sector and SALU, RIOP in American sector.](image)

The monthly mean or the background VTEC is computed by taking the average of the VTEC values of 10 international quiet days. Ionospheric F2 layer critical frequency (foF2) and ionospheric F2 layer true height variations during the observed period is presented by the global foF2 and hmF2 maps provided by IZMIRAN. To study the atmospheric neutral compositional changes, the global [O/N2] maps are used which provide the global thermospheric neutral composition variations obtained from
Global Ultraviolet Imager (GUVI) instrument on board TIMED (Thermosphere Ionosphere Mesosphere Energetics and Dynamics) spacecraft.

**Table 1. Geographic and geomagnetic coordinates of the IGS GPS stations**

| Sectors | Receivers | Geographic | Magnetic | Local time (hr) |
|---------|-----------|------------|----------|----------------|
|         | Name      | Country    | latitude & longitude | dip latitude | LT=UT+12 |
| Asia    | NAUR      | Nauru      | 0.55°S, 166.93°E | 5.35°S | LT=UT+12 |
|         | PNGM      | Papua New Guinea | 2.04°S, 147.37°E | 9.32°S | LT=UT+10 |
| Africa  | MAL2      | Kenya      | 2.99°S, 40.19°E | 6.67°S | LT=UT+3 |
|         | MBAR      | Uganda     | 0.6°S, 30.74°E | 2.83°S | LT=UT+3 |
|         | NKLG      | Gabon      | 0.35°N, 9.67°E | 1.59°N | LT=UT+1 |
| America | SALU      | Brazil     | 2.59°S, 44.21°W | 5.83°N | LT=UT-3 |
|         | RIOP      | Ecuador    | 1.65°S, 78.65°W | 7.89°N | LT=UT-5 |

3. Observational Results

3.1. Variations of interplanetary and geomagnetic conditions during 6-9 September 2017

![Figure 2](image.png)

*Figure 2.* Temporal variations of (a) solar wind speed (b) ram pressure (c) AE index (d) AL/AU index (e) IMF Bz (f) IEF and (g) SYM-H during 6-9 September 2017.
Figure 2 shows 1 min temporal variations of solar wind parameters, namely (figure 2a) solar wind speed, (figure 2b) solar wind pressure (ram pressure), geomagnetic activity indices like (figure 2c) AE index, (figure 2d) AL/AU index, interplanetary indices like (figure 2e) interplanetary magnetic field (IMF Bz), (figure 2f) interplanetary electric field (IEF) and (figure 2g) SYM-H during 6-9 September 2017. All indices show quiet time variation signatures on 6th September i.e. one the day prior to the storm onset. During the storm period, average solar wind speed varied within 450-850 km/s, solar wind pressure varied between 2 and 14 nPa, IMF Bz fluctuated between 17 to -31 nT, IEF varied within +20 to -11 mV/m, AE index reached a maximum 2680 nT, the minimum SYM-H value was recorded -145 nT. The whole scenario portrays the interplanetary and geomagnetic conditions favorable for an intense geomagnetic storm.

The IMF Bz turned northward sharply on 7th September around 00:50 UT indicating the SSC of the storm. There was rapid north-south fluctuation upto 7:00 UT after which it was steady in the northward direction until the sharp increase around 20:30 UT. Again, IMF Bz turned southward around 20:45 UT until it reached the minimum value of -30.85 nT around 23:33 UT after which there was a prolonged north-south rapid fluctuation till 11:30 UT on 8th September. After that IMF Bz sharply turned southward and reached its second minimum value of -15.55 nT around 11:51 UT on the same day after which it gradually reached its quite-time value.

3.2. Variations of ionospheric VTEC during 6-9 September 2017

![Figure 3](image-url)  
Figure 3. Variation of VTEC along with monthly mean values and deviation of VTEC from monthly mean values for stations (a, b) NAUR, (c, d) PNGM, respectively, of Asian sector during 6-9 September 2017.

The variation of VTEC along with monthly mean values and deviation of VTEC from monthly mean values are shown in figure 3 for stations (a, b) NAUR, (c, d) PNGM of Asian sector, in figure 4 for stations (e, f) MAL2, (g, h) MBAR, (i, j) NKLG of African sector and in figure 5 for stations (k, l) SALU, (m, n) RIOP of American sector; during 6-9 September 2017. With the initiation of the storm SSC around 00:50 UT on 7th September, the dayside ionospheric VTEC variation of both the stations shows positive storm effect with an average of 11.43% and 12.46% increase (compared to the quiet conditions of 6th September) over NAUR and PNGM, respectively, of Asian sector. In case of the
African sector, a significant negative storm effect in VTEC is observed over all the three stations (6.47%, 14.19% and 10.94% reduction of VTEC over MLA2, MBAR and NKLG, respectively, compared to the previous day) as the period of SSC and the rapid N-S fluctuation of IMF Bz thereafter, coincided with local post-midnight hours. Interestingly, in the American sector, a negative storm effect is observed over the station SALU (2.92% reduction in VTEC) and a positive storm effect over the station RIOP (10.26% enhancement in VTEC) though it was mostly local pre-midnight hours when the SSC and the rapid N-S fluctuation of IMF Bz occurred.

Figure 4. Variation of VTEC along with monthly mean values and deviation of VTEC from monthly mean values for stations (e, f) MAL2, (g, h) MBAR, and (i, j) NKLG respectively of African sector, during 6-9 September 2017.
After the occurrence of minimum Sym-H excursion (i.e. after the initiation of the recovery phase) around 1:00 UT on 8th September, a sharp increase in VTEC is observed around 1:35-1:50 UT (between 11:35-13:50 LT) for both the stations over Asian sector. The sharp VTEC occurrence over African sector is observed around 14:15-15:30 UT (between 17:15-18:30 LT) i.e. almost during the local afternoon hours which are delayed response. Dural peaks in diurnal VTEC variation are observed for all the three stations of African region, quantitatively 33.3 TECU, 51.9 TECU (around 12:10 LT and 16:30 LT) for NKLG; 31.67 TECU, 45.84 TECU (around 10:54 LT and 18:00 LT) for MBAR and 40.1 TECU, 35.98 TECU (around 13:00 LT and 18:26 LT) for MAL2. Fluctuating VTEC between two maxima occurrence time is observed for the station MAL2. Over the American sector, the sharp VTEC occurrence is observed around 12:48 LT (49.18 TECU) for SALU and 15:42 LT for RIOP. It is worth mentioning that the storm effect was positive during the recovery phase for all the stations of the entire equatorial longitudinal belt (the average percentage increase/decrease values for all the stations are arranged in table 2).

**Table 2. Percentage deviation of VTEC**

| Sectors | Receivers | Percentage deviation of VTEC (compared to the previous day) |
|---------|-----------|-------------------------------------------------------------|
|         |           | 7-09-2017 | 8-09-2017 | 9-09-2017 |
| Asian   | NAUR      | 11.43     | 11.78     | 0.21      |
|         | PNGM      | 12.46     | 12.65     | -10.09    |
| African | MAL2      | -6.47     | 11.76     | -5.54     |
|         | MBAR      | -14.19    | 20.1      | -10.36    |
|         | NKLG      | -10.94    | 2.8       | -21.31    |
| American| SALU      | -2.92     | 22.56     | -27.08    |
|         | RIOP      | 10.26     | 9.18      | -25.01    |

*Figure 5. Variation of VTEC along with monthly mean values and deviation of VTEC from monthly mean values for stations (k, l) SALU, and (m, n) RIOP, respectively, of American sector during 6-9 September 2017.*
3.3. Variations of $f_0F_2$ and $h_mF_2$ during 6-9 September 2017

Figure 6 shows the global variation of (a, b, c, d) ionospheric $F_2$ later critical frequency and (e, f, g, h) ionospheric $F_2$ layer true height during 6-9 September 2017. For reference the locations of the IGS GPS stations of Asian, African and American sectors are shown by red triangles. A careful observation indicates a minor increase in $f_0F_2$ and decrease in $h_mF_2$ values over Asian sector on 7th September compared to the previous quiet day, which is consistent with the positive storm effect observed in VTEC variation. Over the African sector, a decrease in $f_0F_2$ spatial variation is observed, which indicates the negative storm effect over this region. In the American region a noticeable increase in $f_0F_2$ with a concurrent decrease in $h_mF_2$ is observed over the station RIOP which supports the positive storm effect over this station.

On 8th September a significant increase in $f_0F_2$ and a drastic decrease in $h_mF_2$ are observed over the American sector indicating a strong positive storm effect. Over the African and Asian sectors, the increase in $f_0F_2$ and decrease in $h_mF_2$ are not so prominent though these regions also show positive storm effects on that day. On 9th September $f_0F_2$ increases drastically with a concurrent significant increase in $h_mF_2$ clearly indicating the recovery of the positive storm effect of the previous day. On the other hand, in Asian sector, a further decrease in $f_0F_2$ and a concurrent significant increase in $h_mF_2$ are observed which can be easily correlated to the enhancement in VTEC during the local daytime duration over this sector. Over the African sector, moderate variation in $f_0F_2$ and $h_mF_2$ is observed from the previous day which supports very slow recovery from the positive storm effect as clearly seen in VTEC variation over this sector.

![Figure 6](image_url)

**Figure 6.** Variations of (a, b, c, d) ionospheric $F_2$ layer critical frequency and (e, f, g, h) ionospheric $F_2$ layer true height during 6-9 September 2017. The red triangles show the locations of the IGS GPS stations of Asian, African and American sectors.
4. Summary and Discussion
During the main phase of the storm increase in VTEC over the Asian sector is distinct due to the effect of PPEF [12] and the decrease in VTEC over the African and American sectors is due to a weak efficiency of PPEF during daytime [13]. The positive storm effect during the recovery phase of the storm can be due to the disturbed equatorward neutral wind which pushes the F2 layer to higher altitudes where the electron densities tend to increase due to the lower recombination rates. It can also hinder the formation of equatorial ionization anomaly (EIA), which in turn causes the positive storm effects in the equatorial regions and negative ionospheric storm effects in the crest regions [5,14]. The dual peaks (twin peaks or double maxima or midday bite-outs) in VTEC diurnal variation observed over the African stations during the recovery phase (8th September) are the signatures shown in both ring current variations and auroral electrojets related to the onset and recovery phases of sub-storms. The physical mechanism of combined E×B vertical drift effect and altitude dependent F-region chemical loss process can be responsible for the diurnal double maxima. Meridional winds associated with traveling atmospheric disturbances (TADs) can be a possible cause of diurnal ionospheric VTEC midday bite-out disturbance patterns as supported by modeling studies [15].

A sound understanding of the atmospheric neutral compositional changes of any region of interest can be obtained from global [O/N\textsubscript{2}] maps. The ‘South Atlantic Anomaly Region’ which experiences enhanced radiation from particles from the earth’s radiation belts is represented by the white oval patches in the global [O/N\textsubscript{2}] maps. Due to this perturbation the signal from the atmospheric emission is contaminated and consequently the data is removed. An enhancement in [O/N\textsubscript{2}] can be explained due to enhancement in atomic oxygen (O) or reduction in molecular nitrogen (N\textsubscript{2}) or due to the combined effect of both and a reduction in the ratio can be explained by the opposite mechanism [2]. The production or enhancement of the ionospheric plasma at F region heights can be attributed to enhancement in atomic oxygen [7] and the opposite is due to the supply of molecular N\textsubscript{2} from high latitudes which increases recombination probability [16].

![Figure 7](image_url)

**Figure 7.** TIMED/GUVI global maps of [O/N\textsubscript{2}] variations (a, b, c, d) during 6-9 September 2017.

Figure 7 shows the TIMED/GUVI global maps of [O/N\textsubscript{2}] variations (a, b, c, d) during 6-9 September 2017. It can be clearly observed that on 7th September there is a small increase in [O/N\textsubscript{2}] over Asian sector, noticeable decrease over African sector and a considerable increase over and around the station RIOP of American sector which clearly support the observed ionospheric VTEC variations over these
equatorial regions. On 8th September i.e. during the recovery phase of the storm, there is a significant increase in [O/N\textsubscript{2}] over the complete equatorial and low latitude region which distinctly contributes to the enhanced positive storm effect observed over all the stations of the Asian, African and American regions. The further enhancement of [O/N\textsubscript{2}] relates to the positive storm effect over Asian sector on 9th September whereas the reduced [O/N\textsubscript{2}] over African and American sectors are consistent with the recovery of the storm-time VTEC observed over these regions.

5. Concluding Remarks
In this paper, the response of equatorial and low latitude ionosphere during the severe G4-class geomagnetic storm of 8th September 2017 is investigated using the total electron content data (TEC) derived from a longitudinal chain of Global Positioning System (GPS) receivers extended over the equatorial region of Asian, African and American sectors. The underlying physical mechanisms responsible for the longitudinal ionospheric behavior during different seasons are explained and supported by the [O/N\textsubscript{2}] data representing global thermospheric compositional changes. The significant outcomes of this study can be concluded as follows:

a. During the main phase a positive storm effect is observed over the Asian sector, a complete negative storm effect over the African sector and both are observed over American sector.
b. A sharp increase in peak TEC is observed over the complete longitudinal chain during the recovery phase. The storm effect was positive during the recovery phase for all the stations of the entire equatorial longitudinal belt.
c. The results show the decisive contribution of disturbed electric fields (DEFs), storm time disturbed meridional (equatorward) wind as well as the neutral compositional changes over equatorial and low latitudes in the observed ionospheric storm effects.
d. The diurnal twin peaks or double maxima or midday bite-outs in Dural peaks in diurnal VTEC variation are observed for all the three stations of African region which are the combined effect of E×B vertical drift and altitude dependent F-region chemical loss process or the meridional winds associated with traveling atmospheric disturbances (TADs).
e. The significant positive storm effect observed over the complete equatorial latitudinal belt during the recovery phase of the storm can be attributed due to the significant enhancement of thermospheric [O/N\textsubscript{2}] over this region.

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