Conjugate hemispheric response of earth’s ionosphere due to geomagnetic storms occurred during two equinox periods

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Abstract. The ionospheric response of two geomagnetic storms of 2016 occurred during spring equinox (5–8 March, 2016) and autumn equinox (12–15 October, 2016) is investigated using the total electron content (TEC) data derived from Global Positioning System (GPS) receivers located in the equatorial ionization anomaly (EIA) crest regions at northern hemisphere (Tripura University, Agartala, India) and southern hemisphere (Karratha, Australia). While in southern EIA station ionospheric responses for the two storms are found to be symmetric but in northern EIA station the responses are completely asymmetric. The observations are explained by the contribution of storm-time prompt penetration electric fields (PPEFs), disturb dynamo electric fields (DDEFs), disturbed meridional (equatorward) winds as well as the neutral compositional changes over low latitudes.

1. Introduction
Due to the enhanced injection of solar energy in earth’s magnetosphere-ionosphere-thermosphere system, the disturbance termed as geomagnetic storm [1] and the consequent ionospheric storm occurs. The ionospheric storm, which is disturbances in the chemistry and dynamics of the coupled thermosphere and ionosphere system, occurs primarily due to the solar wind energy input [2]. Ions (mostly protons and oxygen ions) and electrons, in the energy range 10–300 keV, produce the magnetic field disturbance by creating an enhanced ring current. The change in earth’s magnetic field during storm leaves a consequent signature in the total electron content of the ionosphere. During positive ionospheric storms, electron density increases due to thermospheric winds [3,4], compositional changes or transport of ionization or electric field changes [5] and during negative storm electron density decreases due to compositional changes of the ionosphere [4].

The enhanced Joule heating at polar latitudes (a) due to precipitation of auroral electrons and protons causing the particle heating, relative motion of plasma (ions) and neutrals, is the main energy source during geomagnetic storms. It changes the global thermospheric wind circulation and neutral composition. The enhanced upward vertical wind at high latitudes rises and increases the molecular rich air in altitude due to storm-induced heating which in turn induces an equatorward meridional wind that further contributes to this increase [3,6]. From high latitudes, the enhanced molecular rich air is transported toward middle to low latitudes also by the background (b) seasonal winds i.e. summer-to-winter interhemispheric wind and (c) the solar-driven diurnal wind [3]. Due to the equal solar illumination over both the hemisphere during spring and autumn equinoxes, the seasonal winds are
directed from high latitudes of both the hemispheres towards equatorial latitudes which are in phase with the storm induced strong equatorward meridional winds. These two winds along with the daytime poleward diurnal wind transport the ionospheric plasma symmetrically from the high latitudes of both the hemisphere towards the equatorial latitudes [7].

In the present analysis, we for the first time compared the characteristics of ionospheric response of two geomagnetic storms of nearly equal strengths during spring equinox (5-8 March, 2016) and autumn equinox (12-15 October, 2016) through TEC variations at two stations, one in northern EIA region and the other in southern EIA region. As the established theory till date suggests a symmetrical ionospheric response (due to in-phase transport of plasma from high to low latitudes) our aim is also to investigate the possible physical mechanism responsible for the observed effects.

2. Data Sources and Processing Methods

The total electron content data is derived from Global Positioning System (GPS) receiver, GSV 4004B dual frequency, in operation at Tripura University (23.76°N,91.26°E), Agartala, India. The receiver tracks up to 11 GPS satellites at the L1 (1575.42 MHz) and L2 (1227.6 MHz) frequencies simultaneously [8, 9]. It provides uncalibrated slant TEC (STEC) data at 1-min sampling rate. After applying a suitable satellite and receiver bias correction, the slant TEC values are converted to vertical TEC (VTEC) following [8]:

\[
VTEC = STEC \times \cos \left[ \arcsin \left( \frac{R_e \cos \theta}{R_e + h_{\max}} \right) \right]
\]

\( R_e = 6378 \text{ km (Earth’s mean radius)}, \ h = 350 \text{ km (height of the ionospheric shell) above the Earth’s surface}, \ \theta = \text{the elevation angle at the ground station}. \)

Data of other station, Karratha (-20.98°N, 117.09°E), Australia in Southern EIA region is collected from IGS website (geoftp01.ucsd.edu/pub). The monthly mean or the background VTEC is computed by taking the average of the VTEC values of 10 international quiet days (wdc.kugi.kyoto-u.ac.jp/dstdir/). To study the temporal variation of F2 layer critical frequency, \( f_0F2 \) the global maps for \( f_0F2 \) are used, obtained from IZMIRAN GIM-TEC (www.izmiran.ru). To study the atmospheric neutral compositional changes, the global [O/N\(_2\)] maps are used (guvitimed.jhuapl.edu/guvi-gallery13on2). The maps provide the global thermospheric neutral composition variations obtained from Global Ultraviolet Imager (GUVI) instrument on board TIMED (Thermosphere Ionosphere Mesosphere Energetics and Dynamics) spacecraft.

3. Observational Results

3.1. Variations of interplanetary and geomagnetic conditions during 5-8 March 2016

Figure 1 (Left panel) shows 5 min temporal variations of interplanetary indices like (figure 1(a)) interplanetary magnetic field (IMF Bz), (figure 1(d)) interplanetary electric field (IEF), solar wind parameters namely (figure 1(b)) solar wind speed, (figure 1c) solar wind pressure (ram pressure), geomagnetic activity indices like (figure 1(e)) AE index, (figure 1(f)) SYM-H, during 5-8 March 2016. From the figure, it can be clearly seen that on the day prior to the storm onset i.e. March 5th, all the interplanetary and geomagnetic indices show quiet time variation signatures. During the storm period, IMF Bz fluctuated between +15 and −15 nT, average solar wind speed increased from 200 to 550 km/s, solar wind pressure gradually increased to 10 nPa, IEF varied between -5 to 8 mV/m, AE index sharply increased to 1300 nT, SYM-H decreased and the minimum value was recorded − 100 nT. The whole scenario portrayed the interplanetary and geomagnetic conditions favorable for an intense geomagnetic storm. On March 6th, the IMF Bz sharply turned from northward to southward at 6.10 UT and after few minutes it again turned to northward and after 9.0 UT it turned southward and continued up to 17.00 UT with fluctuations.
3.2. Variations of interplanetary and geomagnetic conditions during 12-15 October 2016
Figure 1 (right panel) shows 5 min temporal variations of interplanetary indices like (figure 1g) interplanetary magnetic field (IMF Bz), (figure 1j) interplanetary electric field (IEF), solar wind parameters namely (figure 1h) solar wind speed, (figure 1i) solar wind pressure (ram pressure), geomagnetic activity indices like (figure 1k) AE index, (figure 1l) SYM-H, during 12-15 October. From the figure, it can be clearly seen that on the day prior to the storm onset i.e. October 12th, all the interplanetary and geomagnetic indices show quiet time variation signatures. During the storm period, IMF Bz gradually decreased to a minimum value –20 nT, average solar wind speed sharply increased from 320 to 450 km/s, solar wind pressure sharply increased to 14 nPa and then decreased gradually, IEF gradually increased to 8 mV/m, AE index gradually increased to 1500 nT, SYM-H decreased and the minimum value was recorded –100 nT. The whole scenario portrait the interplanetary and geomagnetic conditions favorable for an intense geomagnetic storm. On October 13th, the IMF Bz turned northward to southward at 1.00 UT and continued up to 23.00 UT (October 14th).

3.3. Variations of VTEC over northern EIA station (AGAR) during 5-8 March and 12-15 October 2016
During the main phase of both the storms (figures 2a and 2b) a negative storm effect is observed at northern EIA station (AGAR), with a sharp dual peak observed on 6th March (prominent peak around 6:10 UT) and single peak on 13th October (around 6:25 UT). In both the cases, peak activity occurs earlier in compare to previous (7:36 and 7:12 UT) quiet days. But in recovery phase of geomagnetic storms, marked differences are observed in diurnal VTEC variations. While the 7th March shows a noticeable positive storm effect on March 8 with sharp dual peaks (around 7:30 UT and 12:00 UT), the 13th October storm shows a negative storm effect on October 14 with sharp dual peaks (back to back) during the early morning hours (around 2:00 UT and 5:10 UT). Also on October 14, significant increase in VTEC is observed during the early morning hours compared to the previous day as well as compared to the recovery phase of 7th March storm. The dVTEC variation during the 7th March storm (figure 3c) shows negative dVTEC (up to -10 TECU) during the main and recovery phase. For the 13th October storm (figure 3d), negative dVTEC is observed during the main phase (on October 13) while sharp positive dVTEC followed by a sharp negative dVTEC variation is observed during the recovery phase on October 14. On 15th October VTEC level increases though it is below the monthly mean i.e. a +ve storm effect is observed.
So we observe a remarkable difference between the 7th March storm and 13th October storm, especially in recovery phases, though the two storms are in equinox seasons of the same year and the interplanetary and geomagnetic conditions are not so different in two storms.

![Figure 2. Temporal variations of VTEC (solid line) and monthly mean of VTEC (dashed line) during (a) 5-8 March, 2016 and (b) 12-15 October, 2016; variations of diurnal VTEC deviation from corresponding monthly mean during (c) 5-8 March, 2016 and (d) 12-15 October, 2016 at northern EIA station (AGAR).](image)

3.4. Variations of VTEC over southern EIA station (KARR) during 5-8 March and 12-15 October 2016

During the main phase of both the storms (figures 3e and 3f) positive storm effects are observed at southern EIA station (KARR) on 6th March and 13th October. In both the cases, peak activity occurs in nearly equal time as the previous (7:20 and 4:70 UT) quiet days. But in recovery phase of geomagnetic storms, strong negative storm effects are observed during both the storms with a sharp dual peak on 7th March (prominent peak around 2:48 UT) and single peak on 14th October (around 4:53 UT). The negative storm effects continue in the following days also. The dVTEC variation during the 7th March storm (figure 3g) shows positive dVTEC (up to +10.00 TECU) during the main phase but negative dVTEC (up to -10.00 TECU) during the recovery phase (on 7th March). On 8th March the dVTEC increases (up to -5.00 TECU). For the October storm (figure 3h), positive dVTEC (up to +15.00 TECU) is observed during the main phase (on October 13) while a very little negative dVTEC variation is observed during the recovery phase (on October 14). On 15th October the negative dVTEC (up to -5.00 TECU) is observed.

So, we observe almost similar ionospheric response during the 7th March storm and 13th October storm in the southern EIA station unlike the northern EIA station.
3.5. Variations of ionospheric foF2 during 5-8 March, 2016 and during 12-15 October, 2016

Figure 4 (left panel) shows IZMIRAN GIM-TEC global maps for the temporal variations of F2 layer critical frequency, foF2. Figure 4 (a-d) corresponds to foF2 images for 5-8 March. The corresponding diurnal average values of foF2 for northern EIA station are approximately 4.5, 4.0, 4.5, and 5.0 respectively and for southern EIA station the values are 8.0, 8.5, 7.0, and 6.5 respectively. So on the storm day foF2 decreases (increases) and in the recovery phase it gradually increases (decreases) around AGAR (KARR) stations.

Figure 4 (e-h) (Right panel) corresponds to foF2 images for 12-15 October. The corresponding approximates diurnal average values of foF2 are 5.0, 4.5, 4.0 and 4.5 respectively for northern EIA station and 7.5, 8.0, 6.0 and 5.5 respectively for southern EIA station. Here on the storm day foF2 decreases (increases) and in the recovery phase it further decreases (increases) and in following day it increases (decreases) around AGAR (KARR) stations. So, the observational results are supported by the critical frequency, foF2 global mapping images.

4. Summary and Discussion

During the different periods of storm occurrence in a single year, the solar illumination in both the hemispheres varies which in turn generates (a) the equatorward meridional wind, background (b) interhemispheric seasonal winds and (c) the solar-driven diurnal wind which combinedly affects storm
time ionospheric responses. Also the thermospheric neutral compositions (O/N\textsubscript{2}) throughout both the hemispheres vary and accordingly it contributes to the ionospheric responses.

The negative storm effect during the main phase of both the storms is due to the weak efficiency of PPEF during daytime [10]. The positive storm effect during the recovery phase of the storm can be attributed 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 negative ionospheric storm effects in the crest regions.

\textbf{Figure 4.} Special variations of F2 layer critical frequency, foF2 during 5-8 March, 2016 (left panel) and during 12-15 October, 2016 (Right panel).

The production or enhancement of the ionospheric plasma at F region heights can be attributed to enhancement in atomic oxygen [6] and the opposite is due to the supply of molecular N\textsubscript{2} from high latitudes which increases recombination probability [11]. With this picture in mind the global
thermospheric neutral composition variations or compositional changes and the corresponding response of the ionospheric plasma during the two storm period is explained as follows:

The reduced \([\text{O}/\text{N}_2]\) on 6th March, 216 in figure 6 (a-d) explains the negative storm effect and enhancement (decrement) of \([\text{O}/\text{N}_2]\) in the following days indicates the positive (negative) storm effect during the recovery phase for AGAR (KARR) station which is also seen from GPS TEC (figure 3(a)) and foF2 (figure 5(a-d)). Similarly, the decrease of \([\text{O}/\text{N}_2]\) in 13th October, 216 and also on 14th explains the continued negative storm effect and increase (decrease) in the same indicates the positive (negative) storm effect in the following days for AGAR (KARR) station. The noticeable peak occurrence on 13th of October, 216 storm in the early morning may be due to some solar flare effect which did not influence the earth geomagnetic conditions but left a signature on VTEC.

Figure 5. TIMED/GUVI global maps of \([\text{O}/\text{N}_2]\) during 5-8 March, 2016 (left Panel) and during 12-15 October, 2016 (Right Panel).

During the equinox period both northern and southern hemisphere are equally illuminated by the Sun. So in both the hemispheres seasonal wind flows from high latitude to low latitude i.e. from pole to
equator. During storm period due to electron precipitation at the poles and hence joule heating there is a storm driven wind flow from pole to equator. Clearly the seasonal and storm driven wind flows are in phase in both hemisphere. So the ionospheric response to geomagnetic storms in two equinox periods of the same year should be symmetric In southern EIA station (KARR) the responses are symmetric but in northern EIA station (AGAR) responses are not symmetric. This asymmetry may be due to the longitudinal difference between the two stations. Clearly the result, especially the asymmetry, cannot be explained completely by the available theoretical knowledge and hence further investigation is necessary.

5. Concluding Remarks
The significant outcomes of this study can be concluded as follows:

a. We observe a complete asymmetrical ionospheric response of the 7\textsuperscript{th} March storm and 13\textsuperscript{th} October storm (two equinox periods) during the recovery phases in the northern EIA crest station.

b. A complete symmetrical ionospheric response is observed for the 7\textsuperscript{th} March and 13\textsuperscript{th} October storms (two equinox periods) during the recovery phases in the southern EIA crest station.

c. The symmetrical ionospheric response in the southern EIA crest station can be explained by the combined transport of storm-time meridional winds and the seasonal hemispheric equatorward winds in the southern hemisphere.

d. Though the same in-phase transport is true for northern hemisphere but it cannot explain the observed asymmetric response which needs further investigation.

This investigation is the first of this kind in understanding the ionospheric response to geomagnetic storm during two different equinox periods of a single year and also validating the theories and physical mechanisms established till date which explains the storm time low latitude and EIA region ionospheric response.

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