Article

Investigation of Daytime Total Electron Content Enhancements over the Asian-Australian Sector Observed from the Beidou Geostationary Satellite during 2016–2018

Oluwaseyi Jimoh 1,2, Jiuhou Lei 1,3,4,* and Fuqing Huang 1,3,4

1 CAS Key Laboratory of Geospace Environment, School of Earth and Space Sciences, University of Science and Technology of China, Hefei 230000, China; oluwaseyijimoh@mail.ustc.edu.cn (O.J.); hsfqing@ustc.edu.cn (F.H.)
2 Department of Physics, Adeleke University Ede, Osun P.M.B 250, Nigeria
3 Mengcheng National Geophysical Observatory, University of Science and Technology of China, Hefei 230000, China
4 CAS Center for Excellence in Comparative Planetology, University of Science and Technology of China, Hefei 230000, China
* Correspondence: leijh@ustc.edu.cn

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Abstract: This study focused on the investigation of daytime positive ionospheric disturbances and the recurrence of total electron content (TEC) enhancements. TEC data derived from the Beidou geostationary satellite over the Asian-Australian sector were used to study the occurrence of TEC enhancements during 2016–2018. The occurrence of TEC enhancements under quiet geomagnetic condition was analyzed. Furthermore, the occurrence of TEC enhancements during different geomagnetic storm phases was considered to address the question that relates to the recurrence of TEC enhancements during the recovery phase of geomagnetic storms. The seasonal variation of TEC enhancements displayed equinoctial and solstitial peaks at the middle and low latitudes respectively. Besides, there was no evident systematic latitudinal dependence in the occurrence of TEC enhancements, albeit at the equatorial station, nearly no TEC enhancement was observed under $K_p < 3$. Meanwhile, the occurrences during the main phases of the geomagnetic storms were significantly above the TEC enhancement baselines except at HKWS. The prominence of TEC enhancements during the main phase in comparison with the initial and recovery phases could be attributed to the effects of prompt penetration electric fields and equator-ward neutral winds. Moreover, the pattern of TEC enhancements during the storm recovery indicate the effects of chemical composition changes, winds, and the possible modulation from the lower atmospheric forcing.

Keywords: ionospheric disturbances; TEC enhancements; geomagnetic activity; recovery phase; recurrence

1. Introduction

The changes resulting from ionospheric disturbances are of importance in space physics research, spacecraft orbital design, and in the practical application of global navigation satellite systems (GNSS) and radio communication. As a result of these consequences, it is of relevance to investigate the occurrence of these disturbances, especially at unexpected periods. Ionospheric F2-layer disturbances are driven by different sources, which are broadly classified into three categories, namely solar
radiation, geomagnetic activity (S-disturbances), and meteorological activities (Q-disturbances) [1,2]. The occurrence of ionospheric Q-disturbance variations in the frequency of appearance and their correlations with geomagnetic storm phases have not been well understood and according to previous studies [3,4], these disturbances have been associated with meteorological events, quasi planetary oscillations in the ionosphere, and seismic events. It has also been observed that the origin of the Q-disturbances is different from that of the regular F2 layer storm-time disturbances [2]. Furthermore, positive disturbances caused by meteorological effects under quiet geomagnetic conditions can attain amplitude comparable to the amplitude of a moderate F2-layer storm [5].

The S-disturbances, on the other hand, are mostly due to geomagnetic storms and have been intensively studied [6–9]. During a S-disturbance, the ionosphere can either increase or decrease in ionization density, which is usually referred to as a “positive” or “negative” ionospheric response, respectively. The positive ionospheric response is possibly caused by chemical composition, equatorward thermospheric winds, electric fields from the magnetosphere, and/or dynamo region of the E-layer and downward protonospheric plasma fluxes [7,9]. Whereas, negative ionospheric response is mainly attributed to thermospheric neutral composition changes in the upper atmosphere [10].

Geomagnetic storms usually comprise of three phases: initial, main, and recovery phases [6,11]. Different processes and interactions are at play, depending on the prevalent geophysical and interplanetary conditions during each phase of a geomagnetic storm [12–18]. The mechanisms responsible for total electron content (TEC) enhancements during the initial and main phases are widely reported [8,19–23]. However, the studies on TEC enhancements during the recovery phase are limited and the mechanism is not well understood yet [24–27]. The ionospheric condition during the recovery phase is related to that of immediate or gradual recovery to the condition before the onset of the storm. As a result, large TEC enhancement during the recovery phase of a geomagnetic storm is enigmatic, especially when the solar, interplanetary, and geomagnetic conditions are quiet. Moreover, geomagnetic storms can enhance or reduce the amplitudes of the Q-disturbances. The study of this interaction is still a subject of interest.

The influence of lower atmospheric forcing on the ionosphere during geomagnetic storms, especially during the recovery phase, has recently drawn great attention [28–30]. However, the published results were generally based on one or two individual storms; statistical results are still pending. A long time data analysis from over a fixed longitude sector has the potential to better separate the ionospheric responses driven by the forces from above (storm) and below (lower atmosphere) during geomagnetic storms, as the ionospheric longitudinal variation can be ignored and quiet-time behavior can be well captured from the longer period of observations.

The observation of daytime TEC enhancements during the recovery phase of the 7–8 September 2017 geomagnetic storm over the Asian-Australian sector [29] presents a new challenge to the study of the ionosphere. The observed TEC enhancements persisted for about 4 days and could not be attributed to the effect of the geomagnetic storm but likely due to forcing from the lower atmosphere. Moreover, the TEC enhancements were greater in magnitude during the recovery than the main phase at some of the stations. Recently, [31] also observed enhancement in TEC during the recovery phase of the 27–30 August 2018 geomagnetic storm. Hence, it is important to investigate the recurrence of TEC enhancements during the recovery phase of geomagnetic storms.

The TEC data from 5 ground-based Beidou GNSS receiver stations over the Asian-Australian sector during 2016–2018 were used to study the occurrence of the TEC enhancements in this current study. The quiet and storm phases’ effects on the occurrence of TEC enhancements were also examined.

2. Data and Methods

In this study, the slant total electron content (STEC) was computed from the dual-frequency signals of Beidou GEO satellites with a time resolution of 30 s. The STEC was converted to vertical TEC (VTEC) using a thin shell model, which assumes that the ionospheric electron densities concentrate on a spherical shell ionosphere of infinitesimal thickness at the location of the ionospheric pierce points (IPPs), using a geometry mapping function proposed by [32]. Further details on how
the VTEC was obtained can be found in [33]. The height of the spherical shell ionosphere was assumed to be at 400 km [34]. Beidou GEO satellites have fixed IPPs unlike the IPPs of the other GNSS which greatly vary with time. This makes the TEC observations of Beidou GEO satellites more suitable for investigating ionospheric variations over fixed longitudes than the non-GEO satellites. Presently, there are 5 GEO satellites in the Beidou system [35], but data from only the GEO-2 satellite were used in this study due to its optimal coverage for each receiver.

Data from 5 stations at the middle, low, and equatorial latitudes over the Asian-Australian sector were analyzed. Figure 1 shows the locations of the receivers (green) used in this study and the corresponding IPP of the GEO-2 satellite (red) at each station. Note that four-letter codes (BBKD, HSKD, HKWS, EUSM and KARR) were used to denote the stations and will be used all through this paper. The geomagnetic equator is where the inclination of the geomagnetic field is zero in the international geomagnetic reference field (IGRF) model and the IGRF version used was the 12th generation [36]. The apex geomagnetic coordinate was computed by tracing the magnetic field line at the desired point up to the magnetic field line’s apex and the geomagnetic latitude was determined by the apex altitude [37].

![Location of Beidou GEO TEC Receivers](image)

**Figure 1.** Location of the Global Navigation Satellite System receivers (green) and corresponding ionospheric pierce points (IPPs, red) used in the present study. The blue dash lines indicate the ±20 magnetic latitudes and the magnetic equator.

In order to quantify the TEC enhancements, both absolute TEC change ($\Delta TEC$) and relative TEC change (rTEC) were derived from the hourly TEC data as shown below:
\[ \Delta TEC = TEC - TEC_m, \]  
\[ rTEC = \frac{TEC - TEC_m}{TEC_m} \times 100\%, \]  
where \( TEC \) is the observed TEC value and \( TEC_m \) is the 27 day TEC running median. TEC enhancement is considered to have occurred if \( \Delta TEC \) and \( rTEC \) exceeded 10 TECU and 30\%, respectively, to minimize the inclusion of smaller TEC enhancements owing to regular day-to-day variability; (2) the duration lasted for at least 4 h, which helps to eliminate short-term ionospheric fluctuations; (3) it was during daytime from 0900–1800 LT to eliminate other enhancements associated with nighttime. Furthermore, only one count was considered per day. The 10.7 cm solar radio flux (F10.7), ring current index (Dst), and planetary K index (Kp) obtained from (http://omniweb.gsfc.nasa.gov/) were used in this study to describe the solar and geomagnetic activity conditions.

3. Results

In this section, the results of the daytime TEC enhancements from Beidou GEO-2 satellite at five different stations during 2016–2018 were presented. The occurrence of TEC enhancements during the quiet geomagnetic condition and geomagnetic storm-phases were also examined.

3.1. Assessment of Ionospheric, Geomagnetic and Solar Conditions

Figure 2a–e illustrates the TEC variations during 2016–2018 at BBKD, HSKD, HKWS, EUSM, and KARR, respectively. The shown coordinates in brackets before each station’s code are the IPPs of the geographic latitudes and longitudes and geomagnetic latitudes, respectively. The grey vertical lines were used to denote the end of one year from the beginning of another. Figure 2f,g presents the 10.7 cm solar flux F10.7 and ring current index Dst respectively during the three years under consideration. The magenta solid shapes shown in Figure 2g indicate the selected geomagnetic storms with Dst \( \leq -50 \) nT during 2016–2018. Successive storms with time intervals less than 5 days, were not considered. This was done to avoid misinterpreting the likely effects of the earlier storm as part of the effects of the subsequent storm on the ionosphere. It can be observed from Figure 2f,g that the solar activity and number of geomagnetic storms that occurred decrease from 2016 to 2018. The magnitudes of the TEC from the time series in Figure 2a–e decrease from 2016 to 2018 and also show dependence on solar activity in concert with F10.7 variation. The TEC variations over BBKD and HSKD show semiannual variations with greater TEC magnitude during the March equinox than the September equinox. Spikes depicting TEC enhancements were most prominent at HSKD in Figure 2b.

The TEC observations at HKWS and EUSM showed semiannual variations as seen in Figure 2c,d. The average TEC magnitude at EUSM was lower than at HKWS and this may be associated with the fountain effect due to \( E \times B \) drift. The fountain effect lifts plasma to higher altitudes at the equatorial region and diffuses it along geomagnetic field lines to higher latitudes [38–41]. This leaves the electron density depleted at the equator. The semiannual variation at HKWS was more evident than at EUSM. In the southern hemisphere, the TEC at KARR showed annual variation, implying that the December electron density was on average greater than that of June.
Figure 2. The time series of total electron content (TEC) over (a–e) BBKD, HSKD, HKWS, EUSM, and KARR, respectively. (f) The 10.7 cm solar radio flux (F10.7) and (g) the ring current index (Dst) during 2016–2018 are shown in the bottom panels. The grey vertical dashed lines separate the end of one year from the beginning of another year while the magenta solid shapes indicate Dst < −50 nT under this study. The shown coordinates in brackets are the IPP geographic latitudes, longitudes, and geomagnetic latitudes, respectively, over the stations.

The TEC observations in Figure 2a–e show that the greatest TEC magnitude occurred at the low-latitude station (HKWS) in the Northern Hemisphere, which by geomagnetic coordinate, is close to the equatorial anomaly crest. Furthermore, the TEC magnitude at the equatorial station, EUSM, was greater than at the BBKD, HSKD, and KARR, which are higher latitude stations.

Figure 3 shows the daily TEC variation at HKWS from January to December in the year 2016. The red lines show the daily TEC variations while the blue lines show the 27-day running median.
TEC values. It can be seen that there were several TEC enhancements above the monthly median. The equinoctial months showed more cases of TEC enhancements than the solstice months. Meanwhile, several factors could account for the observed TEC enhancements in Figure 3. These factors may include the variation in solar EUV ionizing flux, geomagnetic activity, or impact of forcing from the lower atmosphere. In the light of these enhancements, the questions to be answered include: what proportion of these enhancements occurred under quiet and disturbed conditions? In addition, how recurrent are these enhancements during the recovery phase of geomagnetic storms?

Figure 4 presents an example of the occurrence of daytime TEC enhancements on 13 and 14 February 2016. The magenta vertical lines marked the daytime interval of 0900–1800 LT. Figure 4a shows both the magnitude of the daily TEC (red curve) and 27 day TEC running median (blue curve). The maximum value of the running median TEC was ~55 TECU while that of diurnal TEC was ~85 TECU at about 1400 LT on 13 February 2016. On 14 February, the peak of the diurnal TEC was ~80 TECU at ~1600 LT. The absolute and relative TEC deviations were shown in Figure 4b, c, respectively. The shaded portions show the TEC deviations above the enhancement thresholds (10 TECU and 30% for absolute and relative deviations respectively for at least 4 h). Figure 4d shows the variation of the Kp index with values mostly below 4 during 12–15 February. Furthermore, it can be observed that the occurrence of TEC enhancements on 13 and 14 February was similar in the sense that they both occurred during a relatively quiet geomagnetic condition (Kp < 4). These are storm-independent TEC enhancements cases as there was no indication of storm occurrence before this time.

**Figure 3.** Daily TEC variation observed at HKWS during January–December 2016. The daily TEC variation and 27-day running median are shown in red and blue lines, respectively.
Figure 4. (a) Daily TEC (red) variation for 12–16 February 2016 and 27-day running median (blue), (b) absolute TEC deviation with the red shaded portions showing where the deviation is above 10 TECU, (c) relative TEC deviation with the red shaded portions showing where the deviation is above 30%, and (d) the Kp index variation. The grey vertical dashed lines separate the end of one day from the beginning of another day while the magenta vertical dashed lines show the daytime interval of 0900–1800 LT.

3.2. Quiet Time Seasonal Variations of the Occurrence of TEC Enhancements

Figure 5 shows the quiet time seasonal variation in the number of days of absolute TEC deviation above 10 TECU (Figure 5a–e) and the relative TEC deviations above 30% (Figure 5f–j) at each station. Basically, four seasons were used: namely March equinox (ME; February, March, and April), June solstice (JS; May, June, and July), September equinox (SE; August, September, and October), and December solstice (DS; November, December, and January). The total number of days of TEC enhancements during the four seasons at each station was given in each figure. The total numbers of days of data during Kp < 3 were 675, 643, 657, and 683 at BBKD, HSKD, HKWS, and KARR, respectively.

In Figure 5a–c, the observed highest number of days of TEC enhancements occurred during the March equinox. The quiet time seasonal variations at BBKD and HKWS showed semiannual variations similar to the background TEC variations in Figure 2. There was no observed TEC enhancement at EUSM in Figure 5d, while four days of enhancements were observed in Figure 5e.

The seasonal variations in the numbers of days of observed TEC enhancements derived through the relative TEC deviation were presented in Figure 5f–j. These seasonal variations showed dissimilarities from the results of Figure 5a–e. The highest number of days was observed at HSKD with N = 92, while the least was at EUSM. The seasonal variations in the number of days of TEC
enhancements derived through the relative deviation approach tend to be more consistent with the observed TEC spikes in Figure 2. These TEC spikes were most prominent at HSKD and this station also observed the highest number of days of TEC enhancements. The seasonal variations were not quite pronounced, although the observed number of days of TEC enhancements exhibited equinocial and solstitial peaks at the middle and low latitudes. The seasonal variations in Figure 5a–e were more influenced by the background TEC seasonal variations shown in Figure 2 than the variations shown in Figure 5f–j. As a result, the TEC enhancements determined through the relative TEC deviation will be used in further analysis, as it does not reflect background seasonal variation. Additionally, observations from EUSM will no longer be considered in the subsequent analyses since F2-layer TEC enhancements at the low and middle latitudes correspond to density depletion at the equatorial latitude due to the ‘fountain effect’ [42].

Figure 6 presents the station distribution of the TEC enhancements occurrence under Kp < 3 condition during 2016–2018. This was obtained by evaluating the percentage ratio between the total number of days of TEC enhancements at each station and the total number of days of available data under Kp < 3 during 2016–2018. The percentage occurrence of TEC enhancements as computed here is useful in determining the quiet time baseline for the occurrence of TEC enhancements over each station. It can be observed that the highest percentage was at HSKD and the least at KARR.

**Figure 5.** Seasonal variations of the number of days of observed TEC enhancements during 2016–2018 under Kp < 3 condition. The variations in (a–e) were derived based on the absolute TEC deviation
and (f-j) through relative TEC deviation. The total number of days of TEC enhancements for all seasons is denoted by N. The seasons were written for short as ME (March equinox), JS (June solstice), SE (September equinox), and DS (December solstice).

![TEC Enhancements Occurrence](image)

**Figure 6.** The station distribution of the TEC enhancements occurrence under Kp < 3 during 2016–2018.

### 3.3. Dependence of TEC Enhancements Occurrence on the Geomagnetic Storm Phases

The dependence of the occurrence of TEC enhancements on the different phases of a geomagnetic storm is another point that needs to be addressed. Geomagnetic storms with Dst < −50 nT during 2016–2018 were identified and selected. For each selected storm, the phases were categorized into the initial phase (MP-1), the main phase (MP), and the recovery phase (RP). The recovery phase was further divided into RP1, RP2, RP3, and RP4, representing 1st, 2nd, 3rd, and 4th day after the main phase, respectively. In this consideration, only the daytime (09:00–18:00 LT) data were analyzed. The days in which sudden storm commencements (SSC) occurred a day before the main phase of a storm were excluded from the count for the initial phase. More also, successive storms with less than a 5-days interval were not considered in this analysis. The summary of the number of events analyzed and rejected during each phase of the geomagnetic storms was presented in Figure 7.

Figure 8 shows the distribution of the TEC enhancements occurrence during different geomagnetic storm phases and is presented to address the question related to the recurrence of TEC enhancements during the recovery phase of geomagnetic storms as observed in [29]. However, a further step was taken to examine the other geomagnetic storm phases. The horizontal black dashed lines show the respective quiet time baselines of TEC enhancements at the four stations, based on the result presented in Figure 6. The initial phase shows the least percentages at BBKD and HKWS (Figure 8a,c) in comparison to the other phases. Furthermore, the percentage occurrence of TEC enhancements during the initial phase was above baseline at KARR in Figure 8d but lower at the other stations. There have been reported cases of pre-storm ionospheric enhancements [21,43–46].
During the main phases (MPs, Figure 8a–d), the occurrences were notably above the baselines, except at HKWS, where it was just slightly above the baseline. The main phase results were quite understandable since there are active drivers such as penetrating electric fields at the low-latitude coupled with penetration of energetic particles at the high latitudes and equator-ward winds, which can strongly perturb the ionosphere during the main phase. The occurrences during the four days of the recovery phase (RP1, RP2, RP3, and RP4) showed a decline as the numbers of days after the main phase increase and were all above the baseline at BBKD. The occurrence was below the baseline during RP1 at HSKD, but later rose above the baseline during RP2. Besides, the occurrences during RP3 and RP4 at HSKD were below the baseline (Figure 8b). Figure 8c showed that the occurrences during RP1 and RP2 were above the baseline at HKWS and at the same time, greater than the occurrence during MP. The TEC enhancement occurrence during RP3 decreased with respect to RP2, although still slightly above the baseline, and later decreased below the baseline during RP4. The result presented in Figure 8a showed that TEC enhancements were recurrent during the four days of the recovery phase. Figure 8b indicates the tendency of recurrence of TEC enhancements during RP2 at HSKD and during the first three days of recovery at HKWS (Figure 8c). In Figure 8d, the occurrence of TEC enhancements at KARR was above the baseline during RP1 and slightly decreased below baseline during RP2. The occurrence was above the baseline during RP3 while there was no record of any occurrence during RP4. Generally, the ionospheric responses exhibited at the four stations during the recovery days are associated with the storm-time effects during the earlier part of the recovery phase and the likely modulation of the F2-layer by the lower atmospheric forcing, as discussed later.

![Figure 7](image-url)  
*Figure 7.* The distribution of the number of events selected (blue) and rejected (yellow) used in analyzing the occurrence of TEC enhancements during different geomagnetic storm phases.
Figure 8. (a–d) The occurrence of TEC enhancements variation with geomagnetic storm phases: the initial phase (MP-1), main phase (MP), and recovery phases; RP1, RP2, RP3, and RP4, denoting 1st, 2nd, 3rd, and 4th day after the main phase respectively. The horizontal dashed lines show the baselines for TEC enhancements under Kp < 3 condition.
4. Discussion

This study aims to investigate the occurrence of TEC enhancements over the Asian-Australian sector and to ascertain the recurrence of TEC enhancements during the recovery phase of geomagnetic storms. The factors that account for ionospheric variability have been previously reported [1–3,47,48] most especially at the mid-latitudes. Some of these factors are associated with solar, geomagnetic, and meteorological sources. The solar ionizing radiation is the major source of ion production in the ionosphere, but the TEC deviation of 30% that was considered of TEC enhancement in this study may rule out the solar ionizing radiation effect as a major player in the observed TEC enhancements. The occasional impulsive energy of solar radiation during events like solar flares may also not be considered as a major player since their effects on the F2-layer ionosphere are usually short-lived [49]. The geomagnetic disturbance effect on the ionosphere has been well reported and known to cause a major positive change during daytime due to the penetration of electric fields and large energy input into the upper atmosphere. It has also been observed that positive F2-layer disturbances do occur at the equatorial and low latitudes at all seasons during the main phase of geomagnetic storms [50,51]. Hence, the probability of the occurrence of TEC enhancement is usually higher during strong than quiet geomagnetic conditions. Notwithstanding, it should be noted that there is the possibility that under quiet geomagnetic condition, a considerable level of auroral activities, which is capable of perturbing the F2-layer, could exist [25,27].

Previous studies have shown that at the high and middle latitudes, daytime positive quiet time disturbances tend towards clustering at the equinoxes [1,3,52–54]. These equinoctial peaks merged to one single peak during the summer at the lower latitudes. In this current study, the quiet time seasonal variation in the number of days of observed TEC enhancements was most prominent during the September equinox at the middle latitude (BBKD). There was no pronounced seasonal variation at the low latitude stations (HSKD and HKWS), although the number of days was highest during the December solstice. The authors in [2] observed this similar feature at the low latitude during medium and low solar activity. The mechanism previously suggested for the equinoctial peaks in seasonal variation of the quiet time TEC enhancements is related to the equinoctial transition in atomic oxygen abundance due to global circulation pattern accompanied by vertical motions [3,55]. Although, it may also be related to the maximal occurrence of geomagnetic disturbances during equinoctial seasons [2,3].

Furthermore, the percentage occurrences of TEC enhancements during the different phases of geomagnetic storms were examined and the results were presented in Figure 8. The percentage occurrence of the observed TEC enhancements during the initial phase was above the baseline at KARR but below at all the other stations (Figure 8a–d). This indicated that there was no systematic latitudinal dependence in the distribution of the TEC enhancements during the initial phase. This result is consistent with the results of [43], who affirmed that solar flare could strengthen pre-storm enhancements occasionally but was not the main driver. The sources due to magnetospheric electric field penetration, soft particle precipitation in the dayside cusp, and auroral activities were also excluded as main drivers of pre-storm enhancements. Common features of daytime positive storm effects were found by [46] at the low/middle geomagnetic latitudes in both hemispheres during the pre-storm phase of three different geomagnetic storms. These authors as well as [21] suggested that long-time penetration electric fields were the most likely process that could produce these daytime pre-storm TEC enhancements. In a case study, the authors of [44] attributed the TEC enhancements during pre-storm at low-latitudes under low geomagnetic activities to the effects of enhanced zonal electric fields due to auroral/magnetospheric activities in some cases and due to planetary wave-type oscillations in the case of 6 January 1998 event. The latter case was suggested because the enhancement took place for a long period under low geomagnetic activity and as a result, was attributed to lower atmospheric forcing.

The occurrence of TEC enhancements during the initial phase at BBKD, a middle latitude station (Figure 8a), was below the baseline, which also downplays on auroral/magnetospheric sources as the potential driver. It can be observed at HKWS (Figure 8c) that the occurrence during the initial phase was below the baseline. It is not presently clear why HKWS had such a low occurrence in comparison
with the other stations. However, more datasets and modeling results may be needed to confirm the main source of TEC enhancements during the initial phase.

During the main phase of geomagnetic storms, there are usually enhancements in the penetration of convective electric fields from the high latitudes into the low latitudes and the deposition of energetic particles into the high latitudes. These storm-time generated electric fields act to enhance or suppress the quiet time zonal electric fields which play an important role in the distribution of ionospheric plasma, most especially at the equatorial and low-latitudes. The sudden southward turn of the north-south component of the interplanetary magnetic field (IMF-Bz) creates a dawn-dusk under-shielding and convective electric field at high latitudes. This propagates to the equatorial and low latitudes as prompt penetration electric field (PPEF) having eastward (westward) polarity on the dayside (night-side). Although the PPEF manifests on the time scales of minutes to hours, the magnitude of the storm may determine the extent of its positive impact on the ionosphere both in time and magnitude. Huang [56] observed that the PPEF effect on the ionosphere could last for long hours, depending on how long the IMF-Bz remains in the southward direction. The eastward PPEF reinforces the vertical $E \times B$ drift and subsequently intensifies the equatorial fountain effect. As a result, the F2-layer peak density is pushed to higher altitudes in this region. Consequently, more plasma is produced due to faster-decreasing loss rate than the production rate at these higher altitudes. Magnetospheric dynamic processes such as substorms could serve as another source of eastward PPEF [57]. The percentage occurrence of TEC enhancements in Figure 8a–d was significantly above the baselines during the main phase in comparison with the other phases. These observations demonstrate the dominant impact of eastward PPEF, which is of magnetospheric origin, by intensifying the equatorial plasma fountain effect.

On the other hand, the neutral wind disturbance dynamo electric fields (DDEF), which arise from the auroral heating, generate equator-ward thermospheric disturbance winds. This manifest several hours after the storm main phase onset [24]. The DDEF has an opposite polarity to that of PPEF and as a result, decreases the height of peak electron density during the daytime. Furthermore, the equator-ward neutral winds lift the F2-layer plasma along the inclined magnetic field lines but tend to decrease the F2-layer peak when circulating poleward. During the main phase of geomagnetic storms, the neutral winds are capable of causing up to 30% or more deviation in TEC during daytime at the middle and low-latitudes [58,59]. The winds are most effective in modifying ionospheric height at the middle latitude and least around the geomagnetic equatorial region.

Strong electron density enhancements have been observed during the recovery phase of geomagnetic storms, both at the F2 and topside layer of the ionosphere [18,29]. The disturbances due to geomagnetic storms can last up to 4 days. Hence, TEC enhancements observed after the recovery phase in some cases have been attributed to ‘post-storm effects’ [25]. These post-storm effects were associated with atmospheric circulation which intensifies the low-latitude eastward zonal winds. Other factors that can contribute to TEC enhancements during the recovery phase include 2-day oscillation of equatorial ionosphere anomaly (EIA) [60], semidiurnal wave in atmospheric tides [61], non-linear interaction between tides and quasi-stationary planetary waves [22], and the combined effect of high-speed solar wind and oscillating IMF Bz [31].

In this study, the occurrences of TEC enhancements during all the recovery days RP1–RP4, RP2, RP1–RP3, and RP1 at BBKD, HSKD, HKWS, and KARR were above baselines respectively. This implies that TEC enhancement during the recovery phase of geomagnetic storms is a recurrent phenomenon. The occurrences were above the baseline during all the recovery days in Figure 8a and these imply that the storm time effect had significant contributions in the enhancements of TEC during the recovery days at the middle latitude. When the results of Figures 5g and 8b are compared, it can be noticed that the most observed number of days of TEC enhancements during the quiet time was at HSKD, but the occurrences of TEC enhancements during most of the recovery days were lower at this station than at BBKD. This implies that the storm time effect was most significant during RP2 but less dominant during the other recovery days at HSKD. Furthermore, the surprising result of Figure 8c, whereby the occurrences during RP1 and RP2 were greater than during MP, shows the complexity that is associated with the occurrence of TEC enhancements during the recovery phase,
especially at the low latitude. However, the result showed Gaussian-like distribution at each station, with build-up around the main phase and decline during the recovery days. The influence of neutral composition and winds during the recovery phase seems dominant at the middle latitude, (Figure 8a), although HKWS, which is a low latitude station, shows similar features to BBKD. It should be noted that there were not many changes observed between the results of Figures 5 and 6 and the results obtained when all the storm phases were removed from the analysis of quiet days TEC enhancements in Figures 5 and 6 (not shown). This seems reasonable as most of the days that fall under these storm phases would have been removed by the condition Kp < 3 in Figures 5 and 6.

Overall, it is suggested that neutral composition, and winds, and the modulating effects of lower atmospheric forcing could play a vital role in the enhancements of TEC, as the disturbance dynamo electric fields tend to be westward and introduce TEC depletion during the recovery phase [7,29]. However, the dominant driver of TEC enhancements during the recovery phase of geomagnetic storms remains unclear. To ascertain the dominant driver of the TEC enhancements, further support from the lower atmospheric observations will be a pursuit in a future study.

5. Conclusions

In this study, we have presented the results of the daytime occurrence of TEC enhancements by using TEC observations from GEO-2 satellite over 5 ground-based GNSS receivers in the Asian-Australian sector from 2016 to 2018. The occurrence of TEC enhancements displayed a preference for the September equinox and December solstice at the middle and low latitudes, respectively. Moreover, the occurrence during the main phase of geomagnetic storms was significantly above the TEC enhancement baselines, while it exhibited recurrence of TEC enhancements during the recovery phase of geomagnetic storms at the northern hemispheric stations. However, further study is still needed to decipher the dominant driver of this occurrence. This study revealed that the TEC enhancements during the recovery phase were associated with the effect of geomagnetic storms and auroral activities. Notwithstanding, the lower atmospheric forcing may have significantly contributed to the observed TEC enhancements amongst other competing factors.

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