Technical Note

The Feature of Ionospheric Mid-Latitude Trough during Geomagnetic Storms Derived from GPS Total Electron Content (TEC) Data

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Abstract: This study aims to investigate the features of the ionospheric mid-latitude trough over North America by using the MIT total electron content data obtained during three geomagnetic storms that occurred in August 2018, September 2017, and March 2015. The mid-latitude trough position sharply moves equatorward from the quiet-time subauroral latitude to mid-latitude with the decrease in SYM-H during geomagnetic storms. We find that the ionospheric behavior of TEC around the mid-latitude trough position displays three kinds of ionospheric storm effect: negative ionospheric storm effect, unchanged ionospheric behavior, and positive ionospheric storm effect. These ionospheric storm effects around the mid-latitude trough position are not always produced by the mid-latitude trough. The ionospheric storm effects produced by the mid-latitude trough are limited in the narrow mid-latitude trough regions, and are transmitted to other regions with the movement of the mid-latitude trough.

Keywords: ionospheric storm effect; mid-latitude trough; GPS TEC

Citation: Yang, N.; Yu, T.; Le, H.; Liu, L.; Sun, Y.-Y.; Yan, X.; Wang, J.; Xia, C.; Zuo, X.; Huang, G. The Feature of Ionospheric Mid-Latitude Trough during Geomagnetic Storms Derived from GPS Total Electron Content (TEC) Data. *Remote Sens.* **2022**, *14*, 369. <https://doi.org/10.3390/rs14020369>

Academic Editor: Filomena Romano

Received: 15 December 2021

Accepted: 11 January 2022

Published: 13 January 2022

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1. Introduction

The mid-latitude trough is a nighttime plasma density depletion structure in the subauroral ionospheric *F* region [1–3]. The depletion structure is typically close to 10 degrees wide in latitude, and appears at all longitudes in both the Northern and Southern Hemispheres [4,5]. The mid-latitude trough most frequently occurs in the nighttime. The mid-latitude trough structure is composed of three parts: a polar boundary, a trough minimum, and an equatorward boundary. The trough position refers to the trough's minimum position. The large density gradients on both boundaries of the mid-latitude trough can provoke severe amplitude and phase fluctuations of radio signals [3,6]; the fluctuations deteriorate the performance of navigation and positioning. For simplicity, the “trough” in this study refers to the mid-latitude trough.

Geomagnetic storms are major ‘space weather’ events. During geomagnetic storms, as geomagnetic activity levels increase, the trough shifts to lower latitudes due to the equatorward expansion of the auroral oval and the high-latitude convection [7–9]. Simultaneously,

the equatorward displacement of the trough can cause obvious negative ionospheric storm effects, as found by various investigations [7,10–14]. During geomagnetic storms, the trough shifts to the mid-latitude ionosphere, thus resulting in the depletion of the local plasma density relative to the quiet-time level at the mid-latitude ionosphere—in other words, a negative ionospheric storm effect. Blagoveshchensky et al. [10] found that the formation of the trough across the oblique propagation path during the 28 April 2001 geomagnetic storm caused a decline in F2MOF (maximum observed frequency reflected from the F2 layer for the oblique incidence sounding signals) and F2LOF (lowest observed frequency reflected from the F2 layer for the oblique incidence sounding signals). Galav et al. [11] showed that the TEC data from Algonquin detected short-duration nighttime depletion caused by the trough during the May 2005 geomagnetic storm. Horvath and Lovell [12] reported that the earlier occurrence of the trough (relative to quiet time) over Goose Bay during the 15 May 2005 geomagnetic superstorm decreased the quiet-time electron densities significantly, and provoked an obvious negative ionospheric storm effect in the area of the trough (~5 degrees of latitude). Liu et al. [14] studied the features of the mid-latitude ionospheric response to the 8 September 2017 geomagnetic storm, and found that a large TEC depletion region in the American sector was related to the equatorward movement of the trough. The geomagnetic storms can induce rapid changes in ionospheric electron density. The rapid changes have strong effects on navigation and positioning [12,15–17], due to the fact that a 1 TECU change in the TEC value is capable of inducing 0.16 m range error [18].

Previous studies suggest that the negative ionospheric storm effect is associated with the equatorward movement of the trough during geomagnetic storms. However, it is not clear whether the equatorward movement of the trough during geomagnetic storms is always accompanied by a negative ionospheric storm effect, or whether the negative ionospheric storm effect around the trough position is always related to the equatorward movement of the trough. The effect of the trough on the mid-latitude ionosphere during geomagnetic storms is examined in detail in this study. The study of such ionospheric behavior contributes to better understanding of the features of the trough and the mechanisms of the ionospheric storm effect associated with the trough during geomagnetic storms. In addition, this study contributes to understanding of the complex behavior and variation mechanisms of the nocturnal mid-latitude ionosphere during geomagnetic storms.

In this study, we selected and analyzed three typical intense geomagnetic storms that occurred during solar cycle 24. The features of the trough during each storm were investigated by inspecting the spatial and temporal variations in TEC in the mid-latitude ionosphere. In the following section, the observation data and TEC analysis methods are described in detail. Section 3 presents results of the trough characteristics and the storm effects of TEC variations in the area of the trough during geomagnetic storms. These results are discussed in Section 4. The conclusions of the research are given in Section 5.

2. Data and Methodology

2.1. Datasets

GPS vertical TEC data released by the Madrigal database developed at the Haystack Observatory of Massachusetts Institute of Technology (MIT) were used to analyze and discuss the response of TEC to geomagnetic storms over North America. Detailed information on the TEC data and their derivation method are described by Rideout and Coster [19]. The spatial resolution of the TEC data is $1^\circ \times 1^\circ$ in geographical coordinates, and the temporal resolution is 5 min. Figure 1 shows an example of the distribution of TEC data over North America during 06–07 UT (Universal Time) on 24 August 2018. Yang et al. [20] found that the trough mainly occurs in the range of 50° – 70° N magnetic latitude (MLAT). Thus, the TEC data in the range of 40° – 75° N MLAT and -90° to -60° E geographic longitude (GLON) were selected to study the features of the trough during geomagnetic storms. The climatological features of the trough structure in the range of -90° to -60° E GLON have been studied and modeled by Le et al. [21].

Figure 1. An example of the distribution of TEC data over North America during 06–07 UT on 24 August 2018. The upper and lower solid black lines represent 75° N and 40° N MLAT, respectively.

The SYM-H index, IMF Bz, Kp index, and solar flux index F10.7 data were extracted from the OMNIWeb database (<http://omniweb.gsfc.nasa.gov> (accessed on 1 November 2021)). The AE geomagnetic activity index data were downloaded from <http://wdc.kugi.kyoto-u.ac.jp/> (accessed on 1 November 2021).

2.2. TEC Analysis Method

We analyzed the TEC to study the trough over North America during geomagnetic storms. The analysis process was as follows: (1) The latitudinal TEC profile was defined as the average of the TEC values within the -90° to -60° E GLON at each MLAT. (2) The local minimum of each latitudinal TEC profile was indicated. (3) The trough position was the TEC minimum in the area of 40–75° N MLAT. To determine the TEC changes for each storm, the TEC absolute deviation was defined as the difference between the TEC and the reference TEC. The reference was the average value of TEC during the period of 7 days before the storm [22].

In the present study, the effect of the storm-associated development of the trough on the nocturnal mid-latitude ionosphere during geomagnetic storms was analyzed almost exclusively for the main phase and the early recovery phase, due to the fact that the trough quickly recovered to the quiet-time subauroral latitude, with a typical timescale in the order of hours [3,19].

3. Results

3.1. August 2018 Storm

3.1.1. Geomagnetic Conditions

The 2018 August storm was the third largest event during solar cycle 24 [23,24]. Figure 2 shows the IMF Bz and geophysical conditions during 24–26 August 2018. An initial phase of the storm occurred after 09 UT on 25 August. The main phase of the storm began at ~16:05 UT on 25 August, as the SYM-H (Figure 2d) began to decrease. Around 07:12 UT on 26 August, the SYM-H (Figure 2d) reached the minimum of -206 nT, indicating the end of the main phase. The IMF Bz turned northward at 09:50 UT on 26 August (Figure 2a).

The corresponding AE (Figure 2b) and Kp (Figure 2c) indices gradually increased to more than 2000 nT and 7, respectively. After ~07 UT on 26 August, the SYM-H (Figure 2d) first increased quickly and then gradually recovered. The values of the F10.7 (Figure 2c) solar flux index were 74 solar flux units (sfu; 1 sfu equals $10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$), 73.1 sfu, and 72.6 sfu on 24–26 August, respectively.

Figure 2. Time series of (a) IMF Bz, (b) AE index, (c) Kp index (dark line) and F10.7 (blue line), and (d) SYM-H index during the period of 24–26 August 2018.

3.1.2. Ionospheric Storm Disturbance during the 2018 August Storm

Figure 3 shows the ionospheric variations for the American sector during the 2018 August storm. Figure 3a displays the TEC distribution in UT-MLAT coordinates. During the quiet day on 24 August, the trough first appeared at 04 UT (~23 LT) for the American sector, and then it slightly moved equatorward before 06 UT, and remained at 62° N in the post-midnight region (06–08 UT, ~01–03 LT). After 08 UT, the trough shifted equatorward in the dawn sector. The trough position changed by 5° in latitude during the quiet day. The TEC value in the trough gradually decreased with time, reaching a minimum value of less than 1.5 TECU during 05–09 UT (~00–04 LT), and then gradually increased. During 01–12 UT on 25 August, before the storm, the trough first appeared at 05 UT (~00 LT), and then remained at 62° N in the post-midnight region (05–07 UT, ~00–02 LT). After 07 UT, the trough gradually moved equatorward in the dawn sector. During this period of time, the trough position changed by $\sim 3^\circ$ in latitude, which is slightly less than the change during the quiet day. The TEC value in the trough first decreased gradually with time, and then increased in the dawn sector, which is similar to that during the quiet day. During the storm's main phase, the trough first occurred at 22 UT (~17 LT) on 25 August, which is earlier than during the quiet day. Afterwards, the trough quickly moved equatorward with the rapid decrease in SYM-H. After 06 UT on 26 August, the SYM-H index gradually decreased, and then began to increase at 08 UT on 26 August, whereas the trough continued to move equatorward with a slower velocity until 09 UT. The equatorward movement of the trough stopped at 09 UT on 26 August; after that, the trough returned to a higher latitude

and disappeared, which is related to the solar extreme ultraviolet (EUV) radiation [5,25]. During the main phase of this storm, the trough position changed by $\sim 20^\circ$, which is much larger than the change during the quiet day. The TEC value in the trough also showed similar temporal variation to that during the quiet day. The TEC value in the trough during 03–10 UT (22–05 LT) was between 1.5 and 2.5 TECU, which is larger than those at the same times during the quiet day.

Figure 3. Ionospheric storm variations of (a) TEC and (b) TEC absolute deviations from the reference for the American sector during the 2018 August storm. The contour levels indicate the 1.5 and 2.5 TECU values. The red asterisks indicate the mid-latitude trough position. The black line shows the SYM-H variations. The local nighttime in the American sector is marked with thick black line segments.

Figure 3b shows the TEC absolute deviations from the reference during the 2018 August storm. During 01–12 UT on 25 August, before the storm, the absolute deviation values of TEC in the area of the trough were near zero (indicated by white), meaning that the TEC value in the trough does not change relative to the quiet-time level. During the main phase, the absolute deviation of TEC in the area of the trough was negative (indicated by blue). It should be noted that the negative ionospheric storm effect aligns well with the trough position. Thus, the negative ionospheric storm effect is clearly related to the trough. The negative ionospheric storm effect caused by the trough was transmitted to lower latitudes through the equatorward movement of the trough. At the polar side of the trough, the absolute deviation value of TEC was positive. It is well known that the polar wall of the trough is formed by the auroral precipitation [3]. During the main phase, the AE index largely increased (see Figure 3b), which implies the enhancement of the auroral

precipitation [26]. In addition, the TEC enhancement at the polar wall of the trough during the main phase was located in the quiet-time mid-latitude trough region around 61° N. Thus, the positive ionospheric storm effect at the polar side of the trough was caused by the mechanism of energetic particle precipitation increasing the ionization in the quiet-time mid-latitude trough region around 61° N [27,28].

3.2. September 2017 Storm

3.2.1. Geomagnetic Conditions

The 2017 September storm with a double main phase was an intense geomagnetic storm event in solar cycle 24 [29,30]. The IMF Bz and geophysical conditions during 6–8 September 2017 are described in Figure 4. The SYM-H shows that a sudden storm commencement occurred at ~00 UT on 7 September 2017 (Figure 4d). The initial phase occurred after ~00 UT. The AE index reached ~1400 nT close to 09:07 UT (Figure 4b), indicating the occurrence of strong geomagnetic activity. The SYM-H shows two main phases on 7 and 8 September (Figure 4d). The first main phase began at ~20:37 UT, as the SYM-H (Figure 4d) began to decrease. During the first main phase of the storm, the SYM-H (Figure 4d) reached a minimum of -144 nT. The IMF Bz (Figure 4a) reached -31.2 nT at ~23:31 UT on 7 September. The corresponding AE (Figure 4b) and Kp (Figure 4c) indices reached their highest magnitudes of ~2447 nT and 8, respectively. At ~02:30 UT on 8 September, the IMF Bz (Figure 4a) turned northward. The second main phase of the storm began at ~11:34 UT on 8 September, as the SYM-H (Figure 4d) began to decrease. During this second main phase of the storm, the SYM-H (Figure 4d) reached a minimum of -122 nT. The associated AE (Figure 4b) and Kp (Figure 4c) indices reached their highest magnitudes of ~2677 nT and 8.3, respectively. The values of F10.7 (Figure 4c) were 134.9 sfu, 130.4 sfu, and 118.5 sfu on 6–8 September, respectively.

Figure 4. Time series of (a) IMF Bz, (b) AE index, (c) Kp index (dark line) and F10.7 (blue line), and (d) SYM-H index during the period of 6–8 September 2017.

3.2.2. Ionospheric Storm Disturbance during the 2017 September Storm

Figure 5 shows the ionospheric storm variations for the American sector during the 2017 September storm. Figure 5a displays the TEC distribution in UT-MLAT coordinates. During the quiet day on 6 September, the trough was located at a latitudinal band of 60–62° N, and showed a small temporal variation. The trough position changed by 2° in latitude during the quiet day. The TEC value in the trough gradually decreased over time, reaching a minimum value of less than 2.5 TECU during 05–10 UT (~00–05 LT), and then gradually increased. During the initial phase of the storm, the trough first occurred at 02 UT (~21 LT) on 7 September, and then gradually moved to a lower latitude, from 67° N at 02 UT (~21 LT) on 7 September to 53° N at 11 UT (~06 LT) on 7 September with the decrease in SYM-H. The trough appeared earlier than during the quiet day. The trough position changed by 14° in latitude during the initial phase of the storm, which is larger than the change during the quiet day. The TEC value in the trough during 05–10 UT (00–05 LT) was between 2.5 and 4.5 TECU—larger than during the quiet day. During the first main phase of the storm, the trough first appeared at 23 UT (~18 LT) on 7 September, which is earlier than the time of the trough's occurrence during the quiet day. Afterwards, the trough quickly moved equatorward from 65° N at 23 UT (~18 LT) on 7 September to 50° N at 02 UT (~21 LT) on 8 September with the rapid decrease in SYM-H. The equatorward movement of the trough stopped at 02 UT on 8 September; after that, the trough returned to higher latitude with a large disturbance, and disappeared at 10 UT (~05 LT) on 8 September. During this period, the trough position changed by 15° in latitude, which is larger than the change during the quiet day. It can be seen that the temporal variation in the trough position changed significantly during the storm. The TEC value in the trough gradually decreased with time, reaching a minimum of less than 2.5 TECU during 07–09 UT on 8 September, and then increased. During the second main phase of the storm, the trough did not occur, because it was daytime.

Figure 5b shows the TEC absolute deviations from the reference during the 2017 September storm. During the initial phase of the storm, the absolute deviation value of TEC was positive (indicated by yellow) at mid- and high latitudes. The positive value at the polar side of the trough was slightly larger than that at the equatorward side of the trough, and the positive value around the trough position was slightly smaller than that at both sides of the trough. The absolute deviation value of TEC at the equatorward side of the trough gradually decreased as time progressed. The larger enhancement of TEC at the polar side of the trough can be attributed to enhanced energetic particle precipitation represented by a large AE value [3,26–28]. The smaller enhancement of TEC around the trough position is partly associated with the trough. The effect of the storm-associated equatorward shift of the trough on the mid-latitude ionosphere was overpowered by the positive storm due to the disturbance wind effect [31–35]. During the first main phase of the storm, the absolute deviation value of TEC around the trough position was negative (indicated by blue) from 23 UT on 7 September to 01 UT on 8 September, and nearly zero (indicated by white) during the first recovery phase of the storm (02–10 UT on 8 September). The absolute deviation value of TEC at both sides of the trough was positive from 23 UT on 7 September to 06 UT on 8 September. After 06 UT on 8 September, the absolute deviation value of TEC was negative at the equatorward side of the trough, whereas the absolute deviation value of TEC remained positive at the polar side of the trough. The negative ionospheric storm effect around the trough position during the first main phase of the storm was clearly related to the occurrence and movement of the trough. The negative ionospheric storm effect caused by the trough was transmitted to lower latitudes through the equatorward movement of the trough. The TEC was unchanged around the trough position during the first recovery phase; this may be related to the storm-associated trough displacement. In addition, the unchanged TEC may also be associated with auroral ionization [36,37]. The combination of these factors causes the TEC value in the trough during the first recovery phase to be very close to the local TEC value during the quiet day. Overall, the absolute deviation value of

TEC was negative in daytime during the second main phase. No obvious trough occurred during the second main phase.

Figure 5. Ionospheric storm variations of (a) TEC and (b) TEC absolute deviations from the reference for the American sector during the 2017 September storm. The contour levels indicate the 2.5 and 4.5 TECU values. The red asterisks indicate the mid-latitude trough position. The black line shows the SYM-H variations. The local nighttime in the American sector is marked with thick black line segments.

3.3. March 2015 Storm

3.3.1. Geomagnetic Conditions

The 2015 March storm, also known as the St. Patrick's Day storm, was the largest geomagnetic storm in solar cycle 24 [38]. The IMF Bz and geophysical conditions during 16–18 March 2015 are described in Figure 6. At ~04:45 UT on 17 March, the SYM-H (Figure 6d) increased abruptly, indicating the storm's sudden commencement (SSC). The main phase of the storm began at ~06:00 UT on 17 March, as the SYM-H (Figure 6d) began to decrease. After that, the SYM-H (Figure 6d) gradually decreased, with two minima of -100 nT around 10 UT and -233 nT around 23 UT on 17 March, indicating the end of the main phase. The IMF Bz turned northward at ~09:30 UT on 17 March and ~00 UT on 18 March (Figure 6a). During the main phase of the storm, the AE (Figure 6b) and Kp (Figure 6c) indices increased to more than 2000 nT and 7, respectively. After ~23 UT on 17 March, the SYM-H (Figure 6d) gradually recovered, with a very long recovery phase. The values of F10.7 (Figure 6c) were 116 sfu, 113.2 sfu, and 113.7 sfu on 16–18 March, respectively.

Figure 6. Time series of (a) IMF Bz, (b) AE index, (c) Kp index (dark line) and F10.7 (blue line), and (d) SYM-H index during the period of 16–18 March 2015.

3.3.2. Ionospheric Storm Disturbance during the 2015 March Storm

The ionospheric storm variations for the American sector during the 2015 March storm are shown in Figure 7. The TEC distribution in UT-MLAT coordinates is displayed in Figure 7a. During the quiet day, the trough first appeared at 04 UT (~23 LT) and 61° N. After that, the trough moved equatorward from 61° N at 05 UT to 58° N at 08 UT with the decrease in SYM-H, and then gradually moved to higher latitude with the increase in SYM-H. During this period, the trough position changed by 3° in latitude. The TEC value in the trough gradually decreased with time, reaching a minimum value of less than 6 TECU during 06–10 UT (~01–05 LT), and then gradually increased. During 17 March—the day of the storm—the trough first appeared at 03 UT (~22 LT) and 64° N, and then sharply moved equatorward from 63° N at 04 UT to 50° N at 09 UT with the rapid decrease in SYM-H. The equatorward movement of the trough stopped at 09 UT on 17 March; afterwards, the trough remained at 50° N until 12 UT. After 12 UT, the trough returned to 52° N at 13 UT, and disappeared thereafter. The trough position changed by 14° in latitude, which is larger than the change during the quiet day. The TEC value in the trough was mainly between 6 and 8 TECU during 03–10 UT (22–05 LT) on 17 March, and increased to more than 8 TECU after 10 UT on 17 March. The TEC value in the trough during 06–10 UT (01–05 LT) on 17 March was larger than those at the same times during the quiet day. During the recovery phase of the storm, the trough first appeared at 54° N and 22 UT (~17 LT) on 17 March, which is earlier than it appeared during the quiet day. The equatorward movement of the trough stopped at 00 UT on 18 March; afterwards, the trough remained at ~51° N till 05 UT on 18 March, and then gradually moved poleward from 51° N at 05 UT to 59° N at 11 UT on 18 March with the increase in SYM-H. During this period, the trough position changed by 8° in latitude. The TEC value in the trough gradually decreased from more than 8 TECU at 22 UT on 17 March to less than 4 TECU between 04 UT and 11 UT on 18 March.

Figure 7. Ionospheric storm variations of (a) TEC and (b) TEC absolute deviations from the reference for American sector during the 2015 March storm. The contour levels indicate the 4, 6, and 8 TECU values. The red asterisks indicate the mid-latitude trough position. The black line shows the SYM-H variations. The local nighttime in the American sector is marked with thick black line segments.

Figure 7b shows the TEC absolute deviations from the reference during the 2015 March storm. After the onset of the SSC at ~04:45 UT on 17 March, the absolute deviation value of TEC was positive (indicated by yellow) at the polar side of the trough, and negative (indicated by blue) around the trough position and at the equatorward side of the trough. The negative ionospheric storm effect at latitudes between 40° N and 45° N disappeared during the period of 11–15 UT. The positive ionospheric storm effect at the polar side of the trough can be attributed to the mechanism by which energetic particle precipitation increases the ionization in the quiet-time trough region around 60° N [3,26–28]. The negative ionospheric storm effect around the trough position and at the equatorward side of the trough covers a wide latitude range, and is not limited to the area of the trough; thus, the negative ionospheric storm effect is not related to the trough. The negative ionospheric storm effect has also been well explained through the variation of the neutral composition by Astafyeva et al. [22]. Compared with the negative ionospheric storm effect induced by the neutral composition changes, the effect of the storm-associated equatorward displacement of the trough on the mid-latitude ionosphere can be negligible. During the recovery phase of the storm, there are negative absolute deviations of TEC at all latitudes between 40° N and 75° N (indicated by blue), with the exception of positive values at latitudes between 40° N and 46° N during the period of 00–06 UT on 18 March. This negative storm is also explained through the variation of the neutral composition by Astafyeva et al. [22]. Compared with the negative ionospheric storm effect induced by the neutral composition

changes, the effect of the storm-associated displacement of the trough on the mid-latitude ionosphere can be negligible during the recovery phase of the storm.

4. Discussion

During the three intense geomagnetic storms, the temporal variation of the trough position in the night sector changed significantly as compared with that during the quiet day. The temporal variation of the trough position in the night sector differs essentially from one storm to another. During the quiet day, the temporal variation of the trough position in the night sector for the American sector is actually its local time variation. However, the temporal variation of the trough position in the night sector during geomagnetic storms is mainly associated with the temporal variation of the geomagnetic activity. The temporal variation of the trough position during geomagnetic storms is consistent with the temporal variation of the SYM-H. The trough position moves equatorward with the decrease in SYM-H, and poleward with the increase in SYM-H. During the initial and main phases of the storm, the trough appears earlier as compared with that during the quiet day. During this period, the trough sharply moves equatorward from the quiet-time subauroral latitude to mid-latitude with the decrease in SYM-H. The trough moved equatorward by around 20° , 15° , and 14° during the main phases of the storms on 26 August 2018, 8 September 2017, and 17 March 2015, respectively. The movements were larger than those during the quiet day and the statistical results [20,39]. The trough stopped moving near the minima of SYM-H, accompanied by the northward turning of IMF Bz (Figures 2, 4 and 6). The northward turning of IMF Bz can usually induce an eastward perturbed electric field at nighttime [40]. The eastward perturbed electric field can uplift the ionosphere and further lead to positive TEC changes at lower latitudes [41]. The positive TEC changes can stop the equatorward movement of the trough. The relationship between the trough and the perturbed electric field can be further examined in the future. During the early recovery phase of the storm, the trough also appears earlier than during the quiet day. The trough moves poleward with the increase in SYM-H.

During the three intense geomagnetic storms, the temporal variation of TEC values in the trough was similar to that during the quiet day. The TEC value in the trough first gradually decreased with time, and then increased in the morning region. The temporal variation of TEC values in the trough are mainly consistent with the previous statistical results [5,42,43]. The TEC value in the trough was larger during 03–10 UT (~22–05 LT) on the storm day of 26 August 2018, during 05–10 UT (00–05 LT) on the storm day of 7 September 2017, and during 06–10 UT (01–05 LT) on the storm day of 17 March 2015, compared to the values at the same times during the quiet day. The larger TEC value in the trough is due to the trough being infilled by the auroral ionization region, which shifts equatorward during the initial phase and main phase of the three geomagnetic storms [36,37].

During the three intense geomagnetic storms, the levels of geomagnetic activity caused variations in the trough position and the TEC values in the trough. Simultaneously, the equatorward displacement of the trough can lead to ionospheric variation. During the three intense geomagnetic storms, the behavior of ionospheric variation in the area of the trough showed both commonalities and differences. The ionospheric behavior at the polar side of the trough displayed the same positive ionospheric storm effect during the initial and main phases of the three geomagnetic storms. The positive ionospheric storm effect is associated with the mechanism by which energetic particle precipitation increases the ionization in the quiet-time trough region [3,26–28].

The ionospheric behavior at the equatorward side of the trough showed different ionospheric storm effects during the three geomagnetic storms. The ionospheric behavior at the equatorward side of the trough displayed a positive ionospheric storm effect during the main phase of the 2018 August storm and during the initial phase of the 2017 September storm, a positive ionospheric storm effect followed by a negative ionospheric storm effect during the first main phase and first recovery phase of the 2017 September storm, and a

negative ionospheric storm effect during the main and recovery phases of the 2015 March storm. These ionospheric storm effects cover a wide latitude range at the equatorward side of the trough.

The ionospheric behavior around the trough position also showed different ionospheric storm effects during the three geomagnetic storms. Ionospheric behavior around the trough position differs essentially from one storm to another. Ionospheric behavior around the trough position displayed a negative ionospheric storm effect during the main phases of the three geomagnetic storms and the recovery phase of the 2015 March storm, unchanged ionospheric behavior during the first recovery phase of the 2017 September storm, and a positive ionospheric storm effect during the initial phase of the 2017 September storm.

During the main phases of the 2018 August storm and 2017 September storm, the ionospheric behavior around the trough position was dominated by the striking negative ionospheric storm effect. The negative ionospheric storm effect was limited to the narrow area of the trough and transmitted to other regions with the equatorward displacement of the trough. The negative ionospheric storm effect is related to the storm-associated equatorward displacement of the trough. In the mid-latitude ionosphere, this kind of negative ionospheric storm effect produced by the trough is different from that produced by other mechanisms, such as subauroral polarization streams (SAPs) and neutral composition disturbance. The negative ionospheric storm effect caused by the storm-associated equatorward displacement of the trough is limited to the narrow area of the trough, whereas the negative ionospheric storm effect caused by neutral composition disturbance usually covers a wider latitude range due to the transportation of the equatorward storm-induced winds [44]. In addition, the negative ionospheric storm effect produced by the development of SAPs is limited to the SAPs region and in the pre-midnight sector [12,45]. During the main phase and recovery phase of the 2015 March storm, the ionospheric behavior around the trough position was also dominated by the negative ionospheric storm effect. Unlike the main phases of the 2018 August storm and 2017 September storm, the negative ionospheric storm effect during the main phase and recovery phase of the 2015 March storm was not limited to the narrow area of the trough, but covered a wide latitude range. The negative ionospheric storm effect has been attributed to the variation of the neutral composition by Astafyeva et al. [22]. During the 2015 March storm, the effect of the mid-latitude trough on the mid-latitude ionosphere was negligible compared with the negative ionospheric storm effect induced by neutral composition disturbance. Thus, it is demonstrated that the negative ionospheric storm effect around the trough position during geomagnetic storms is not always associated with the equatorward expansion of the trough.

During the first recovery phase of the 2017 September storm, the ionospheric behavior around the trough position showed no significant changes. The TEC value in the trough was very close to the quiet-time level. The unchanged ionospheric behavior was limited to the narrow area of the trough, and was transmitted to other regions with the displacement of the trough. This unchanged ionospheric behavior around the trough position is associated with the storm-associated displacement of the trough and auroral ionization [36,37].

During the initial phase of the 2017 September storm, the ionospheric behavior around the trough position displayed a positive ionospheric storm effect. The positive ionospheric storm effect was also seen at both sides of the trough, and covered a wide latitude range. However, the positive ionospheric storm effect around the trough position was slightly smaller than that at both sides of the trough. It is clear that the effect of the storm-associated equatorward displacement of the trough on the mid-latitude ionosphere was overpowered by the positive ionospheric storm effect. Thus, it is also demonstrated that the equatorward movement of the trough during geomagnetic storms is not always accompanied by a negative ionospheric storm effect.

5. Conclusions

In this study, MIT TEC data were employed to study the trough characteristics and the effects of the equatorward displacement of the trough on the mid-latitude ionosphere

during three intense geomagnetic storms in solar cycle 24. Our findings demonstrate that the equatorward movement of the trough during geomagnetic storms is not always accompanied by a negative ionospheric storm effect (e.g., the positive ionospheric storm effect during the initial phase of the 2017 September storm). We also found that the negative ionospheric storm effect around the trough position during geomagnetic storms is not always associated with the equatorward movement of the trough (e.g., the negative ionospheric storm effect during the main phase of the 2015 March storm was associated with the neutral composition disturbance). The following conclusions can be drawn:

- (1) The temporal variation of the trough position in the night sector differs essentially from one storm to another. The temporal variation of the trough position in the night sector during geomagnetic storms is mainly related to the temporal variation of the geomagnetic activity. During geomagnetic storms, the trough appears earlier as compared with that during quiet days. The trough position moved equatorward by around 20° , 15° , and 14° for the storms on 26 August 2018, 8 September 2017, and 17 March 2015 respectively. The movements were larger than the statistical results. The trough stopped moving near the minima of SYM-H, accompanied by the northward turning of IMF Bz;
- (2) During the three intense geomagnetic storms, the temporal variation of the TEC value in the trough was similar to that during the quiet day. However, the TEC value in the trough during the initial phase and main phase of the three geomagnetic storms was larger than that during the quiet day;
- (3) During the three intense geomagnetic storms, the ionospheric behavior around the trough position displayed a negative ionospheric storm effect during the main phases of the three geomagnetic storms and the recovery phase of the 2015 March storm, unchanged ionospheric behavior during the first recovery phase of the 2017 September storm, and a positive ionospheric storm effect during the initial phase of the 2017 September storm. The negative ionospheric storm effect around the trough position during the main phases of the 2018 August storm and 2017 September storm, as well as the unchanged ionospheric behavior around the trough position during the first recovery phase of the 2017 September storm, are associated with the storm-associated displacement of the trough. These ionospheric storm effects around the trough position produced by the trough are limited to the narrow area of the trough, and are transmitted to other regions with the displacement of the trough. However, the rest of the ionospheric storm effects around the trough position are not limited to the narrow area of the trough, and cover a wide latitude range; these ionospheric storm effects are not caused by the trough.

Author Contributions: N.Y. and T.Y. conceived the ideas, performed the data analyses, and wrote the manuscript; H.L., L.L., Y.-Y.S., X.Y. and J.W. contributed significantly to analysis and manuscript preparation; C.X., X.Z. and G.H. helped to perform the analysis with constructive discussions. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the National Natural Science Foundation of China (41904142, 41822403, 41774165), the National Key Research and Development Program (2017YFE0131400), the Post-doctoral Innovation Project of Hubei Province (1232035), the B-type Strategic Priority Program of the Chinese Academy of Sciences (XDB41000000), and the Youth Innovation Promotion Association CAS.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The MIT TEC data is available at <http://cedar.openmadriral.org/> (accessed on 1 November 2021). The SYM-H index, IMF Bz, Kp index, and solar flux index F10.7 data are available at <http://omniweb.gsfc.nasa.gov> (accessed on 1 November 2021). The AE geomagnetic activity index data is available at <http://wdc.kugi.kyoto-u.ac.jp/> (accessed on 1 November 2021).

Acknowledgments: The authors gratefully acknowledge MIT Haystack’s Madrigal database mirror site at the Institute of Geology and Geophysics, Chinese Academy Sciences (<http://cedar.openmadrigal.org/> (accessed on 1 November 2021)), for MIT TEC data.

Conflicts of Interest: The authors declare no conflict of interest.

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