High-Speed Solar Wind Imprints on the Ionosphere During the Recovery Phase of the August 2018 Geomagnetic Storm

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Abstract The low-latitude ionospheric TEC observed by the Beidou geostationary satellite showed large enhancement during 27–30 August 2018 of the storm recovery phase. The cause of the positive ionospheric storm during the recovery phase has yet to be resolved. In this study, multiple observations, including aurora, high-latitude convection, potential, and the TEC maps, were used to study the contributions from the high-speed solar wind to the ionosphere during the recovery phase of the storm. It was found that the high-speed solar wind was effective in modulating the intensity and the size of the auroral oval, high-latitude convection, and potential pattern. The Thermosphere Ionosphere Electrodynamics General Circulation Model generally reproduced the observed evolution of the ionosphere at high latitudes during the recovery phase of the storm, and it was used to quantitatively investigate the effects of the high-speed solar wind on the recovery phase ionosphere. The results suggested that the high-speed solar wind caused increase of TEC at auroral oval was about 2 TECU. The high-speed solar wind, combined with oscillating interplanetary magnetic field Bz, led to the enhancement of the low-latitude prompt penetrating electric fields and increased the low-latitude TEC of about 2 TECU. Therefore, the high-speed solar wind was a possible driver to the ionospheric positive storm during the recovery phase, but the causes for the more than 10-TECU enhancement at low and middle latitudes during the recovery phase of this event are unknown.

1. Introduction

During the geomagnetic storm times, the energy and momentum depositions from the coronal mass ejection (CME) into the terrestrial upper atmosphere via magnetic reconnection with the magnetosphere significantly influences the ionosphere-thermosphere (I-T) system (e.g., Buonsanto, 1999; Burns et al., 2007; Lyon, 2000; Prölls, 1995, 1997; Richmond & Lu, 2000, and references therein). The ionospheric disturbances during the initial and main phases of geomagnetic storm conditions have been studied for decades (see the references in the review papers, Buonsanto, 1999; Burns et al., 2007). During the recovery phase of geomagnetic storms, the energy and momentum that injected from solar wind into the upper atmosphere are significantly less than that during the main phase since the magnetic reconnection is suppressed under the quiet condition of the interplanetary magnetic field (IMF). Consequently, the changes in the ionosphere during the recovery phase are generally thought to be controlled by the variations of the thermospheric compositions and the ionospheric disturbance dynamo electric fields, which tends to decrease or even reverse the quiet time low-latitude electric field during daytime (Blanc & Richmond, 1980; Fejer et al., 1983; Fejer & Emnett, 2003). As a result, the daytime electron density in the middle and low latitudinal ionosphere is often observed to be lower than the quiet time value during the recovery phase of geomagnetic storms (Balan et al., 2013). Lei et al. (2018) reported that the daytime low-latitude ionospheric total electron content (TEC) during the recovery phase of September 2017 storm was much greater than the quiet time value, and this enhancement during the recovery phase can last for more than 3 days. With regard to the August 2018 storm that driven by the CME on 25 August, the
enhancement of the daytime low-latitude ionospheric TEC measured by the Beidou geostationary satellite C03 was also observed during the main phase on 26 August and recovery phase on 27–30 August (see in Figure 1a). However, the physical mechanisms that result in the ionospheric positive storm during the recovery phase have yet been understood. Nowadays, Global Navigation Satellite Systems (GNSS) provide the capability of measuring the positions in real time with an accuracy of several centimeters to meters. The ionospheric effects are still the main factor that limits the precision and reliability of GNSS positioning (Wautelet et al., 2009). Moreover, the loss of lock of GNSS signal due to the ionospheric scintillation significantly affects the GNSS-aided military applications as well as civilian communication systems (Conker et al., 2003). Therefore, understanding the mechanisms that result in the ionospheric variability would contribute to the accurate prediction of the ionosphere and the associated GNSS-aided applications.

It is notable that the high-speed solar wind stream (HSS) hit the Earth’s magnetosphere at ~22 UT on 26 August 2018, and it acted with the Earth’s magnetosphere for more than 3 days during the recovery phase of the August 2018 storm (Abunin et al., 2019). The HSS is a substantial factor affecting the I-T system. The solar wind dynamic pressure, which is proportional to the product of density and the square of solar wind speed, is an important factor for controlling the shape and size of the magnetosphere (Fairfield, 1991). Additionally, the high-speed solar wind can modulate the I-T system, such as the magnetospheric convection (Denton et al., 2009), the cross polar cap potential (CPCP) (Bruntz et al., 2012; MacDougall & Jayachandran, 2001; Sergeev & Kuznetsov, 1981), the particle precipitation and auroral power (Liou et al., 1998), and the Joule heating (Palmroth et al., 2004), by interacting with the magnetosphere. The HSS can also disturb the middle latitudinal ionosphere for multiple days (Denton et al., 2009; Lei et al., 2008). Moreover, as suggested by Burns et al. (2012), the continuing effects during the HSSs are capable of leading to extended periods of storm effects on the I-T system for many days, and the cumulative effects can even be comparable with the CME-driven storms (Turner et al., 2009). However, during the CME-driven storms, the effects of the high-speed solar wind on the I-T system are seldom considered. An interesting question is thus proposed that should we consider the contribution from high-speed solar wind to the I-T system during the recovery phase of geomagnetic storms?

Figure 1. (a) Variations of total electron content (TEC) obtained from Beidou geostationary satellite C03 as a function of ionospheric pierce point latitudes over the Asian-Australian sector from 23 to 30 August 2018. Variations of (b) solar wind velocity and density, (c) the IMF Bz, By components, and geomagnetic activity indices (d) Kp and (e) SYM-H from 23 to 30 August 2018. The solar extreme ultraviolet flux proxy F10.7 (red) during this period is shown in (d). The yellow shadows denote the period analyzed in this study.
In this study, we focus on the effects of the high-speed solar wind on the ionosphere during the recovery phase of the August 2018 geomagnetic storm. Multiple observations combined with model simulations are used to evaluate the contributions from the solar wind velocity to the high-latitude ionosphere during the recovery phase of geomagnetic storm. Furthermore, the effects of the high-speed solar wind on the middle- and low-latitude ionosphere during the recovery phase are discussed.

2. Solar and Geophysical Conditions of the August 2018 Storm

The solar wind velocity and density during 23–30 August are shown in Figure 1b, and the corresponding temporal variations of meridional (Bz) and zonal (By) components of IMF are shown in Figure 1c. The solar wind velocity and density were about 400 km/s and 4/cm³, and the Bz and By were almost 0 on the whole day of 23 August. The Kp index (shown in Figure 1d) was less than 2 on 23 August, and the SYM-H in Figure 1e generally did not change on that day. As suggested by Abunin et al. (2019), the August 2018 storm during 24–30 August was caused by two CMEs and a followed HSS. The temporal variations of the solar wind density, solar wind velocity, and IMF during the storm have been described in Abunin et al. (2019) and Astafyeva et al. (2020) in detail. The Bz reached its minimum value of about −17 nT at 05 UT on 26 August, and the Kp and SYM-H index reached the peak of 7+ and a minimum of −207 nT at 06 UT on 26 August. The solar wind velocity increased from about 08 UT on 26 August indicating the arrival of HSS at the early recovery phase of the August 2018 storm. The sharp changes in the solar wind density and IMF By and Bz should be related to the interaction of the tail of the CME and the HSS. Then, the HSS itself acted the Earth’s magnetosphere from about 22 UT on 26 August, since the solar wind density remained a constant value of about 3/cm³ after that time. The solar wind velocity reached its peak of greater than 600 km/s at 18 UT on 27 August. The IMF By and Bz remained nearly 0 nT during 27–30 August. The Kp index increased again to a peak of 6− at 18 UT on 27 August, which was ascribed to the slight southward turning of Bz during 09–21 UT on that day. Note that, the solar EUV flux proxy F10.7 shown in Figure 1d generally did not change during the entire phase of the August 2018 storm, and the maximum and minimum values of F10.7 were 74 and 71, respectively.

3. Results

3.1. Observation Results at High Latitude

The aurora produced by the particle precipitation is closely related to the interaction between the solar wind and the Earth’s magnetosphere. The field-aligned current system is the creation of aurora and its associated particle precipitation, and the aurora arcs always lie within the latitudinal region of the field-aligned current (Armstrong et al., 1975; Kamide, 1982). About ~75% auroral energy that precipitates into the ionosphere is carried by the diffuse aura (Newell et al., 2009; Sandford, 1968). The diffuse aurora that locates at the latitude range of 55° to 70° is mainly driven by the precipitation of electrons (with energies from hundreds of eV to 10 keV) from the magnetospheric plasma sheet (Fontaine & Blanc, 1983; Hardy et al., 1985, 1989; Khazanov et al., 2014). In this study, we used the Special Sensor Ultraviolet Spectrographic Imager (SSUSI), a far-ultraviolet (FUV) imager which observes FUV spectrum in 5 bands: HI Lyman α (121.6 nm), OI (130.4 nm), OI (135.6 nm), N₂ LBHS (1,400–1,600 Å), and N₂ LBHL (1,600–1,800 Å) (Paxton et al., 2002; Sotirelis et al., 2013), onboard the polar orbiting Defense Meteorological Satellite Program (DMSP) F18 satellite (Paxton et al., 2002) to analyze the changes in the particle precipitation from the magnetosphere into the upper atmosphere during the recovery phase of the August 2018 storm. DMSP F18 satellite has a period of ~101 min and inclination of ~98.9° (Hardy et al., 1984). It should be noted that, during the considered period, the SSUSI images detected by DMSP F18 in Northern and Southern Hemispheres were at dayside and nightside, respectively. In this study, we used the N₂ LBHS emission (the shorter wavelength of Lyman-Birge-Hopfield bands), which was mostly produced by impact excitation from the precipitating electrons and secondary electrons (with energies below 500–600 eV) produced by protons, as Zhou et al. (2019) did. The LBHS optical emissions have been widely used to indicate the electron precipitation over the auroral oval (Strickland et al., 1983).

The SSUSI polar images, with magnetic local noon at the top of each image, for Northern and Southern Hemispheres are shown in Figures 2c–2f and 2g–2j, respectively. The gray radial lines and circles represent the magnetic local time (MLT) and magnetic latitude (MLAT). The solar wind velocity and Bz on the quiet
Day 23 August and the recovery phase (27–29 August) are shown in Figures 2a and 2b for reference. Because the Bz showed a slight southward turning after 9 UT on 27 and 28 August, we chose the SSUSI images around 4–5 UT, when the contributions from the solar wind velocity to the I-T system could be better isolated, for analysis. The median time of each image is marked by the cyan (for Northern Hemisphere) and the orange (for Southern Hemisphere) lines in Figures 2a and 2b. Since there were not sufficient number of observations between 4 and 5 UT on 29 August, the auroral images on 29 August shown in Figures 2f and 2j were at around 3 UT. The observations on 23 August were used as the quiet time reference because the geomagnetic conditions on that day were relatively quiet. Comparing with the quiet time auroral ovals on 23 August shown in Figures 2c and 2g, both the daytime (Northern Hemisphere) and nighttime (Southern Hemisphere) aurora extended to lower latitudes during 27–29 August, when the solar wind velocity was higher. Additionally, the intensity of the nighttime aurora during the recovery phase of this storm increased prominently than the daytime aurora did, especially on 27 and 28 August. These results were generally consistent with the statistical results by Milan et al. (2010), who suggested that the auroral intensity increased with solar wind velocity, and the peak latitudes of auroral oval extended to lower latitude as solar wind velocity increased.

High-latitude electrodynamics is another significant factor that affects the I-T system when the magnetosphere is disturbed. The high-latitude ionospheric electrostatic potential field of magnetospheric origin is subject to the interaction of the solar wind and IMF with the Earth’s magnetosphere and ionosphere. This electrostatic field can lead to a two-cell convective flow of ionospheric plasma (Axford & Hines, 1961). In this study, we employed data from the Super Dual Auroral Radar Network (SuperDARN) (Chisham et al., 2007; Greenwald et al., 1995) to provide information regarding ionospheric potential and the related convection flow. The plasma drift observed from the SuperDARN has a 2-min temporal resolution, and these data are mapped into the magnetic coordinate system. In this study, we used the assimilated high-latitude potential and plasma drift from SuperDARN observations in the Northern Hemisphere (Cousins et al., 2013) since these radars can provide a much more comprehensive coverage than those in Southern Hemisphere.

Figure 2. Variation of solar wind velocity and IMF Bz on (a) 23 August and (b) 27, 28, and 29 August. The LBHS images (in the unit of kR) observed by DMPS F18/SSUSI in the (c-f) Northern Hemisphere and (g-j) Southern Hemisphere on 23, 27, 28, and 29 August. The results are mapped into the geomagnetic coordinate with magnetic local noon at the top of each panel.
Figure 3a displays the temporal variation of the CPCP in the Northern Hemisphere from 27 to 30 August 2018. The CPCP on 23 August, which represents the quiet time reference, is also shown by the gray line in Figure 3a. It is seen that the CPCP during the recovery phase varied dramatically, especially on 27 August and the first half-day of 28 August. As mentioned above, the IMF was relatively quiet during 0–9 UT on those days; we thus show the high-latitude convection and potential at 4 UT during the recovery phase in Figure 3c–3e. The CPCPs at the considered time are marked by the cyan bars in Figure 3a. The convection and potential at 4 UT on 23 August are shown in Figure 3b for comparison. It can be seen that the convection patterns on 27 and 28 August extended equatorward to lower latitudes than that on 23 August, and the convection velocity was also enhanced dramatically as compared with the quiet reference. Additionally, the convection pattern and velocity on 29 August (shown in Figure 3e) was slightly greater than that on 23 August.

3.2. Simulation Results at High Latitude

The observation results suggested that the high-speed solar wind would modulate the shape and intensity of the auroral oval and the high-latitude convection pattern. It should be noted, however, the contributions from the high-speed solar wind to the high-latitude ionosphere cannot be clearly isolated from the observations because of the day-to-day variabilities in the I-T system. In this study, we used the National Center for Atmospheric Research Thermosphere Ionosphere Electrodynamics General Circulation Model (TIEGCM) by Richmond et al. (1992) to study the effects of solar wind velocity on the I-T system during the recovery phase of the August 2018 storm. The TIEGCM can self-consistently solve the coupled nonlinear momentum, energy, and continuity equations for neutral and ion species at the altitudinal range of about 97 to 500 km, which is dependent upon the solar activity. The TIEGCM can provide the self-consistent simulation parameters, such as neutral and ionized species, wind, temperature, and electric fields, in the I-T system. The basic model setup and inputs of the TIEGCM were the same as those in Ren and Lei (2017). The horizontal resolutions in the TIEGCM were 2.5° × 2.5° in longitude and latitude, and the vertical resolution was one-fourth of a scale height. It should be pointed out that the high-latitude convection used in the TIEGCM was specified by the Weimer model (Weimer, 2005), which was driven by solar wind and IMF data. Additionally, the aurora and its related energetic particle precipitation used are calculated by the model described in Roble and Ridley (1987).
In order to evaluate the contributions from the solar wind velocity to the I-T system, we conducted two simulation runs. For the first default simulation run (Run-1), we used the solar wind and IMF data from the ACE satellite to derive the high-latitude convection and particle perception pattern. In the comparative run (Run-2), the solar wind velocity from 0 UT on 27 August (see the gray shading in Figure 1) was set as a constant of 400 km/s. In this way, the contributions from the solar wind velocity to the I-T system could be isolated.

The simulated Northern Hemisphere CPCP from Run-1 is shown in Figure 4a. The blue dotted line in Figure 4a denotes the CPCP during 27–30 August, and the gray line represented the quiet time reference on 23 August. The absolute values of the CPCP during quiet time and recovery phase of this storm were greater than the corresponding observed values shown in Figure 3a. The differences between the CPCP during the recovery phase and quiet time are shown in Figure 4b. The red dotted line represents the observational results, and the blue one is the corresponding simulation results. It is seen that the TIEGCM can generally reproduce the contributions from the IMF and solar wind to the ionospheric CPCP as compared with the condition on 23 August. The simulated Northern Hemisphere convection patterns corresponding to the observations (shown in Figures 3b–3e) are displayed in Figures 4c–4f. Comparing with the quiet reference in Figure 4c, the convection patterns on 27 and 28 August enhanced prominently and also extended to lower latitudes, and the simulated convection on 29 August was slightly weaker than that on 23 August. This situation was generally consistent with the observation results, although the observed convection patterns on 29 August was slightly stronger than that on 23 August. Overall, the TIEGCM can generally reproduce the variabilities of the high-latitude potential and convection during the recovery phase of the August 2018 storm during 27–30 August.

It should be noted that the geomagnetic conditions on 23 August were not extremely quiet, so that the changes of the analyzed parameter between the recovery phase and 23-August are partly associated with the elevation of solar wind velocity. Since TIEGCM can generally reproduce the changes of the high-latitude ionospheric electric field, convection, and auroral pattern, the simulation results were effective in the quantitative investigation of the impacts of high-speed solar wind streams on the ionosphere during the recovery phase.

**Figure 4.** Variations of (a) the simulated CPCP during 27–30 August (blue dotted line) and the quiet time reference on 23 August (gray line) and (b) the observed (red dotted line) and simulated (blue dotted line) differential CPCP with respect to the corresponding quiet time reference. (c–f) The simulated potential (in the unit of kV) and convection at 4 UT in the Northern Hemispheres on 23, 27, 28, and 29 August. The results are mapped into the geomagnetic coordinate with magnetic local noon at the top of each panel.
The difference between the simulated CPCPs from Run-1 and Run-2, which denotes the contribution from the enhanced solar wind velocity to the CPCP, is shown by the red dotted line in Figure 5a. The IMF Bz and solar wind velocity are also shown in Figure 5a for comparison. It should be noted that the enhancement of solar wind speed was a contributor to the ionospheric CPCP, and the magnitude of the enhancement of CPCP was closely associated with the solar wind velocity. Additionally, it is seen that the oscillation of the CPCP caused by the increased solar wind velocity is also strongly modulated by the IMF Bz fluctuation. This is understandable since the solar wind has much more dramatic consequences under the condition of southward IMF (Boudouridis et al., 2004; Lee et al., 2007; Lee & Lyons, 2004; Meurant et al., 2004). The effects of the enhancement of solar wind velocity on the Northern Hemisphere convections at 04 UT on 27–29 August are shown in Figures 5b–5d. It was seen that the solar wind velocity was effective in contributing to the enhancement of the convection velocity.

As suggested in Figure 2, the solar wind velocity had effects on the shape and intensity of the auroral oval, which would influence the ionospheric electron content. In this study, we used the MIT Haystack Observatory (Madrigal database) TEC maps to display the effects of the solar wind velocity on the high-latitude ionospheric electrons. Because there was not sufficient coverage of the TEC observations at the high latitudes of the Southern Hemisphere, only the MIT-TEC maps in the Northern Hemisphere were considered. Since the geomagnetic conditions were relatively quiet during 0–9 UT on these analyzed days, the observed MIT-TEC during 0–9 UT on each day was binned by fixing MLT and MLAT, and the median value in each bin was used. The changes in the MIT-TEC maps during the recover phase with respect to the quiet time TEC on 23 August are shown in Figures 6a–6c. Here we mainly focused on the TEC change around the auroral oval. It is seen that the enhancement of the particle precipitation during the recovery phase had effect on the increase of nighttime TEC of about 1 TEC unit (TECU; 1 TECU = 10^{16} \text{ m}^{-2}) at the auroral region, which is much greater than the day-to-day variability of the TEC in this region. Additionally, the TEC inside the auroral oval showed a slight decrease, especially at the dusk side. By comparing with the changes of TEC on 27 and 28 August, the nighttime TEC at the auroral oval on 29 August was slightly greater than that on 23 August. This was generally consistent with the observed aurora by the SSUSI F18 (see in Figure 2), which showed the equatorward extension of auroral oval and the enhancement of the nighttime particle precipitation during the recovery phase.
The corresponding simulation results in the Northern Hemisphere are shown in Figures 6d–6f. Note that, in order to compare with the observation results, the simulation results displayed in Figure 6 were also binned in the same way with the observations. As shown in Figures 6d–6f, due to the equatorward extension of the auroral oval, the TEC at the auroral oval was greater than the quiet time value and the TEC at higher latitudes inside the auroral oval showed slight decreases. Moreover, the nighttime increase of TEC at the auroral zone was greater than that during daytime. Consequently, the enhancement of TEC during the recovery phase was much easier to be observed during nighttime. It has been discussed previously that the geomagnetic conditions on 23 August were not exactly quiet, the difference may not totally be contributed by the increase of solar wind velocity. The differential TEC between Run-1 and Run-2 are shown in Figures 6g–6i, in which the contributions from the high-speed solar wind to the ionosphere were clearly isolated. It was noted that the data used here were also binned in the same way with the observations. The enhancement of the TEC at the auroral oval was greater than the corresponding values shown in Figures 6d–6f, and the maximum increase of the TEC that caused by the enhancement of solar wind velocity was about 2 TECU at around midnight. This situation was consistent with the statistical results in Liou et al. (1998), who suggested that the solar wind velocity is one of the important parameters in controlling

![Figure 6](image_url)

**Figure 6.** The (a–c) observed and (d–f) simulated changes in TEC (in the unit of TECU) during 27–29 August with respect to the quiet reference on 23 August. (g–i) The differential TEC (in the unit of TECU) between the default run (Run-1) and controlled simulation (Run-2) during 27–29 August. The data are binned in geomagnetic latitude and magnetic local time during 0–9 UT on each day. The results are mapped into the geomagnetic coordinate with magnetic local noon at the top of each panel.
the nightside aurora, and the enhancement of the night sector auroral emissions is related to both the reconnection and viscous-like interaction mechanisms.

The contributions from the enhancement of solar wind velocity to the high-latitude F-layer electron density were further analyzed. Here we used the simulated electron density on fixed pressure surface $Z_p = 2$ (~270 km) at 04 UT on 27–29 August to investigate the effects of solar wind velocity on the ionosphere. The differences in the F-layer electron density between Run-1 and Run-2 are shown in Figure 7. The changes of the electron density on the Northern Hemisphere ionosphere are shown in Figures 7a–7c, and Figures 7d–7f display the changes of the electron density on the Southern Hemisphere ionosphere. The high-speed solar wind caused equatorward extension of the auroral oval and the increase of F-layer electron density at the auroral oval. As expected, the electron density inside the auroral oval showed a slight decrease.

By comparing the changes in the Northern Hemisphere (Figures 7a–7c) and Southern Hemisphere (Figures 7d–7f), the enhancement of F-layer electron density that caused by the particle precipitation was greater at Southern Hemisphere (winter hemisphere) than that at Northern Hemisphere (summer side). This situation was consistent with the statistical results in Shue et al. (2002), who suggested that the solar wind velocity increases the auroral brightness mainly on the nightside and the winter case.

Overall, the observation and simulation results suggested that the high-speed solar wind had an effect on the high-latitude ionosphere via various processes during the recovery phase of the August 2018 geomagnetic storm. The high-speed solar wind caused the equatorward extension of auroral oval during the recovery phase. The enhancement of auroral particle precipitation and the equatorward extension of auroral oval during the recovery phase caused the 2-TECU increase of TEC at the auroral oval and the 1-TECU decrease of TEC inside the aurora zone. In the meanwhile, the electron density at F-layer also increased about $1 \times 10^5$/cm$^3$ at the auroral oval due to the high-speed solar wind, though most of the electrons were precipitated into the E region. The contributions from the high-speed solar wind to the polar ionosphere were greater in winter hemisphere than that in summer hemisphere. The high-speed solar wind also influenced the high-latitude electric field and its potential during the storm recovery phase. The enhancement of

Figure 7. Changes of simulated electron density (in the unit of $1 \times 10^5$/cm$^3$) at 4 UT on fixed pressure surface $Z_p = 2$ (~270 km) between the default run (Run-1) and controlled simulation (Run-2). The results on the Northern Hemisphere during 27–29 are shown in (a)–(c), the corresponding results on the southern hemisphere during 27–29 are shown in (d)–(f). The results are mapped into the geomagnetic coordinate with noon at the top of each panel.
The differential TEC at 110°E during 27-30 August between Run 1 and Run 2 is further shown in Figure 8c as a function of day and MLAT. The change in the vertical plasma drift (differential between Run 1 and Run 2) that ascribed to the high-speed solar wind is shown by the blue line in Figure 8b. It was seen that the high-speed solar wind was a contributor to the enhancement of the eastward electric fields. This increased eastward electric fields caused the enhancement of the upward drift of the daytime equatorial plasma, that is, the enhancement of the equatorial fountain effect. Consequently, the high-speed solar wind was a contributor to the enhancement of the TEC at the EIA region. The maximum (percentage) increase of TEC from Run 1 was about 20% and 30% greater than that on 23 August. It was noted that TIEGCM can also reproduce the positive recovery phase storm as was observed by Beidou TEC. However, the maximum (percentage) increase of TEC that related to the high-speed solar wind during the recovery phase was on the order of about 10 kV, and the maximum increase of associated high-latitude convection velocity was about 20 m/s. Moreover, the changes in the high-latitude CPCP closely depended on the direction of IMF Bz.

3.3. Middle and Low-Latitude Results

The TECs measured by the Beidou geostationary orbit (GEO) satellite C03 in the Asian-Australian sector were used to illustrate the low-latitude ionospheric evolution during the recovery phase of the August 2018 storm. The GEO TEC is effective in deriving the stable and continuous temporal and spatial variation of the lower-latitude ionosphere since the ionospheric piece points (IPPs) almost do not change (Huang et al., 2017). The receive stations used in this study are listed in Table 1. Figure 8a displays the variations of the differential TEC with respect to quiet reference vertical TEC on 23 August as a function of MLAT over the Asian-Australian sector from 27 to 30 August 2018. The black contour lines in Figure 8a represent the percentage increases of Beidou TEC are 100% and 200% as compared with the TEC on 23 August. Different from the expected negative ionospheric storm during the recovery phase, the daytime TEC at lower latitudes during these 3 days showed TEC enhancement compared with the quiet time reference. The increase of TEC at the equatorial ionization anomaly (EIA) region was about 10–15 TECU. Moreover, the increase in TEC was more than 200% on 27 and 28 August. The corresponding simulated differential TEC at 110°E during 27–30 August with respect to the quiet reference on 23 August from Run-1 is shown in Figure 8b. The contour lines in Figure 8b denote the simulated TEC is 20% and 30% greater than that on 23 August. It was noted that TIEGCM can also reproduce the positive recovery phase storm as was observed by Beidou TEC. However, the maximum (percentage) increase of TEC from Run-1 was about 2 TECU (~30%), which was prominently lower than the more than 10-TECU (~200%) enhancement of the Beidou TEC at the EIA region.

The differential TEC at 110°E during 27–30 August between Run-1 and Run-2 is further shown in Figure 8c as a function of day and MLAT. The change in the vertical plasma drift (differential between Run-1 and Run-2) that ascribed to the high-speed solar wind is shown by the blue line in Figure 8b. It was seen that the high-speed solar wind was a contributor to the enhancement of the eastward electric fields. This increased eastward electric fields caused the enhancement of the upward drift of the daytime equatorial plasma, that is, the enhancement of the equatorial fountain effect. Consequently, the high-speed solar wind was a contributor to the enhancement of the TEC at the EIA region. The maximum (percentage) increase of the TEC that related to the high-speed solar wind was ~1 TECU (10%).

4. Discussion

The results presented in Figures 4 and 6 indicate that the TIEGCM generally reproduced the evolution of the convection and particle precipitation at high latitudes during the recovery phase of the August 2018 geomagnetic storm. Further, the controlled simulation, in which the solar wind velocity during 27–30 August was set as a constant value of 400 km/s, was conducted to analyze the contribution from the high-speed solar wind to the ionosphere. The comparison results suggested that the high-speed solar wind was effective in changing the aurora and convection patterns during the recovery phase of the geomagnetic storm. However, it was found that the TIEGCM cannot reproduce the observed more than 10-TECU enhancement of the low-latitude ionospheric TEC during the recovery phase of the August 2018 geomagnetic storm. In this study, the effects of the high-speed solar wind on the ionosphere during the recovery phase were further discussed.

As shown in Figure 8c, the high-speed solar wind was a contributor in modulating the daytime eastward electric fields. This increased eastward electric field during daytime in the TIEGCM was generally attributed to the prompt penetrating electric fields (PPEFs) due to the temporary failure of the shielding mechanism (Jaggi & Wolf, 1973). The PPEF depends closely on the solar wind and the IMF Bz (Kelley et al., 2003; Nishida, 1968; Vasyliunas, 1970). It has been found that the magnetosphere-ionosphere...
system reacts to the solar wind electric field as a high pass filter letting the electric field penetrate to the magnetic equator (Kelley, 1989; Vasyliunas, 1972). Furthermore, the efficiency of the penetrating electric fields is much higher under the conditions of the southward IMF than that of northward IMF (Huang et al., 2007; Nicolls et al., 2007). Consequently, the slight fluctuation of IMF \( B_z \) can result in the PPEF in the low-latitude ionosphere. It was also found that the high-speed solar wind combines with the IMF \( B_z \) fluctuation can lead to the long-duration continuous prompt penetration effects of interplanetary electric field into the equatorial ionosphere (Koga et al., 2011; Wei et al., 2008). Note that the solar wind controls the interplanetary electric field \( E_{sw} = -V_{sw} \times B \), which drives the currents flowing between the solar wind and the Earth’s magnetosphere. Therefore, the high solar wind velocity was effective in contributing to the enhancement of daytime eastward electric fields in the low-latitude ionosphere during the recovery phase of geomagnetic storm and thus contributed to the ionospheric fountain effect.

As shown in Figure 8b, the high-speed solar wind mainly resulted in the increase of TEC in the EIA region indicating the effect of the high-speed solar wind to the low-latitude ionosphere was dominated by the PPEF during the recovery phase. Note that the varying IMF \( B_z \) itself, especially for the weakly negative \( B_z \), can also modulate the terrestrial ionosphere. Additionally, the HSS can lead to the enhancement of the ratio of atomic oxygen to molecular nitrogen number densities (\( O/N_2 \)) by modulating the thermospheric circulation, and thus slightly contribute to the TEC increase of electron density at lower latitude, which is consistent with the study of Chen et al. (2016). Overall, the maximum increase of TEC during the recovery phase of the August 2018 storm was about 2 TECU in the TIEGCM as shown in Figure 8b, which was significantly lower than the observation results (more than 10 TECU) at the EIA region. This situation suggests that the high-speed solar wind indeed can modulate the low-latitude ionosphere during the storm recovery phase, whereas the ~2-TECU enhancement of the low-latitude ionosphere simulated by the TIEGCM, which is associated with the high-speed solar wind streams combining with the oscillating IMF \( B_z \), is lower than the 10-TECU enhancement seen in the observations.

Figure 8. (a) Variations of differential TEC (in the unit of TECU) obtained from Beidou geostationary satellite C03 with respect to the quiet day TEC on 23 August as a function of ionospheric pierce point latitudes over the Asian-Australian sector from 27 to 30 August 2018. The contour lines in (a) represent the 100% and 200% enhancement of TEC with respect to the quiet day TEC on 23 August. (b) The differential TEC from Run-1 with respect to the quiet reference on 23 August as a function of time and magnetic latitude during 27–30 August. The contour lines in (b) represent the percentage enhancement of TEC with respect to the simulated quiet day TEC on 23 August. (c) The differential TEC (in the unit of TECU) at 110°E between Run-1 and Run-2 as a function of day and magnetic latitude during 27–30 August. The contour lines in (c) represent the 10% enhancement of TEC with respect to the default simulation results in Run-1. The changes of equatorial vertical plasma drift at 110°E between Run-1 and Run-2 is also shown in (c) for comparison.
The positive ionospheric storm of more than 10-TECU enhancement during the recovery phase requires further investigation. The comparison result suggested that the enhancement of equatorial eastward electric field during the recovery phase was prominently underestimated. One of the possible mechanisms is the lower atmospheric forcing, which was also discussed in Lei et al. (2018). As is known that the neutral wind in the ionospheric E region plays a significant role in producing the ionospheric current and electric fields (Heelis, 2004; Richmond, 1995). The increase of the poleward winds or the westward winds in the E region can cause the increase of daytime eastward electric field and thus intensify the equatorial fountain effect. Moreover, it was found that the HSSs can lead to the more than 100% increment of the daytime low-latitude TEC during solar minimum by enhancing the PPEF (e.g., Candido et al., 2018; Verkhoglyadova et al., 2013). Consequently, it is unclear whether the TIEGCM capture the variation of the PPEF that related to the varying solar wind velocity and IMF Bz.

5. Summary

In this study, multiple observations, including aurora, high-latitude convection, potential, and TECs, were used to study the possible contributions from the high-speed solar wind to the ionosphere during the recovery phase of the August 2018 geomagnetic storm. It was found that the high-speed solar wind contributed to the particle precipitation and the equatorward extension of the auroral oval. The high-speed solar wind was also effective in modulating the high-latitude convection and potential. The TIEGCM controlled simulation run was conducted for the quantitative investigation of the effects of high-speed solar wind on the ionosphere during the recovery phase. The simulation results suggested that the high-speed solar wind could result in the about 2-TECU enhancement of TEC at the auroral oval. Additionally, high-speed solar wind combining with the oscillating IMF Bz caused about 2-TECU enhancement of TEC at low latitude in the TIEGCM model. Consequently, the high-speed solar wind was a possible contributor to the ionospheric positive storm during the recovery phase, but the dominant effect that results in the large enhancement of low-latitude ionospheric TEC during the recovery phase of the August 2018 geomagnetic storm requires further investigation.

Data Availability Statement

Beidou GEO TEC data are provided by the University of Science and Technology of China and the Data Center for Geophysics, National Earth System Science Data Sharing Infrastructure at BNOSE, IGGCAS (http://gnss.stern.ac.cn), MIT-TEC data by the Madrigal database (http://madrigal.haystack.mit.edu/cgi-bin/madrigal/madInvent.cgi), SuperDARN (http://vt.superdarn.org), and DMSF/SSUSI auroral FUV data (https://ssusi.jhuapl.edu/data_products). The TIEGCM simulation codes are available from the website (https://www.hao.ucar.edu/modeling/tgcm/). The TIEGCM simulation data, analysis codes, and analysis routines are available online (from http://iono.ustc.edu.cn/expdata/Publications/August_2018_storm/).

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