Statistical Study of F-Region Short Period Ionospheric Disturbances Related to Convection in the Lower Atmosphere Over Wuhan, China

Zhenlin Yang1, Sheng-Yang Gu1, Yusong Qin1, Chen-Ke-Min Teng2, Fuqing Huang3, Wenjie Sun4, and Xiankang Dou1

1Electronic Information School, Wuhan University, Wuhan, China, 2Beijing Institute of Applied Meteorology, Beijing, China, 3School of Earth and Space Sciences, CAS Key Laboratory of Geospace Environment, University of Science and Technology of China, Hefei, China, 4Beijing National Observatory of Space Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China

Abstract We investigated the relationship between convective activity and F-region short-period ionospheric disturbances at middle latitudes from 2018 to 2020. The ionospheric variations were extracted from the total electron content (TEC) data obtained by the BeiDou geostationary orbit receiver in Wuhan, China, while the convective activities were represented by precipitation data from the fifth generation European Center for Medium-Range Weather Forecasts Reanalysis (ERA5). Additionally, an ionosonde located in Wuhan, China, was used to study the variation in the sporadic E (Es)-layer. Seasonal variations in the convective activity and TEC disturbances were studied. It was found that short-period ionospheric disturbances occurred mainly around summer midnight and around the June solstice. In addition, the correlations between convective activity and the ionosphere have also been studied. A positive correlation between precipitation and short-period ionospheric disturbances was found. Similarly, precipitation and \( f_s E \) also had a positive correlation. By analyzing the precipitation azimuth and upward propagation of convective gravity waves, we proposed a possible coupling mechanism between the ionosphere and the troposphere, through which convective gravity waves could indirectly affect F-region short-period ionospheric disturbances by modulating the Es-layer.

Plain Language Summary The impact of convective activity on the ionosphere has been studied for a long time. However, researchers have mostly focused on the effects of deep convective events on the ionosphere, such as typhoons or tornadoes. Little attention has been given to the effects of seasonal convective variations on ionospheric disturbances. This study used data from ionosonde, BeiDou geostationary orbit total electron content observations, ERA5 wind fields, and precipitation data to reveal the statistical relationships between convective activity and short-period ionospheric disturbances. Short-period ionospheric disturbances show a clear seasonal variation, which fits well with the characteristics of medium-scale traveling ionospheric disturbances. We found that disturbances with periods below 50 min have a positive correlation with convective activities. According to our statistics, although short-period ionospheric disturbances become active with increased convective activity, the relationship between ionospheric disturbances and convective activity was not solely determined by convective strength but was also related to the relative position of the convective activity and ionospheric observation site. The propagation processes of gravity waves thus play an important role in tropospheric and ionospheric coupling.

1. Introduction

The ionospheric disturbance is a wave-like plasma activity that impacts remote sensing systems, navigation and positioning, and other long-range communication works. To maintain the safety of human space activities and reduce related economic losses, the study of ionospheric disturbances is necessary and has been a popular topic in space physics.

Internal atmospheric dynamics have been identified as one of the main causes of ionospheric disturbances, especially convective activity. The study of the relationship between convective activity and the ionosphere can provide a unique perspective on ionosphere-atmosphere coupling (Azeem et al., 2015; Bauer, 1958; Chen et al., 2020; Chou et al., 2017; Georges, 1973; Lay, 2018; Nishioka et al., 2013; Peng et al., 2021; Wen & Jin, 2020). The ionospheric disturbances caused by convective activity are generally traveling ionospheric disturbances (TIDs). For
decades of study, researchers have been devoted to revealing the effect of convective activity on the ionosphere. Nishioka et al. (2013) detected concentric ionospheric wave disturbances during the 2013 Moore tornado event and believed that gravity waves released from the supercell were trapped in a thermal duct in the thermosphere and that the leaking energy from thermal ducts excited gravity waves to affect the ionosphere. Azeem et al. (2015) reported that concentric fluctuations were detected in the atmosphere at different altitudes during a convective storm in North Texas on 4 April 2014 and considered that a part of the convective gravity waves survived through upward propagation and eventually reached the ionosphere. Vadas and Azeem (2021) investigated the largest-amplitude concentric TIDs from GPS over the United States on 25–26 March 2015. They found that the TIDs are most likely induced by secondary gravity waves from local horizontal body forces created by the dissipation of primary gravity waves from deep convection. These findings have also been confirmed by other studies (Liu et al., 2021; Maurya et al., 2019; Miyoshi et al., 2018; Snively & Pasko, 2008; Vadas & Becker, 2018; Zhao et al., 2020). To date, the effects of convective activity on the ionosphere have various explanations. However, there is consensus among researchers that gravity waves play a key role in the coupling between the ionosphere and troposphere.

The ionospheric response due to gravity waves has been studied for a long time. For several types of ionospheric irregular phenomena, such as TIDs (Miyoshi et al., 2018; Otsuka et al., 2011), Es-layers (Tang et al., 2021; Wang et al., 2021), and plasma bubbles (Wu et al., 2017), gravity waves are one of their main sources. Gravity waves play a vital role in the modification of structural and dynamic processes in the middle and upper atmosphere (Feng et al., 2005; He et al., 2021; Lindzen, 1981; Wu et al., 2015; Zhang, Chen et al., 2020; Zhang, Le et al., 2020). The upward propagation of gravity waves transports energy from the lower atmosphere to the upper atmosphere through propagation and dissipation to modify the background atmospheric conditions and even affect the ionospheric plasma distribution. As research progresses, researchers believe that some mechanisms could generate gravity waves: airflow through topographic obstacles (Alexander & Teitelbaum, 2007; Eckermann et al., 2007; Hines, 1989) and dynamic and convective instability caused by high wind shear and moist convection in the troposphere (Lindzen, 1981; Nishioka et al., 2013; Wu et al., 2015). In addition, some special natural hazard events and space weather events can also generate gravity waves, such as earthquakes, volcanic eruptions, geomagnetic storms, and solar eclipses (Astafyeva, 2019; Chimonas & Hines, 1970; Hegai et al., 2006; Karan & Pallamraju, 2018; Meng et al., 2019; Zhang et al., 2017). Since convective activity is widespread in the atmosphere, this becomes the most important excitation source of gravity waves. Therefore, the coupling mechanism between the ionosphere and the troposphere has always been a valuable issue. However, most relevant studies have focused their analysis on the effects of deep convective events on the ionosphere. The gravity waves generated by regular convective activities can also transfer energy and momentum into the mesosphere lower thermosphere (MLT) and the ionospheric region directly or via secondary gravity waves and affect the local dynamics (Horinouchi, 2002; Nakamura et al., 2003; Vadas & Becker, 2018). Few studies have focused on the relation of seasonal variations between convective activity and the ionosphere from a statistical perspective (Yu et al., 2017).

During many decades of research, various observations have been used for ionospheric detection, such as radars (Bullett & Mabie, 2018; Goncharenko et al., 2018), satellite measurements (Luo et al., 2020; Mrak et al., 2018), ionosondes (Wang et al., 2021) and global navigation satellite systems (GNSSs) (Huang et al., 2017; Padokhin et al., 2019; Zhang, Chen et al., 2020; Zhang, Le et al., 2020). In particular, GNSSs are increasingly being used due to their ability to detect ionospheric total electron content (TEC) variations with high temporal resolution. TEC is an excellent diagnostic tool for the upper ionospheric electron density. As a result, TEC is widely used to determine F-region ionospheric variations. In recent years, China has built the BeiDou global satellite navigation system. Unlike other GNSSs, BeiDou has five geostationary orbits (GEO) satellites. GEO observations are superior to past GNSS observations due to their spatial stability and continuity of observations and are used by an increasing number of researchers (Hu et al., 2017; Sun et al., 2020; Yang et al., 2018).

In this study, we tried to enrich the relationship between convective activity and ionospheric disturbances through statistical studies. The seasonal variations in ionospheric disturbances and convective activities at middle latitudes are statistically analyzed. Additionally, we analyzed the condition for the upward propagation of gravity waves through wind field data. Combining these results, we presented our view of the coupling mechanism between the ionosphere and troposphere. Section 2 introduces the data used in the work, Section 3 describes the statistical methodology and presents the statistical results, and Section 4 discusses the propagation of gravity waves and their effects on the ionosphere.
2. Data

We counted the ionospheric disturbance variation in the Wuhan area, China, from 1 January 2018 to 31 December 2020. The ionospheric observations used in this study were obtained from theBeiDou GEO GNSS receiver (WHHP), whose time resolution was 30 s. For the daily data, we derived TEC data from the same GEO satellite whose pseudorandom numbers are C-01. For the other four GEO satellites, the elevation angles of satellites C-04 and C-05 were too small (less than 30°), which may lead to TEC data inaccuracy due to the multipath effect. Therefore, we did not use data from these two satellites. For the C-01, C-02, and C-03 satellites, the integrity of the TEC data from C-01 and C-03 was better than that from C-02. However, the geographic locations of the ionospheric pierce points (IPPs) from C-01 and C-03 were close, and the statistical results are similar. The IPP is the intersection of the ionosphere and the receiver-satellite line under the ionospheric thin-layer model at a height of 300 km. Therefore, we used the TEC data from C-01 in this study. The WHHP receiver was located at 31.02°N, 114.45°E, Wuhan, China, and the IPP of the C-01 satellite was located at 29.02°N, 116.42°E. In addition, to study the variation in the Es-layer, we used the ionosonde data (WHZL) from the Data Centre for Meridian Space Weather Monitoring Project. The WHZL was located at 30.53°N, 114.61°E, Wuhan, China. The geographic information about each device and the IPP are shown in Figure 1.

To study convective variations throughout the year, we used global precipitation data with a temporal resolution of 1 hr from ERA5 to represent regional convective variations. ERA5 is the fifth generation ECMWF reanalysis for the global climate and weather for the past 4–7 decades. Reanalysis combines model data with observations from around the world to form a globally complete and consistent data set using the laws of physics (Hersbach et al., 2020). The precipitation data are presented in a grid format according to latitude and longitude, and the grid resolution is 0.25° × 0.25° (latitude by longitude). As shown in Figure 1, the contour map represents the distribution of daily precipitation in southeastern China on Day 125 (May 4, 2020).

To analyze the upward propagation of gravity waves generated by convection activity and background wind field conditions, we used wind field data from ERA5. The reanalysis data extend from the Earth’s surface to 0.01 hPa (approximately 80 km height), which has 137 pressure levels and a horizontal resolution of 2.5° × 2.5° (latitude by longitude).
3. Results

3.1. GEO TEC and Ionospheric Disturbance Event Analysis

Figure 2 shows the data processing and spectral analysis of TEC data, using data on Day 125 (May 4), 2020, as an example. Figure 2a shows GEO-TEC data from the WHHP receiver. The GEO-TEC data show good continuity and can fully demonstrate clear diurnal variations and some small time-scale ionospheric disturbances. For an in-depth study of these ionospheric disturbances, spectral analysis of TEC data is necessary. Before the spectral analysis, the long-period variations in TEC data were removed. Since the period of gravity waves varies from...
a few minutes to dozens of minutes, a high-pass filter was utilized here to remove the long-period variation in the TEC data, and the fluctuation components with periods less than 100 min were retained, as shown in an example in Figure 2b. Filtering highlights the small time-scale ionospheric disturbances. On Day 125, there was a significant disturbance at approximately 2200 local time (LT). To study the specific parameters of these ionospheric disturbances, such as duration and magnitude, the Stockwell transform (S-transform) was used to analyze the filtered data, which was an extension of the continuous wavelet transform based on a scaling movable Gaussian window. The S-transform provides frequency-dependent resolution while maintaining a direct relationship with the Fourier spectrum, which makes it easy to find small wave signals (Stockwell et al., 1996; Wright et al., 2011). Figure 2c shows the period-time variations in ionospheric disturbances at WHHP on Day 125, and the color bar indicates the magnitude of the TEC disturbance. As Figure 2c shows, the ionospheric TEC experienced a fluctuation at approximately 2200 LT with an approximately 40-min period and lasted 2 hr. The maximum amplitude of disturbance was approximately 0.2 TECu (1 TEC unit (TECu) is equivalent to 10^{16} electrons per square meter (Mannucci et al., 1998)). Figure 2 shows that our analytical method can clearly distinguish short-period ionospheric disturbances and that the method is feasible. Therefore, we first explored the propagation characteristics of the ionospheric disturbance event during Day 125, 2020, and the possible relationship with convective activity.

To explore the propagation characteristics of periodic ionospheric disturbance events on Day 125, 2020, observations from the two GEO receivers (HFKD and HSKD) around the WHHP are analyzed. Additionally, to explore the possible relationship between ionospheric disturbance and convective activity, precipitation data from ERA5 and the critical frequency of Es-layer \( f_E \) data from the WHZL ionosonde were used. The geographic locations of the IPPs from these receivers are shown in Figure 3a. The filtered TECs from these observations and the variation in \( f_E \) are shown in Figures 3b and 3c. Obvious time lags can be found between these filtered TECs. By shifting the filtered TEC data back and forth to obtain a time lag having a maximum cross-correlation coefficient, the time lag between WHHF and HFKD is approximately 120 s. Considering the distance between the two IPPs, this suggests that the front of TID reached both places almost simultaneously. However, the disturbance phase of the filtered TEC from the HSKD was significantly delayed compared to that of the other two receivers. The time lags of HSKD about WHHP and HFKD are approximately 2,610 and 2,340 s respectively. Moreover, based on these time lags and the geographic locations of the IPPs, the phase speed of the TID can be estimated to be approximately 94.67 m/s and the azimuthal direction of the TID can be estimated to be approximately 147.8°. A detailed description of the calculation process can be found in Matsushima et al. (2022). Figures 3d and 3e show the S-transform analysis of the filtered TEC from WHHP and \( f_E \) from WHZL. From Figure 3d and 3e, a wave signature with a period of approximately 45 min appears in the Es-layer at 2000 LT and was detected by GEO-TEC at 2130 LT. This demonstrates the upward propagation of the wave signature. Additionally, Figure 3f shows the regional maximum hourly average precipitation.

Figure 3. Examples of the periodic ionospheric disturbance event on Day 125, 2020. (a) The geographic locations of the ionospheric pierce points (IPPs) from three global navigation satellite systems (GNSS) receivers. (b) Filtered total electron content (TEC) data from three GNSS receivers. (c) Time series of the critical frequency of Es-layer, \( f_E \). Spectral analysis on (d) filtered TEC from WHHP and (e) \( f_E \) from WHZL using the S-transform. (f) Time series of the regional maximum hourly average precipitation.
three receivers are geographically close to each other, and there were similar statistical results.

### 3.2. Seasonal Variations in Ionospheric Disturbances

We analyzed the seasonal variation in ionospheric disturbances from 2018 to 2020 with periods below 100 min, as shown in Figure 4. To confirm the period and occurrence time of each disturbance, we treated each local maximum in the time-period spectrum as a disturbance, and the disturbance amplitude must be greater than 0.08 TECu. The amplitude of medium-scale traveling ionospheric disturbances (MSTID) varies within the range of 3%–13% relative to background TEC (Afraimovich et al., 2008; Oinats et al., 2016). The daily minimum TEC values in WHHP C-01 are approximately 2–4 TECu. Therefore, the lowest disturbance amplitude would be approximately 0.06 (2 × 0.03) TECu. Combined with the TEC data near Wuhan for 3 years, we believe that 0.08 TECu was an appropriate threshold. Based on this criterion, the number of ionospheric disturbances occurring in each month was analyzed first. As shown in Figure 4, the ionospheric disturbances were more active in summer, specifically from May to August, and the number of ionospheric disturbances during summer was ∼1.5–2 times the number in other seasons. This seasonal variation was an interesting phenomenon, therefore, we further analyzed which period range fluctuations dominated this phenomenon. In Figure 4, the blue and red bars represent the seasonal variation in ionospheric disturbances with periods greater than 50 min and lower than 50 min, respectively. The two types of ionospheric disturbances show very different seasonal variations. Ionospheric disturbances with a period greater than 50 min were almost evenly distributed over each month, with a slight increase in the summer months. However, most ionospheric disturbances with a period less than 50 min occurred from May to August, with the greatest number of occurrences in May and June and a certain amount of decline in July and August. Therefore, the ionospheric disturbances active in summer were mainly due to disturbances with periods less than 50 min.

The temporal characteristics of ionospheric disturbances were also worth studying. The upper panel of Figure 5 shows local time and seasonal variations in the ionospheric disturbances with periods below 100 min in monthly and hourly bins. The ionospheric disturbances strongly depended on the season and local time. In winter, ionospheric disturbances tended to occur around noon. In summer, however, ionospheric disturbances tended to occur around midnight, and most disturbances occurred before midnight. Similarly, Figure 5b shows local time and seasonal variations in the ionospheric disturbances with periods below 50 min in monthly and hourly bins, which shows that the ionospheric disturbances with periods below 50 min appeared mainly at midnight in summer and had a peak occurrence rate around the June solstice. Contrasting the number of ionospheric disturbances with periods below 100 min, it could be found that the ionospheric disturbances with periods below 50 min are dominant during the summer night. The anomalous and concentrated distribution of ionospheric disturbances with periods below 50 min was brought to our attention, and we then delved into the possible causes of this phenomenon. The following ionospheric disturbances refer to ionospheric disturbances with periods below 50 min.

### 3.3. Short-Period Ionospheric Disturbances and Convective Activity

According to the statistics above, short-period ionospheric disturbances become active during the summer. Internal atmospheric dynamics have always been one of the key causes of ionospheric disturbances. For the mid-latitudes of southern China, summer is the peak of convective activity during the year. Then, the increased occurrence of short-period ionospheric disturbances in summer may be due to internal atmospheric dynamics. Therefore, it is worth investigating in depth whether convective activity contributes to this phenomenon.

Convective activity through gravity wave propagation affects the upper atmosphere and even the ionosphere. The horizontal propagation of gravity waves can reach hundreds or even thousands of kilometers. Therefore, convective activity at the IPP location cannot be studied alone but rather the regional convective situation. Convective...
activity is a complex process. To measure the intensity of convective activity, we used precipitation to represent the intensity of convective activity.

Figure 6 illustrates the seasonal variation in ionospheric disturbances and precipitation. The top panel of Figure 6 shows the monthly average precipitation from 2018 to 2020, and the bottom panel of Figure 6 displays the monthly average amplitude of short-period ionospheric disturbance from 2018 to 2020. The region of statistical precipitation ranged from 110°E to 125°E and 25°N to 35°N, as shown in Figure 1. The monthly average
precipitation was the monthly average of the maximum daily precipitation in this region. The monthly average amplitude of short-period ionospheric disturbance referred to the monthly average of the daily maximum amplitude of ionospheric disturbance with a period below 50 min. In Figure 6, the seasonal variation in precipitation and ionospheric disturbance was consistent, and both reached a maximum in summer. However, the peaks of precipitation and ionospheric disturbance did not coincide over time. The peak of precipitation occurred from May to August, but the peaks of ionospheric disturbance occurred around May and June. The precipitation from July to August is as intense as that from May to June. However, the ionospheric disturbances from July to August were weaker than those from May to June.

We further analyzed the correlation between precipitation and ionospheric disturbances, as shown in Figure 7. In the top panel of Figure 7, blue points illustrate the occurrence rate of short-period ionospheric disturbances when daily maximum precipitation exceeded a certain value, and the red line is the trend curve of the results. The advantage of this statistical approach is that it ensures that there are sufficient data at each stage and avoids results being affected by anomalous data or insufficient amounts of data. The occurrence rate of ionospheric disturbance increased with increasing precipitation. This indicated that as the convective activities become active, the probability of ionospheric disturbances also increased. In the bottom panel of Figure 7, blue points illustrate the average amplitude of short-period ionospheric disturbances when daily maximum precipitation exceeded a certain value, and the red line is the trend curve of the results. Similarly, the amplitudes of ionospheric disturbances and precipitation also showed a positive correlation. As convective activities become active, the strength of ionospheric disturbances can be enhanced in some way. Combining seasonal variations and correlation statistics, it seems that convective activity can make short-period ionospheric disturbances active. However, as shown in Figure 6, while the degree of convective activity is equal between June and July, the intensity of ionospheric disturbance is different. This indicated that the relationship between ionospheric disturbances and convective activity was not solely determined by convective strength. Convective gravity waves play an important role in the coupling mechanism between the ionosphere and the troposphere. Therefore, we inferred that differences in the propagation processes of convective gravity waves also affect the strength of ionospheric disturbances.

3.4. Background Wind Field and Precipitation Distribution

After decades of research, researchers generally agree that the upward propagation of gravity waves is highly dependent on the background wind field. It is generally accepted that the same-direction background wind field impedes the upward propagation of gravity waves, while a background wind field in the opposite direction does not (Lindzen, 1981; Nishioka et al., 2013). Therefore, under similar background wind field conditions, the observation of convective gravity waves at the same observational site can be influenced by the variation in the location of convective activity.

We first investigated the location of convective activity relative to the observational site (here, it refers to the IPP between WHHP and GEO C-01) during summer. Figure 8a shows the average regional precipitation from May to June over 3 years. Similarly, Figure 8b shows the average regional precipitation from July to August over 3 years. Based on past studies, the rain belts in China moved from southern China to the Yangtze River basin in late June (Guochang et al., 1985). As shown in Figures 8a and 8b, the rain belts are more concentrated before the June solstice, appearing mainly to the southwest of the observational site. As the time comes to July, the rain

Figure 6. The top (bottom) panel shows statistics of the monthly average regional precipitation (average amplitude of the short-period ionospheric disturbance with periods less than 50 min).

Figure 7. The top (bottom) panel is the correlation analysis between precipitation and the occurrence rate (average amplitudes) of ionospheric disturbance.
Figure 8. The average regional precipitation from May to June (a) and July to August (b) over 3 years. The average zonal and meridional wind fields over 116°E, 29°N from May to June (c and e) and July to August (d and f) over 3 years.
belts decrease in the southwest and move more to the east and northeast. This is a variation in orientation from southwest to the east and northeast relative to our observational site. In probabilistic terms, eastward convective gravity waves are more likely to be detected at our observational site in May and June (if they could successfully propagate upward), and westward convective gravity waves are more likely to be detected in July and August (if they could successfully propagate upward). Variations in the source location of convective activity may have contributed to the differential ionospheric disturbances around the June solstice. However, which direction of gravity waves can easily propagate upward is determined by the background wind condition. Therefore, the variation in the background wind field in summer needs to be studied.

Since the IPP of the observation was at approximately 116°E, 29°N, the local ERA5 wind field data were used for research. Figures 8c and 8d show the local time-altitude variation in the average zonal wind fields at 116°E, 29°N from May to June and July to August over 3 years. Similarly, Figures 8e and 8f show the local time-altitude variation in the average meridional wind from May to June and July to August over 3 years. The altitude ranged from Earth's surface to ~80 km. For the zonal and meridional winds, the positive values were eastward and northward, respectively. Solid contour lines indicate positive values, dash-dot contour lines indicate negative values, and specially marked dashed contour lines are zero values. For zonal winds, eastward winds were present from Earth’s surface to the bottom of the stratosphere, and the maximum speed was approximately 15 m/s. However, the wind field reversed westward as the height increased, and the maximum westward wind reached over ~50 m/s. However, the difference was that the eastward wind speed from May to June was lower than that from May to June, but the westward wind speed was faster than that from May to June. The maximum westward wind speed from July to August reached over ~60 m/s. In addition, the height of the wind field reversal decreased from the bottom of the stratosphere (May and June) to the troposphere (July and August). For the entire summer, the direction of the meridional wind field underwent several transitions as the height increased. However, the wind fields were not very strong, with an average wind speed below 15 m/s. The filtering effect of gravity waves by the meridional wind was relatively limited due to its low wind speed. Overall, the wind fields from May to August were relatively consistent.

In Figures 5 and 6, short-period ionospheric disturbances were mainly concentrated from May to August and reached their maxima around May and June, which occurred mainly around midnight. According to previous studies that focused on gravity waves, gravity waves tend to propagate in the opposite direction to that of background winds as a result of wind-filtering effects (Lindzen, 1981; Maurya et al., 2019; Nishioka et al., 2013). In summer, as shown in Figures 8c–8f, the zonal wind fields above the troposphere were dominated by westward winds, and the whole meridional wind fields were relatively weak. In terms of wind field conditions, eastward gravity waves could easily propagate upward to the upper atmosphere. Furthermore, the tropospheric eastward winds in July and August are weaker than those in May and June. This means that the filter effect of eastward gravity waves is weaker from July to August and that the wind field conditions were more favorable for eastward gravity waves to propagate upward. In general, the filtering effect of the background wind field was consistent during the summer, and eastward gravity waves can easily propagate upward.

Combining the location of convective activity relative to the observational site and the filtering effect of the background wind field, ionospheric disturbances associated with convective activity were more likely to be observed when convective activity occurs west of the observational site. From Figures 8a and 8b, the rain belts transfer from the southwest side to the east side relative to the observational site. The transfer of rain belts induces a decrease in eastward gravity waves, and the background wind field impedes the upward propagation of westward gravity waves. The variation in gravity wave direction caused by the transformation of convective activity distribution could well explain why the magnitudes and number of ionospheric disturbances in Figures 4 and 6b are not particularly large from July to August. This also illustrates that the variations in the location of convective activities and the propagation process of gravity waves also play a key role in ionospheric and tropospheric coupling.

4. Discussion

4.1. Geomagnetic and Solar Activity Conditions

In Section 3, we argue for a positive correlation between short-period disturbances and precipitation. In addition, the variations in the location of precipitation and the propagation process of gravity waves appeared to play a key role in ionospheric and tropospheric coupling. However, geomagnetic variation and solar activity were also
important factors that caused ionospheric disturbances. Therefore, it is also important to verify whether ionospheric disturbances were caused by specific geomagnetic and solar activity. We investigated the variations in the solar flux proxy $F_{10.7}$ and the 3-hr planetary $K_p$ index ($K_p$) from May 1 to August 31 over 3 years, as shown in Figure 9. Typically, a solar flux of less than 100 is considered low solar activity, and more than 150 is considered high solar activity. When $K_p$ reaches over 3, the geomagnetic activities become active, and when $K_p$ reaches over 5, Earth is considered to have undergone a geomagnetic storm. Therefore, $K_p$ is grouped into two ranges to investigate the geomagnetic variations: $K_p < 3$ and $K_p \geq 3$. From the left panels of Figure 9, solar activity mostly remained at low levels. The right panels of Figure 9 show the local time and daily variations in the $K_p$ index in daily and hourly bins. A few moderate magnetic storms occurred throughout the summer, but there was no regularity in the time of occurrence. The overall geomagnetic index tended to be quiet, with a value of less than 3. These indices suggested that the concentrated occurrence of the short-period ionospheric disturbances in summer was not due to geomagnetic activity or solar activity.
4.2. Convective Activity, Sporadic E and Ionospheric Disturbances: Indirect Effects

According to our statistics, most short-period ionospheric disturbances occurred around summer midnight. Previous studies have shown that summer medium-scale traveling ionospheric disturbances (MSTIDs) at middle latitudes mostly occurred around midnight (Otsuka et al., 2011; Otsuka, Tani, et al., 2008). This indicated that our observations were consistent with these studies. However, past studies pointed out that nighttime MSTIDs are not caused by gravity waves. Numerous studies have shown that nighttime MSTIDs are generated by Perkins instability and E-F regions coupling. The coupling effect of the E and F regions in the generation of MSTIDs was suggested to explain the fast growth of the Perkins instability. Polarization electric fields driven by the inhomogeneous electron density in an Es-layer promote the growth of the Perkins instability (Kelley et al., 2003; Lee et al., 2021; Tsuchiya et al., 2020; Wan et al., 2020). These results suggested that convective gravity waves were not a direct cause of nighttime ionospheric disturbances in summer. However, can convective activity have an indirect effect on nighttime ionospheric disturbances?

It has been accepted that MSTIDs at night during the summer are associated with the Es-layer and that MSTIDs activity is closely correlated with \( f_s E_s \) (Huang et al., 2018; Otsuka et al., 2008; Wan et al., 2020). The Es-layer is an ionized cloud at altitudes from 90 to 130 km that is composed of metallic ions (Haldoupis, 2011; Tang et al., 2021; Zhou et al., 2017). In general, the wind shear is responsible for the formation of the Es-layer, and wind fields in opposite directions converge the metal ions in a thin layer to form Es-layer (Wang et al., 2021; Yamazaki et al., 2021). This indicated that the formation of the Es-layer was closely related to the background wind field conditions. According to previous studies, gravity waves can cause a convergence of winds and introduce a wind shear condition that can induce Es-layer (Feng et al., 2005; Miles & John, 1961).

Based on the above, the ionospheric disturbances reach their peak from May to June. To determine the specific variations in Es-layer due to precipitation, we examined the average daily variations in \( f_s E_s \) under intense precipitation days (daily regional maximum precipitation over 65 mm) and calm days (daily regional maximum precipitation below 15 mm) from May to June over 3 years, as shown in Figure 10. In Figure 10, the curves of intense days and calm days have similar trends and the standard deviation of hourly average \( f_s E_s \) (error bar) was added. However, the average \( f_s E_s \) and the error bars on intense precipitation days were overall larger than those on calm days. This indicated that the wind shear effect in the MLT region was stronger on intense days than on calm days. Calm days and intense days account for 10% of the total days in the statistic, respectively. It is necessary to analyze the correlation between precipitation, \( f_s E_s \), and ionospheric disturbances for total days in the statistics.

We studied the relationship between the daily average regional maximum precipitation and daily average \( f_s E_s \), from May to June over 3 years. The statistical strategy was the same as the method used in Figure 7. Figure 11a shows the correlation between the daily average regional maximum precipitation and daily average \( f_s E_s \) from May to June over 3 years. The blue points illustrate the daily average regional maximum precipitation when the daily average \( f_s E_s \) exceeded a certain value, and the red line is the trend curve of the results. The daily average regional maximum precipitation and daily average \( f_s E_s \) were positively correlated. This suggests that the plasma density of the Es-layer increased with enhanced convective activity. We also studied the relationship between the daily average \( f_s E_s \) and the average amplitude of the daily maximum ionospheric disturbance from May to June over 3 years. From Figure 11b, blue points illustrate the positive correlation between the daily average \( f_s E_s \) and the average amplitude of the daily maximum ionospheric disturbances, and the red line is the trend curve of the results. The trend in Figure 11b is similar to that in Figure 11a, which indicates that the Es-layer is closely related to the F-region ionospheric disturbances. (This correlation result is consistent with previous studies, e.g., by Otsuka et al. (2008)). Additionally, from Figure 5, the summer nighttime ionospheric disturbances occur mostly from 2000 LT to 0100 LT (next day). Therefore, similar to Figures 11a and 11b, we also studied the relationship between nighttime average regional maximum precipitation, nighttime average \( f_s E_s \), and maximum ionospheric disturbance from May to June over 3 years, as shown in Figures 11c and 11d. The time range in nighttime studies...
decreased from the total day to 1500 LT–0100 LT (next day) compared with Figures 11a and 11b. This choice of time range considers that the vertical velocity of gravity waves was approximately 5–10 m/s (Vadas, 2007) and that the Es-layer was at altitudes from 90 to 130 km, it takes approximately 2–5 hr for convective gravity waves to propagate to the E region. The ionospheric disturbances increase from 1900 LT to 0100 LT (next day), as Figure 5 shown, so it is appropriate to start the nighttime study at 1500 LT. This choice of time range not only considers the propagation of gravity waves but also considers some more rapid electrodynamic processes between the troposphere and ionosphere (Davis & Johnson, 2005; Qin et al., 2011), therefore, the end of the time range is 0100 LT (next day). Similar to Figures 11a and 11b, precipitation, Es-layer, and ionospheric disturbance also exhibit a positive correlation during nighttime. This further supported our results that there is a relationship between convective activity and nighttime ionospheric disturbances.

The driving effect of atmospheric tides plays an important role in the dynamical process of the MLT, and tidal winds can produce a wind shear effect (Cox & Plane, 1998; Dou et al., 2013; Haldoupis, 2011). Similarly, gravity waves play a key role in the coupling between the MLT and troposphere (Hines, 1989; Niranjan et al., 2012). The formation, eruption, and receding of convective activity is a complex and long (hours or even tens of hours process (Nishioka et al., 2013; Trachte & Bendix, 2012)), and this process can excite a larger number of gravity waves with different scales than calm days (Dutta et al., 2009; He et al., 2021). The upward propagation of these convective gravity waves can enhance the tidal background in the MLT region through nonlinear interactions (Haldoupis et al., 2004; Liu et al., 2014). Enhanced tidal winds provide stronger wind shear effects, which result in \( f_{\text{E}} \), being larger than on calm days.

Apart from gravity waves, lightning electrical effects are also believed to be another convective factor that can affect the ionosphere (Davis & Johnson, 2005; Qin et al., 2011). There is no doubt about this factor. However, lightning can only occur during strong convective weather. Our statistics also include calm days and mild precipitation days. According to Figures 4, 6, and 8, if the lightning electrical effect was used as the only influencing factor, then there should not be a significant decrease in the magnitude and number of occurrences of ionospheric disturbances in July and August. It was not sufficient to consider the lightning electrical effect alone as the only cause. Additionally, our statistical results were also more consistent with the propagation mechanism of gravity waves. Therefore, we suggest the gravity wave factor dominates this statistic.

---

**Figure 11.** (a and c) Correlation analysis between daily (nighttime) average precipitation and daily (nighttime) average \( f_{\text{E}} \), from May to June over 3 years. (b and d) Correlation analysis between the average amplitude of the daily (nighttime) maximum ionospheric disturbance and the daily (nighttime) average \( f_{\text{E}} \), from May to June over 3 years.
In addition, $f_sE$ reaches a peak around noon, but ionospheric disturbances occur mainly around midnight. A possible reason for this is that the electrodynamic coupling between the E and F regions may have been short-circuited due to the high electrical conductivity of the E region during daytime (Otsuka et al., 2011). The Perkins instability and E-F regions coupling may only occur at night.

Based on the discussion above, we proposed a possible indirect mechanism between the troposphere and the ionosphere. The increased convective activities could modulate the ionosphere in the E region, possibly through the atmospheric variations caused by gravity waves, improve the inhomogeneity of the E region and then promote the growth of the Perkins instability between the E and F regions. Finally, the strength of the ionospheric disturbances was intensified. Furthermore, this indirect effect requires two triggering conditions. First, convective gravity waves can propagate upward to enhance the wind shear effect in the MLT region. Second, the condition of Perkins instability and E-F regions coupling needs to be satisfied. The indirect mechanism is shown in Figure 12.

5. Conclusion

In this research, we studied F-region short-period ionospheric disturbances over Wuhan, China, from 2018 to 2020 using BeiDou GEO TEC data. We found that short-period (less than 50 min) ionospheric disturbances mainly occurred at midnight in summer. The short-period ionospheric disturbances had a peak occurrence rate around the June solstice. In addition, we studied the precipitation variations in the Wuhan area from 2018 to 2020 using ERA5 precipitation data. Precipitation and short-period ionospheric disturbances exhibit consistent seasonal variations, and precipitation had a positive correlation with short-period ionospheric disturbances in the occurrence rate and amplitude. By studying the regional variation in summer rain belts and background wind conditions, we found that the variations in the location of convective activities and the propagation process of gravity waves also play a key role in ionospheric and tropospheric coupling. While the Es-layer has always been considered to be closely related to summer nighttime ionospheric disturbances, our study showed positive correlations between $f_sE$, either regional precipitation or the F-region ionospheric disturbances. Based on these results, we believe that convective gravity waves could indirectly affect short-period ionospheric disturbances by modulating the E-region ionosphere. Atmospheric variations caused by convective gravity waves exacerbate the inhomogeneity of the E region and provide the initial perturbation of the Perkins and E-F coupling instability, and eventually, the strength of the ionospheric disturbances was enhanced.

Figure 12. Schematic of the coupling mechanisms between the troposphere and ionosphere.
Data Availability Statement
The ERA5 precipitation and wind field data are available at https://cds.climate.copernicus.eu. The Kp index and solar flux proxy data were downloaded from https://omniweb.gsfc.nasa.gov. HFKD and HSKD GNSS TEC data were obtained from the National Space Science Data Center, National Science & Technology Infrastructure of China (http://www.nssdc.ac.cn/eng/). WHHP GNSS TEC data were provided by the Beijing National Observatory of Space Environment, Institute of Geology and Geophysics Chinese Academy of Sciences through the Geophysics Center, National Earth System Science Data Center (http://wdc.geophys.ac.cn), The ionosonde data were provided by the Data Centre for Meridian Space Weather Monitoring Project https://data.meridianproject.ac.cn/.

Acknowledgments
This work was funded by the National Natural Science Foundation of China (20420110, 20420111, 20420112), the Fundamental Research Funds for the Central Universities (2042021k045), and the Chinese Meridian Project. The data in the article was provided by Beijing National Observatory of Space Environment, Institute of Geology and Geophysics Chinese Academy of Sciences through the Geophysics center, National Earth System Science Data Center (http://wdc.geophys.ac.cn). The authors also thank the data resources from the National Space Science Data Center, National Science & Technology Infrastructure of China (http://www.nssdc.ac.cn/eng/).

References
Afrainovich, E. L., Perevalova, N. P., & Zhivetiev, I. V. (2008). Relative amplitude of the total electron content variations depending on geomagnetic activity. Advances in Space Research, 42(7), 1231–1237. https://doi.org/10.1016/j.asr.2007.09.003
Alexander, M. J., & Teitelbaum, H. (2007). Observation and analysis of a large amplitude mountain wave event over the Antarctic Peninsula. Journal of Geophysical Research, 112, D21103. https://doi.org/10.1029/2006JD007930
Astafyeva, E. (2019). Ionospheric detection of natural hazards. Reviews of Geophysics, 57(4), 1265–1288. https://doi.org/10.1029/2019rg000668
Azemm, I., Yue, J., Hofmann, L., Miller, S. D., Straka, W. C., & Crowley, G. (2015). Multisensor profiling of a concentric gravity wave event propagating from the troposphere to the ionosphere. Geophysical Research Letters, 42(19), 7874–7880. https://doi.org/10.1002/2015GL069593
Bauer, S. J. (1958). An apparent ionospheric response to the passage of hurricanes. Journal of Geophysical Research, 63(1), 265–269. https://doi.org/10.1029/jo063i001p00265
Bullett, T., & Mabie, J. (2018). Vertical and oblique ionosphere sounding during the 21 August 2017 solar eclipse. Geophysical Research Letters, 45(8), 3690–3697. https://doi.org/10.1029/2017GL077413
Chen, J., Zhang, X., Ren, X., Zhang, J., Freeshah, M., & Zhao, Z. (2020). Ionospheric disturbances detected during a typhoon based on GNSS phase observations: A case study for typhoon Mangkhut over Hong Kong. Advances in Space Research, 66(7), 1743–1753. https://doi.org/10.1016/j.asr.2020.06.006
Chimonas, G., & Hines, C. O. (1970). Atmospheric gravity waves induced by a solar eclipse. Journal of Geophysical Research, 75(4), 875. https://doi.org/10.1029/JA075i004p00875
Chou, M. Y., Lin, C. H., Yue, J., Tsai, H. F., Sun, Y. Y., Liu, J. Y., & Chen, C. H. (2017). Concentric traveling ionosphere disturbances triggered by Super Typhoon Meranti (2016). Geophysical Research Letters, 44(3), 1219–1226. https://doi.org/10.1002/2016GL072205
Cow, R. M., & Plane, J. M. C. (1998). An ion-molecule mechanism for the formation of neutral sporadic Na layers. Journal of Geophysical Research, 103(D6), 6349–6359. https://doi.org/10.1029/97JD03376
Davis, C. J., & Johnson, C. G. (2005). Lightning-induced intensification of the ionospheric sporadic E layer. Nature, 435(7043), 799–801. https://doi.org/10.1038/nature03638
Dou, X. K., Qiu, S. C., Xue, X. H., Chen, T. D., & Ning, B. Q. (2013). Sporadic and thermospheric enhanced sodium layers observed by a lidar chain over China. Journal of Geophysical Research: Space Physics, 118, 6627–6643. https://doi.org/10.1002/jgra.50579
Dutta, G., Ajay Kumar, M. C., Vinay Kumar, P., Venkat Ratnam, M., Chandrashaker, M., Shubagki, Y., et al. (2009). Characteristics of high-frequency gravity waves generated by tropical deep convection: Case studies. Journal of Geophysical Research, 114, D18109. https://doi.org/10.1029/2008JD011332
Eckermann, S. D., Ma, J., Wu, D. L., & Broutman, D. (2007). A three-dimensional mountain wave imaged in satellite radiance throughout the stratosphere: Evidence of the effects of directional wind shear. Quarterly Journal of the Royal Meteorological Society, 133(629), 1959–1975. https://doi.org/10.1002/qj.187
Feng, L., Liu, A. Z., Swenson, G. R., Hecht, J. H., & Robinson, W. A. (2005). Observations of gravity wave breakdown into ripples associated with dynamical instabilities. Journal of Geophysical Research, 110, D09S11. https://doi.org/10.1029/2004jd004849
Georges, T. M. (1973). Infrasound from convective storms: Examining the evidence. Reviews of Geophysics and Space Physics, 11(3), 571–594. https://doi.org/10.1029/RG011i003p00571
Goncharenko, L. P., Erickson, P. J., Zhang, S.-R., Galkin, I., Coster, A. J., & Jonah, O. F. (2018). Ionospheric response to the solar eclipse of 21 August 2017 in Millstone Hill (42N) observations. Geophysical Research Letters, 45(10), 4601–4609. https://doi.org/10.1002/2018GL077334
Guochang, X., Meifang, L., & Zhiyin, Z. (1985). Seasonal variation of rain-belts over China. Advances in Atmospheric Sciences, 2(3), 368–375. https://doi.org/10.1007/bf02627753
Haldopouls, C. (2011). Midlatitude Sporadic E: A typical paradigm of atmosphere-ionosphere coupling. Space Science Reviews, 168(1–4), 441–461. https://doi.org/10.1007/s11214-011-9786-8
Haldopouls, C., Puncheva, D., & Mitchell, N. J. (2004). A study of tidal and planetary wave periodicities present in midlatitude sporadic Eayers. Journal of Geophysical Research, 109, A02302. https://doi.org/10.1029/2003ja010253
He, Y., Zhu, X., Sheng, Z., Zhang, J., Zhou, L., & He, M. (2021). Statistical characteristics of inertial gravity waves over a tropical station in the western Pacific Based on high-resolution GPS radiosonde soundings. Journal of Geophysical Research: Atmospheres, 126, e2021JD043719. https://doi.org/10.1029/2021JD043719
Hegai, V. V., Kim, Y. P., & Liu, J. Y. (2006). The ionospheric effect of atmospheric gravity waves excited prior to strong earthquake. Advances in Space Research, 37(4), 653–659. https://doi.org/10.1016/j.asr.2004.12.049
Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. Quarterly Journal of the Royal Meteorological Society, 146(730), 1999–2049. https://doi.org/10.1002/qj.3803
Hines, C. O. (1989). Tropopausal mountain waves over Arecibo: A case study. Journal of the Atmospheric Sciences, 46(4), 476–488. https://doi.org/10.1175/1520-0469(1989)046<0476:tmmwas>2.0.co;2
Horiuchi, T. (2002). Convectively generated mesoscale gravity waves simulated throughout the middle atmosphere. Geophysical Research Letters, 29(21), 2007. https://doi.org/10.1029/2002gl016669
Hu, L., Yue, X., & Ning, B. (2017). Development of the BeiDou ionospheric observation network in China for space weather monitoring. Space Weather, 15(8), 974–984. https://doi.org/10.1002/2017sw001636
Huang, F., Lei, J., & Dou, X. (2017). Daytime ionospheric longitudinal gradients seen in the observations from a regional BeiDou GEO receiver network. *Journal of Geophysical Research: Space Physics, 122*, 6552–6561. https://doi.org/10.1002/2017ja023881

Huang, F., Lei, J., Dou, X., Luan, X., & Zhong, J. (2018). Nighttime medium-scale traveling ionospheric disturbances from airglow imager and global navigation satellite systems observations. *Geophysical Research Letters, 45*(1), 31–38. https://doi.org/10.1002/2017gl076408

Karan, D. K., & Pallamraju, D. (2018). Effect of geomagnetic storms on the daytime low-latitude thermospheric wind dynamics. *Journal of Atmospheric and Solar-Terrestrial Physics, 170*, 35–47. https://doi.org/10.1016/j.jastp.2018.02.003

Kelley, M. C., Makela, J. J., Vlasov, M. N., & Sun, A. (2003). Further studies of the Perkins stability during space weather month. *Journal of Atmospheric and Solar-Terrestrial Physics, 65*(10), 1071–1075. https://doi.org/10.1016/j.jastp.2003.07.001

Lay, E. H. (2018). Ionospheric irregularities and acoustic/gravity wave activity above low-latitude stormsystems. *Geophysical Research Letters, 45*(1), 90–97. https://doi.org/10.1002/2017gl076058

Lee, W. K., Kil, H., & Paxton, L. J. (2021). Global distribution of nighttime MSTIDs and its association with E region irregularities seen by CHAMP Satellite. *Journal of Geophysical Research: Space Physics, 126*, e2020JA028836. https://doi.org/10.1029/2020ja028836

Lindgren, R. S. (1981). Turbulence and stress owing to gravity wave and tidal breakdown. *Journal of Atmospheric and Solar-Terrestrial Physics, 44*(11), 944–946. https://doi.org/10.1016/0022-1230(81)90205-8

Luo, W., Xiong, C., Xu, J., Zhu, Z., & Chang, S. (2020). The low-latitude plasma irregularities after sunrise from multiple observations in both hemispheres during the recovery phase of a storm. *Remote Sensing, 12*(18), 2897. https://doi.org/10.3390/rs12182897

Mannucci, A. J., Wilson, B. D., Yuan, D. N., Ho, C. H., Lindqvist, U. J., & Runge, T. F. (1998). A global mapping technique for GPS-derived ionospheric total electron content measurements. *Radio Science, 33*(3), 565–582. https://doi.org/10.1029/97rs07207

Matsushima, R., Hosokawa, K., Sakai, J., Otsuka, Y., Ejiri, M. K., Nishioka, M., & Tsugawa, T. (2022). Propagation characteristics of sporadic E and medium-scale traveling ionospheric disturbances (MSTIDs): Statistics using HF Doppler and GPS-TEC data in Japan. *Earth Planets and Space, 74*(1), 60. https://doi.org/10.1186/s40622-022-01616-3

Maurya, A. K., Cohen, M. B., Nirajan Kumar, K., Phanikumar, D. V., Singh, R., Vineeth, P. K., & Kishore Kumar, K. (2019). Observation of very short period atmospheric gravity waves in the lower ionosphere using very low frequency waves. *Journal of Geophysical Research: Space Physics, 124*, 9448–9461. https://doi.org/10.1029/2019ja027360

Meng, X., Vergados, P., Komjathy, A., & Verkhoglyadova, O. (2019). Upper atmospheric responses to surface disturbances: An observational perspective. *Radio Science, 54*(11), 1076–1098. https://doi.org/10.1029/2019rs006558

Miles, J. W., & John, W. J. J. O. F. M. (1961). On the stability of heterogeneous shear flows. *Journal of Fluid Mechanics, 10*(4), 496. https://doi.org/10.1017/s0022112061000305

Miyoshi, Y., Jin, H., Fujisawa, H., & Shinagawa, H. (2018). Numerical study of traveling ionospheric disturbances generated by an upward propagating gravity wave. *Journal of Geophysical Research: Space Physics, 123*, 2141–2155. https://doi.org/10.1002/2017ja025110

Mrač, S., Semet, J., Drob, D., & Huba, J. D. (2018). Direct EUV/X-ray modulation of the ionosphere during the August 2017 total solar eclipse. *Geophysical Research Letters, 45*(9), 3820–3828. https://doi.org/10.1029/2017gl076771

Nakamura, T., Aono, T., Tsuda, T., Adrmanzo, A. G., Achmad, E., & Suranto (2003). Mesospheric gravity waves over a tropical convective region observed by OH airglow imaging in Indonesia. *Geophysical Research Letters, 30*(17), 1882. https://doi.org/10.1029/2003gl017619

Nirajan Kumar, K., Ramkumar, T. K., Krishnaiah, M. (2012). Analysis of large-amplitude stratospheric mountain wave event observed from the AIRS and MLS sounders over the western Himalayan region. *Journal of Geophysical Research, 117*, D22210. https://doi.org/10.1029/2011jd017410

Nishioka, M., Tsugawa, T., Kubota, M., & Ishii, M. (2013). Concentric waves and short-period oscillations observed in the ionosphere after the Chelyabinsk Meteor. *Geophysical Research Letters, 40*(21), 5581–5586. https://doi.org/10.1002/2013gl057963

Oinats, A. V., Nishitani, N., Ponomarenko, P., Bergardt, O. L., & Ratovisky, K. G. (2016). Statistical characteristics of medium-scale traveling ionospheric disturbances revealed from the Hokkaido East and Ekaterinburg HF radar data. *Earth Planets and Space, 68*(1), 8. https://doi.org/10.1186/s40623-016-0390-8

Otsuka, Y., Kotake, N., Shiokawa, K., Ogawa, T., Tsugawa, T., & Saito, A. (2011). Statistical study of medium-scale traveling ionospheric disturbances observed with a GPS receiver network in Japan. In *Aeronomy of the Earth’s atmosphere and ionosphere* (pp. 291–299).

Otsuka, Y., Tani, T., Tsugawa, T., Ogawa, T., & Saito, A. (2008). Statistical study of relationship between medium-scale traveling ionospheric disturbance and sporadic E layer activities in summer night over Japan. *Journal of Atmospheric and Solar-Terrestrial Physics, 70*(17), 2196–2202. https://doi.org/10.1016/j.jastp.2008.07.008

Padokhin, A. M., Tereshin, N. A., Yasyukevich, Y. V., Andrevea, E. S., Nazarenko, M. O., Yasyukevich, A. S., et al. (2019). Application of BDS-GEO for studying TEC variability in equatorial ionosphere on different time scales. *Advances in Space Research, 63*(1), 257–269. https://doi.org/10.1016/j.asr.2018.08.001

Peng, H., Yao, Y., Kong, J., Zhou, C., & Kao, C. (2021). GNSS-based statistical analysis of ionospheric anomalies during Typhoon Landings in Taiwan/Japan. *IEEE Transactions on Geoscience and Remote Sensing, 59*(6), 5272–5279. https://doi.org/10.1109/TGRS.2020.3004829

Qin, J., Celetin, S., & Pasko, V. P. (2011). On the inception of streamers from sprite halo events produced by lightning discharges with positive and negative polarity. *Journal of Geophysical Research, 116*, A06305. https://doi.org/10.1029/2010ja016366

Snievel, J. B., & Pasko, V. P. (2008). Excitation of ducted waves in the lower thermosphere by tropospheric sources. *Journal of Geophysical Research, 113*, A06303. https://doi.org/10.1029/2007ja012693

Stockwell, R. G., Mansinha, L., & Lowe, R. P. (1996). Localization of the complex spectrum: The S transform. *IEEE Transactions on Signal Processing, 44*(4), 998–1001. https://doi.org/10.1109/78.492555

Sun, W., Wu, B., Wu, Z., Hu, L., Zhao, X., Zheng, J., et al. (2020). IONISE: An ionospheric observational network for irregularity and scintillation in East and Southeast Asia. *Journal of Geophysical Research: Space Physics, 125*, e2020JA028055. https://doi.org/10.1029/2020ja028055

Tang, Q., Zhao, J., Yu, Z., Liu, Y., Hu, L., Zhou, C., et al. (2021). Occurrence and variations of middle and low latitude sporadic E layer investigated with longitudinal and latitudinal chains of ionosondes. *Space Weather, 19*(12), e2021sw002942. https://doi.org/10.1029/2021sw002942

Tsuchiya, S., Shiokawa, K., Otsuka, Y., Nakamura, T., Yamamoto, M., Connors, V., et al. (2020). Wavenumber spectra of atmospheric gravity waves and medium-scale traveling ionospheric disturbances based on more than 10-year airglow images in Japan, Russia, and Canada. *Journal of Geophysical Research: Space Physics, 125*, e2019ja026807. https://doi.org/10.1029/2019ja026807
Vadas, S. L. (2007). Horizontal and vertical propagation and dissipation of gravity waves in the thermosphere from lower atmospheric and thermospheric sources. *Journal of Geophysical Research, 112*, A06305. https://doi.org/10.1029/2006ja011845

Vadas, S. L., & Azem, I. (2021). Concentric secondary gravity waves in the thermosphere and ionosphere over the continental United States on March 25–26, 2015 from deep convection. *Journal of Geophysical Research: Space Physics, 126*, e2020JA028275. https://doi.org/10.1029/2020ja028275

Vadas, S. L., & Becker, E. (2018). Numerical modeling of the excitation, propagation, and dissipation of primary and secondary gravity waves during wintertime at McMurdo Station in the Antarctic. *Journal of Geophysical Research: Atmospheres, 123*, 9326–9369. https://doi.org/10.1029/2017ja027974

Wan, X., Xiong, C., Wang, H., Zhang, K., & Yin, F. (2020). Spatial characteristics on the occurrence of the nighttime midlatitude medium-scale traveling ionospheric disturbance at topside ionosphere revealed by the Swarm Satellite. *Journal of Geophysical Research: Space Physics, 125*, e2019JA027739. https://doi.org/10.1029/2019ja027739

Wang, J., Zuo, X., Sun, Y. Y., Yu, T., Wang, Y., Qiu, L., et al. (2021). Multilayered sporadic-E response to the annular solar eclipse on June 21, 2020. *Space Weather, 19*(3), e2020SW002643. https://doi.org/10.1029/2020sw002643

Wen, Y., & Jin, S. (2020). Traveling ionospheric disturbances characteristics during the 2018 Typhoon Maria from GPS observations. *Remote Sensing, 12*(1), 746. https://doi.org/10.3390/rs12040746

Wright, C. J., Rivas, M. B., & Gille, J. C. (2011). Intercomparisons of HIRDLS, COSMIC, and SABER for the detection of stratospheric gravity waves. *Atmospheric Measurement Techniques, 4*(8), 1581–1591. https://doi.org/10.5194/amt-4-1581-2011

Wu, J. F., Xue, X. H., Hoffmann, L., Dou, X. K., Li, H. M., & Chen, T. D. (2015). A case study of typhoon-induced gravity waves and the orographic impacts related to Typhoon Mindulle (2004) over Taiwan. *Journal of Geophysical Research: Atmospheres, 120*, 9193–9207. https://doi.org/10.1002/2015jd023517

Wu, K., Xu, J., Wang, W., Sun, L., Liu, X., & Yuan, W. (2017). Interesting equatorial plasma bubbles observed by all-sky imagers in the equatorial region of China. *Journal of Geophysical Research: Space Physics, 122*, 10596–10611. https://doi.org/10.1002/2017ja024561

Yamazaki, Y., Arras, C., Andoh, S., Miyoshi, T., Shinagawa, H., Harding, B. J., et al. (2021). Examining the wind shear theory of sporadic E with ICON/MIGHTI winds and COSMIC-2 Radio 2 occultation data. *Geophysical Research Letters, 49*(1), e2021GL096202. https://doi.org/10.1029/2021gl096202

Yang, H., Yang, X., Zhang, Z., & Zhao, K. (2018). High-precision ionosphere monitoring using continuous measurements from BDS GEO Satellites. *Sensors, 18*(3), 714. https://doi.org/10.3390/s18030714

Yu, B., Xue, X., Lu, G., Kuo, C. L., Dou, X., Gao, Q., et al. (2017). The enhancement of neutral metal Na layer above thunderstorms. *Geophysical Research Letters, 44*(19), 9555–9563. https://doi.org/10.1002/2017gl074977

Zhang, R., Le, H., Li, W., Mu, H., Yang, Y., Huang, H., et al. (2020). Multiple technique observations of the ionospheric responses to the 21 June 2020 Solar Eclipse. *Journal of Geophysical Research: Space Physics, 125*, e2020JA028450. https://doi.org/10.1029/2020ja028450

Zhang, S. R., Erickson, P. J., Goncharenko, L. P., Coster, A. J., Rideout, W., & Vierinen, J. (2017). Ionospheric bow waves and perturbations induced by the 21 August 2017 Solar Eclipse. *Geophysical Research Letters, 44*(24), 12067–12075. https://doi.org/10.1002/2017gl076054

Zhang, W., Chen, G., Zhang, S., Gong, W., Chen, F., He, Z., et al. (2020). Statistical study of the midlatitude mesospheric vertical winds observed by the Wuhan and Beijing MST radars in China. *Journal of Geophysical Research: Atmospheres, 125*, e2020JD032776. https://doi.org/10.1029/2020jd032776

Zhao, Y., Deng, Y., Wang, J. S., Zhang, S. R., & Lin, C. Y. (2020). Tropical cyclone-induced gravity wave perturbations in the upper atmosphere: GITM-R simulations. *Journal of Geophysical Research: Space Physics, 125*, e2019JA027675. https://doi.org/10.1029/2019ja027675

Zhou, C., Tang, Q., Song, X., Qing, H., Liu, Y., Wang, X., et al. (2017). A statistical analysis of sporadic E layer occurrence in the midlatitude China region. *Journal of Geophysical Research: Space Physics, 122*, 3617–3631. https://doi.org/10.1002/2016ja023135