IONISE: An Ionospheric Observational Network for Irregularity and Scintillation in East and Southeast Asia

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Abstract An Ionospheric Observational Network for Irregularity and Scintillation in East and Southeast Asia (IONISE) is developed to identify and study the short-term and fine-scale ionospheric variations over China. The IONISE network mainly includes three crossed chains of Beidou geostationary satellite total electron content (TEC)/scintillation receivers along 110°E, 23°N, and 40°N respectively, multisite portable digital ionosondes and bistatic very high frequency radars. Based on the IONISE observations, we report some preliminary results of ionospheric disturbances and irregularities, including (1) initially generated and zonally drifting equatorial plasma bubbles and related scintillations, (2) traveling ionospheric disturbances from middle to low latitudes, (3) drift of strong sporadic E structures over a wide area of more than 1,000 km, (4) fine-scale ionospheric perturbation and regional TEC gradient, and (5) general features of ionospheric response to geomagnetic storms. Possible mechanisms responsible for these ionospheric phenomena are discussed. The IONISE provides new data set for investigation on ionospheric disturbances of various scales in a broad region with dense observations along specific latitude/longitude.

Plain Language Summary There are various types of ionospheric variations under different triggering conditions. To reveal possible sources responsible for short-term variability of ionosphere, trace the occurrence and movements of ionospheric irregularities and associated scintillations along the same longitude/latitude, and capture ionospheric disturbances of various scales over China, an Ionospheric Observational Network for Irregularity and Scintillation in East and Southeast Asia (IONISE), which consists of multiple types of instruments including Beidou geostationary (BD-GEO) total electron content (TEC)/scintillation receiver, portable digital ionosonde (PDI), and very high-frequency (VHF) radar, is developed. The BD-GEO TEC/scintillation measurements continuously made at the dense array of fixed ionospheric pierce points can track ionospheric disturbances of various scales along the same longitude/latitude, making it possible for investigation of different types of ionospheric disturbances. The Doppler velocity measurements by PDI are sensitive to ionospheric perturbations with weak amplitude which may be difficult to be detected from the general parameters such as F layer peak or virtual height derived from ionosonde observation. The spatially separated VHF radars with imaging capability of field aligned irregularities (FAIs) may capture the fine-scale evolution of FAIs. The preliminary results presented in this paper demonstrate the capability by IONISE for ionospheric disturbances of various scales such as equatorial plasma bubbles, traveling ionospheric disturbances, strong sporadic E structure, fine-scale ionospheric perturbation, regional TEC gradient, and ionospheric response to geomagnetic storms. It is expected that new observations from the IONISE will help to achieve a better understanding on the potential mechanisms for the multiscale ionospheric disturbances.

1. Introduction

The ionosphere is disturbed under everlasting internal and interplanetary perturbations of various scales. Multiscale ionospheric disturbances can cause electromagnetic interferences to various radio applications such as radio broadcasting, radio communication, satellite navigation and radar positioning, and influence space weather in a climatological sense, thus making impacts on human life to varying extents. Though
various observations have been performed and lasted for decades, the inner nature and underlying mechanism for each type of ionospheric perturbation still remain unclear to some extent.

In East and Southeast Asia, previous observations showed that large-scale ionospheric perturbations for example traveling ionospheric disturbances (TIDs) can occur in both daytime and nighttime. The TIDs have different preferred propagating directions and seasonal occurrence rates (e.g., Ding et al., 2011; Otsuka et al., 2011, 2013). Though the occurrence of TID is mainly a midlatitude phenomenon, previous studies also showed TID occurring in low-latitude regions (e.g., Narayanan et al., 2014; Shiokawa et al., 2002). These different features of TIDs were related to different mechanisms. More recently, Huang et al. (2019) reported a peak occurrence of daytime TID at ~21°N over the low-latitude region of Asian-Australian sector. The potential sources and generation mechanisms still remain unclear.

The small-scale ionospheric irregularities producing serious scintillations at low latitudes are usually related with equatorial plasma bubbles (EPBs). During geomagnetic storms, EPBs may rise to high enough altitude and extend to middle latitude along magnetic field lines (e.g., Aa et al., 2018; Li et al., 2009; Ma & Maruyama, 2006). Also, EPBs can travel more than 2,000 km in the longitudinal direction. This causes that in the longitudes/latitudes where the ionospheric background condition is not favorable for the generation of EPB, EPB irregularities and scintillations can also be observed due to zonally drifting EPBs generated elsewhere (e.g., Li et al., 2016). On the other hand, the occurrence of ionospheric sporadic $E$ ($E_s$) layer which was traditionally considered as irregular is also revealed to have local time (LT) preference of daytime and post-sunset period owing to the advancement of detection techniques. Combination of observational results of ionosondes and very high-frequency (VHF) radars revealed a close relationship between strong $E_s$ structures and $E$-region filed-aligned irregularities (FAIs) (e.g., Ning et al., 2012; Ogawa et al., 2002; Patra et al., 2009).

It was found that the horizontal elongation pattern and drift of $E_s$ structures resemble those of TIDs. The similarities between the two phenomena in different altitude regions indicate some coupling process between different layers of the ionosphere (e.g., Otsuka et al., 2008; Xie et al., 2020).

Besides the large- and small-scale ionospheric variations, the background ionospheric total electron content (TEC) often shows sudden enhancements embedded in the daily variation during various LT periods on geomagnetic quiet days (e.g., Balan et al., 1994; Liu et al., 2013, 2020; Luan et al., 2008). The ionospheric variations with various temporal and spatial scales cannot be explored with a single type of instrument at a single station, because it suffers the narrow field of view, missing the opportunity to witness the evolution of ionospheric disturbances in a broader horizon including when, where, and how they are generated. Combination of observations from different detection techniques in a network can compensate for each other. Several regional and global observational networks have been constructed in the past and shown great advantages in ionospheric investigation. The Low-latitude Ionospheric Sensor Network (LISN) across the South American continent enables the investigation of complex day-to-day variability and extreme state of disturbance that occurs in the equatorial ionosphere (Valladares & Chau, 2012). The dense Global Navigation Satellite System (GNSS) Earth Observation Network (GEONET) over Japan which consists of thousands of GNSS receivers facilitates researchers to derive the morphology and dynamics of multitype ionospheric disturbances in the middle latitude of East Asia (Sagiya, 2004). The Southeast Asia Low-latitude Ionospheric Network (SEALION) consisting of multiple ionosondes provides great potential to study the ionosphere-thermosphere dynamics (Maruyama et al., 2007). The International GNSS Service (IGS) Working Group on ionosphere provides a valuable database for investigating the ionospheric disturbances globally since its establishment in the late 1990s through data sharing (Beutler et al., 1999).

These regional and global networks were mostly built and developed in early decades. The fast evolution of disturbances and irregularities calls for the upgrading of traditional instruments such as the ionosondes and GNSS receivers over China. Most of the ionosondes still remain low temporal resolution of more than 10 min, and the GNSS receivers can only track Global Positioning System (GPS) signals. In recent years, the Russian GLObal Navigation Satellite System (GLONASS), the European Union’s Galileo, and the Chinese BeiDou navigation satellite System (BDS) are putting into operation. The number of GNSS satellites available to be tracked by ground-based receivers has increased greatly (e.g., Hu et al., 2017; Huang et al., 2017; Xiong et al., 2016). Especially in the Asia-Australia sector, five BDS geostationary (BD-GEO) satellites can be tracked to provide continuous TEC/scintillation observations which avoid the mixed temporal-spatial effect as that of non-GEO satellites. On the other hand, a kind of portable digital ionosonde (PDI) for vertical
and oblique observations was developed recently to capture fast ionospheric disturbances (Lan et al., 2018). The combination of BD-GEO TEC/scintillation receiver as well as other advanced instruments with an elaborately-selected sites distribution will make special contribution to investigating various ionospheric disturbances and present unprecedented advantages comparing to the large-scale regional/global networks with scattered sites distribution.

To identify and study when, where, and how the short-term and fine-scale ionospheric variations occur over China middle and low latitudes, the Beijing National Observatory of Space Environment (BNOSE) is building an Ionospheric Observational Network for Irregularity and Scintillation in East/Southeast Asia (IONISE). The IONISE mainly consists of (1) three crossed chains of BD-GEO TEC/scintillation receivers along 110°E, 23°N, and 40°N respectively, (2) multistatic PDIs, (3) bistatic VHF radars, and (4) a number of complementary BD-GEO TEC/scintillation receivers, airglow imagers, and ionosondes in China and adjacent regions. In this paper, the IONISE is presented. Some preliminary results from the IONISE are given to indicate how the short-term and various scales ionospheric variations over China can be detected and diagnosed. Possible mechanisms responsible for the ionospheric variations are discussed.

2. IONISE Instruments and Sites Distribution

The IONISE has a data center in Beijing to archive and process data from all the sites. There have been 57 GNSS TEC/scintillation receivers which can track BD-GEO signals, five PDIs, and a monostatic VHF radar operating routinely. The geographic distribution of IONISE observational sites and instrumentation type of each site are illustrated in Figure 1.

Figure 1. The geographic distribution of IONISE sites. The dots represent the fixed IPPs. The other symbols represent different types of instruments. The left bottom inset shows the site distribution at Hainan.
The GNSS TEC receiver uses the Novatel OEM-628 card to track signals of GPS, GLONASS and BDS with sampling rate up to 5 Hz and derives TEC of the three GNSS constellations. The GNSS TEC and scintillation receiver is PolaRx5S, which can track signals of BDS, GPS, GLONASS, Galileo, and Satellite-Based Augmentation System (SBAS) with sampling rate up to 100 Hz and derive TEC, phase, and amplitude scintillation index. The Novatel OEM-628 card and PolaRx5S receiver were redeveloped to be integrated with processing and monitor units. For convenience to manage the stations, we name the monitors with OEM card and PolaRx5S receiver as BG2 and BG3, respectively. Based on a series of self-developed software for data acquisition, display and transferring, and system monitoring, the BG2 and BG3 monitors, with power consumption less than 20 W, can be operated automatically in an unattended manner.

There are five BD-GEO satellites visible for GNSS applications in the Asia-Australia sector. Tracking the BD-GEO signal can provide continuous ionospheric TEC/scintillation observations at five fixed ionospheric pierce points (IPPs) for each receiver. Besides the five BD-GEO satellites, the BG3 monitor can also track signals of four GEO satellites of SBAS and get scintillation index of these satellites. Due to the single frequency beacon of SBAS-GEO signals, TEC cannot be derived. The BG3 monitor is able to get TEC (scintillation index) of five (nine) GEO satellites. As shown in Figure 1, the IONISE east-west (EW) chain along 23°N consists of 11 BG2/BG3 monitors, which have ~55 fixed IPPs for TEC/scintillation observation. The IONISE north-south (NS) chain along 110°E consists of 16 BG2/BG3 monitors, which provide five BD-GEO fixed IPP chains along ~104.4°E, ~107.7°E, ~109.6°E, ~112.0°E, and ~114.6°E, respectively. The IPPs are calculated by assuming a thin ionosphere at 300-km altitude. Further, there are 10 BG2/BG3 monitors at Hainan which form a denser short-baseline GNSS network. The BD-GEO TEC/scintillation measurements continuously made at the dense array of fixed IPPs can track EPBs along the same longitude/latitude, making it possible for EPB/scintillation short-term forecasting/early warning. The construction of IONISE EW chain along 40°N is on the way.

PDI was designed and developed to capture short-period ionospheric disturbances with weak amplitude which may not be detected by TEC measurements. For details of the instrument, please see Lan et al. (2018). Briefly, PDI is small in size so that can be quickly assembled and set up at temporary field stations. PDI can work at both vertical and oblique detection mode for multistatic observation by employing precise GPS timing technique. The long-term unattended fast detection mode (with a time interval less than 1 min) of PDI ensures its capability for capturing short-period disturbances for long time. From the recorded raw data, both common ionograms and high-accuracy ionograms with Doppler information can be acquired. Up to now, five PDIs have been routinely operated at Beijing (40.3°N, 116.2°E), Wuhan (30.5°N, 114.4°E), Shaoyang (26.9°N, 111.5°E), Sanya (18.4°N, 109.6°E), and Ledong (18.4°N, 109.0°E). The three PDIs at Beijing, Wuhan, and Shaoyang work at ordinary vertical detection mode with temporal resolution of 15, 7.5, and 5 min respectively. For the two PDIs at low-latitude stations Sanya and Ledong which are separated by ~70 km, they are operated as multistatic mode with temporal resolution of 1 min for reconstructing regional background ionospheric density profile. The PDI at Sanya is for transmission and reception. The PDI at Ledong is for reception. At present, no interesting reconstruction results are obtained from the bistatic PDI. Under the IONISE, we are planning to build more PDI receivers, which are located at similar latitude (~18°N or lower) but separated by a few tens to hundreds of kilometers in longitude, aiming to characterize low latitude F-region bottomside plasma density perturbation structure in the EW direction which may help to investigate the seed perturbations for EPBs in the East and Southeast Asia sector. Observations over Brazil have shown that F-region bottomside wave structures serving as precursor to EPB development occur at both equatorial and low latitudes (Abdu et al., 2015).

The bistatic VHF coherent scatter radars include one main radar for transmission and reception, and one subradar separated by ~3 km away from the main radar at Ledong. A major goal of the bistatic radars is to perform high spatial resolution interferometry observation of ionospheric irregularity, to reveal small-scale structures of irregularities and to investigate their fine-scale evolution. The 3-dB field of views for both the main radar transmitted beam and the subradar received beam are relatively large, more than 5° that provide enough overlapping to do interferometry imaging of ionospheric irregularities. The long baseline (~3 km) provides a high angular resolution of ~0.12°. The main radar, which is a part of the Meteor (and ionospheric) Irregularity Observation System (MIOS, http://mios.geophys.ac.cn/) and consists of 135 antennas with a peak power of 72 kW, is still under construction. The subradar will be updated from the Sanya VHF radar (Li et al., 2012), which has been relocated at Ledong. After the installation of the main
radar, the subradar will be operated only for reception. Now, the subradar works with an operating frequency of 47.5 MHz and a peak power of 24 kW. The radar is sensitive to irregularities of 3-m scale size and is a useful tool to study the ionospheric $E$, valley, and $F$-region irregularities over Hainan (e.g., Li et al., 2017; Ning et al., 2012; Xie et al., 2018). The antenna array is composed of six identical modules (each module consists of $2 \times 2$ five element Yagi antennas) aligned in the EW direction that can receive backscatter echoes separately and independently. The radar has the capability to steer the beam within ±45° due north, usually in five directions with azimuth and zenith angles of (45°, 33°), (32°, 29°), (0°, 23°), (328°, 29°), and (315°, 33°) from east to west. The 3-dB beam width of the central beam is 16° in EW and 36° in NS. The antenna pattern satisfies the perpendicular condition to geomagnetic fields at both $E$ and $F$ regions and can detect the coherent echoes arising from field-aligned irregularities.

It is relevant to mention that there are some instruments which are not primary for ionospheric observation in the IONISE stations, such as all-sky meteor radar, which can also be employed for deriving ionospheric information. Whereas all-sky meteor radar is usually employed to obtain neutral winds from the radial velocities of specular meteor echoes, Xie et al. (2019) and Wang et al. (2019) developed the capability for observing ionospheric $E$-region irregularities under the all-sky meteor mode. Most of the IONISE sites, including the chains of BD-GEO TEC/scintillation receivers, were operated after 2018.

3. EPB Irregularity and Scintillation Occurrence Tracing

EPBs that rise to high enough altitude were frequently detected over the low-latitude station Sanya during postsunset hours of equinoctial months at solar maximum (Li et al., 2012). However, in recent years, the solar activity was very low that is unfavorable for the occurrence of EPBs. No strong scintillation case with $S_4$ index exceeding 0.5 was recorded. Previous studies have shown that EPBs usually drift in the EW direction in large zonal scales from a few hundred to thousand kilometers in Southeast Asia (e.g., Carter et al., 2014; Li et al., 2013). Regarding to this, the measurements by IONISE provide a good chance for investigating the onset longitude, the zonal drift, and the latitudinal extent of EPBs and associated scintillations. Since the latitude of the northernmost TEC/scintillation receiver along 110°E is about 40°N (Figure 1), the measurements by IONISE may also help to identify possible mechanisms responsible for the occurrence of middle-latitude irregularities and scintillations. Figures 2–4 show an example of EPB irregularities and scintillations on 20 March 2019. As presented in Figure 2, the backscatter echo intensity profiles from five beams of the VHF radar at Ledong show that during 1500–1730 universal time (UT, LT ≈ UT + 8), the backscatter echoes due to $F$-region irregularities appeared in four beams, above ~300-km altitude (corresponding to an apex altitude of ~650 km over the magnetic equator). The echoes appeared firstly in the western beams and subsequently in the eastern ones, indicating the eastward drifts of irregularity structure. The irregularity backscatter echoes disappeared in the easternmost beam. Based on the radar observations, we can infer approximately that the irregularity structure was generated in the western longitudes of radar.

To obtain the onset longitude of the zonally drifting irregularity structure, we investigated the TEC and scintillation observations from the chains of fixed IPPs. Figures 3a–3c show the observations of TEC at fixed IPPs along the chains of 108.5°E, 17.0°N, and 21.7°N. From the latitudinal variation of TEC obtained along 108.5°E (Figure 3a), TEC depletion was observed at latitudes lower than 22°N. There was no obvious time difference between the occurrences of depletion structure over different latitudes. Two TEC depletion structures were captured by the low-latitude chain of 17.0°N (Figure 3b), as indicated with arrows labeled A and B. The depletion A was first observed at 101.4°E around 1310 UT, drifting eastward and disappeared around 1600 UT at 109.7°E. The depletion B was first observed at 101.4°E around 1430 UT, drifting in a smaller zonal scale than that of depletion A and disappeared around 1540 UT at 105.2°E. The mean zonal drift velocities of the structures A and B were estimated, ~80 and ~90 m/s, respectively. At the higher latitude chain of 21.7°N (Figure 3c), TEC depletion was detected only between 108°E and 110°E, corresponding to the structure A. Figure 3d shows the observations of scintillation index $S_4$ along the chains of 17.0°N and 21.7°N during 1200–1600 UT. In general, the occurrence of scintillation coincided well with that of TEC depletion along 17.0°N. Two groups of scintillation events (labeled A and B), with maximum $S_4$ of ~0.4 and ~0.2, were consecutively observed from the western to eastern longitudes.

Figure 4 shows a sequence of maps of the rate of TEC index (ROTI) (Pi et al., 1997). Each map includes ROTI values of all the tracked satellites (with elevation angle larger than 25°) within ±15 min of the marked UT.
The high ROTI values represent the occurrence of kilometer-scale irregularities. Due to the sparsely distributed IPPs at lower latitudes, the irregularity structure seen from the map is not as clear as the measurements at the fixed IPPs. Generally, it can be seen from the map that the irregularities, which were generated in the western longitudes and confined at latitudes lower than ~22°N, reached the longitude near the radar (~110°E), and disappeared gradually after ~1630 UT.

At low and middle latitudes, the F-region irregularities could be generated through the local instability process or due to the extending of EPBs along magnetic field lines (e.g., Li et al., 2009; Ma & Maruyama, 2006; Yokoyama et al., 2011). The Rayleigh-Taylor (RT) instability is widely accepted as the mechanism responsible for the generation of EPBs. After sunset, the F-region bottomside steep vertical plasma density gradient is favorable for generating EPBs under proper seeding source (Kelley, 2009). For the present case, the irregularity structures correspond to EPBs, which are generated over the magnetic equator, rising to higher altitudes and extending to higher latitudes (less than ~22°N), and being detected at different latitudes near simultaneously. Through a comparison of observations from the radar and the chains of fixed IPPs, it is evident that the EPB causing radar backscatter echoes was initially observed around 101.4°E. For the other EPB (also being initially observed around 101.4°E), it disappeared before approaching the radar longitude.

Figure 2. The range-time signal-to-noise ratio (SNR) maps of backscatter echoes from five beams of the Ledong VHF radar during 1200–2000 UT on 20 March 2019. The superimposed vertical axis in the left of each panel shows the corresponding height. The direction (in azimuth and zenith) of line of sight of each beam is shown in the right top of each panel.
Previous studies showed that large-scale plasma density perturbation wave-like structures (LSWS) occurring at $F$-region bottomside is an important condition for EPB generation (e.g., Li et al., 2012; Tsunoda, 2010). The LSWS could cause periodic occurrence of EPBs in longitude (e.g., Abdu et al., 2009; Patra et al., 2013). Based on the present IONISE data set, the source location of generation of periodic EPBs within 95°–120°E can be estimated. The LSWS, however, cannot be directly detected. This calls for multistatic PDIs in these longitudes to reconstruct regional ionospheric density profile, which may provide detailed information on the $F$-region bottomside plasma density perturbation.

4. Characterizing TID

TIDs are often observed at middle latitudes (e.g., Ding et al., 2011; Otsuka et al., 2011, 2013). During solar minimum, medium-scale TIDs (MSTIDs) with typical scale sizes ranging 100–1,000 km were observed to extend to farther lower latitudes than during the solar maximum (e.g., Narayanan et al., 2014; Shiokawa et al., 2002). By employing the IONISE database, TIDs with various scales were frequently observed. Figure 5 shows a case of consecutive MSTIDs which propagated to the low-latitude region on 9 August 2019. The TEC obtained from the two NS chains of fixed IPPs along 107.7°E and 112.0°E and the EW chain of fixed IPPs along 21.7°N are shown in Figures 5a–5c. The geographic longitude/latitude of each NS/EW chain is the mean value of longitudes/latitudes of corresponding IPPs. Each TEC curve of the NS/EW chain is offset by the latitude/longitude of the corresponding IPP. From Figures 5a–5c, we can see TEC perturbations embedded in the daily variation occurred during 1200–2200 UT along all the chains. Generally, these perturbations were originated from higher latitudes (eastern longitudes) and propagated to lower latitudes (western longitudes) gradually, with periods ranging 0.5–1.5 hr. The results show that the propagating direction of disturbances was southwestward, consistent with the typical feature of nighttime MSTIDs.
To get the propagating features more clearly, the detrended TEC (DTEC) was calculated by subtracting the 1-hr running average from each TEC time series at fixed IPPs, as shown in Figures 5d–5f. DTEC of the two NS chains along 107.7°E and 112.0°E was calculated (Figures 5d and 5e). Along the EW chain 21.7°N, there were more fixed IPPs within 96–120°E. The dense IPPs along the EW chain enable us to plot DTEC as functions of longitude and UT (Figure 5f). As can be seen from the NS chains (Figures 5d and 5e), there are various traveling disturbances which could be originated from relatively low or higher latitudes and propagated to lower latitudes. Most of the traveling disturbances reached low latitude ~16°N. The largest perturbation magnitude which was up to ~1.5 TECU appeared at 25–33°N. In Figure 5f, six pairs of positive and
negative phase fronts can be seen evidently between 96°E and 120°E during 1400–2000 UT. Each pair of phase fronts spanned ~5° or more in longitudes, which was estimated to be ~500 km or more in the EW direction. As indicated by the linear fitting lines in Figure 5f, the propagating velocities of the six phase fronts in the EW direction $V_w$ were estimated to be 107–139 m/s (westward). In the NS direction, the velocities $V_s$ were about 139–217 m/s (southward) which were derived from Figure 5e (as indicated by the superimposed slant lines). The phase velocities of the traveling disturbances were calculated based on the two velocity vectors of $V_w$ and $V_s$, as schematically illustrated in Figure 5g. During per unit time, the distance of a phase front swept across in the EW (NS) direction will be equal to $V_w$ ($V_s$) numerically. Thus, the propagating velocity perpendicular to the elongation of the phase front will be equal to $V$ numerically, where $V$ is the true phase velocity and is given as

$$V = \frac{V_w \times V_s}{\sqrt{V_w^2 + V_s^2}}$$

By using this method, we estimate the phase velocity ranging ~85–117 m/s. The azimuth of disturbance propagation, which is defined as the angle clockwise from geographic north (labeled as $\theta$ in Figure 5g), was estimated to be ~232–237°. These disturbances fall into the category of MSTIDs.

The case of nighttime MSTIDs propagating southwestward occurred during summer time, when the occurrence of nighttime MSTID is quite often from previous statistical results (e.g., Ding et al., 2011; Kotake et al., 2007; Otsuka et al., 2011; Shiokawa et al., 2003). For the present case, the period, maximum

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**Figure 5.** (a–c) The variations of TEC and (d–f) of detrended TEC (DTEC) derived from the observations along the north-south (107.7°E, 112.0°E) and east-west (21.7°N) chains of fixed IPPs, as functions of latitudes/longitudes and time, on 9 August 2019. (g) Schematic diagram showing the calculation of phase velocity and azimuth angle of MSTIDs.
magnitude, phase velocity, and azimuth were estimated to be ~0.5–1.5 hr, ~1.5 TECU, ~85–117 m/s, and ~232–237°, respectively. Based on dense GPS receiver network, Otsuka et al. (2011) reported the statistical characteristics of summer nighttime MSTIDs over Japan, with phase velocity ranging between 60 m/s and 140 m/s and azimuth ranging between 210° and 270°. Ding et al. (2011) reported the period, phase velocity, and azimuth of nighttime MSTIDs over central China of 20–70 min, 50–230 m/s, and 170–300°, respectively. The present results coincide well with previous studies, indicating that TIDs can be identified from the two crossed chains with limited BD-GEO TEC receivers, instead of hundreds of GPS sites. One interesting point of the present case is that the TEC perturbations reached lower latitudes (~16°N), but the perturbation amplitude decreased apparently. The relatively larger background electron density at lower latitudes could play a role on the weakened TIDs. As suggested by Shiokawa et al. (2002) and Narayanan et al. (2014), the nighttime MSTIDs tend to disappear when they encounter a region of electron density enhancement, which contributes to the increase in field line-integrated Pedersen conductivity, thus playing a role in suppression of the polarization electric fields that are responsible for the existence of MSTIDs. At solar minimum when the equatorial ionization anomaly (EIA) crest shifts to lower latitudes, MSTIDs could reach lower latitudes.

5. Tracking Strong $E_s$ Layer and Possible $E_s$ Irregularities Producing Scintillation

Besides ionospheric F-region irregularities, the TEC measurements by IONISE are sensitive to strong $E_s$ structures. Traditionally, the observation of $E_s$ layer is from ionosondes. Recently, Maeda and Heki (2014, 2015) reported that the $E_s$ structures with critical frequency ($f_{\text{o}E_s}$) high enough can cause TEC disturbances. Sun et al. (2018) afterwards reported the statistical occurrences of strong $E_s$ disturbances in BD-GEO TEC data, in a comparison with simultaneous ionosonde observations. In general, when $f_{\text{o}E_s}$ is higher than 14 MHz, the $E_s$ structure can be detected by TEC.

Figures 6 and 7 show cases of strong $E_s$ structure (which drifts over a large longitude and latitude region) detected by the BD-GEO TEC of IONISE at both daytime and nighttime on 6 June 2019. It can be seen from the EW chain along 22.7°N (Figure 6a), positive spike-like structures with short period TEC enhancements were observed during 0000–0400 UT at the longitudes of 102–114°E. As indicated by the slant arrow, these
Spike-like structures appeared earlier at eastern longitudes and drifted westwards. Previous studies suggested that these spike-like structures on TEC curves are induced by strong $E_s$ structures (Maeda & Heki, 2014, 2015; Sun et al., 2018). Figure 6b shows TEC obtained from the fixed IPP at 22.5°N/111.3°E in zoomed axes. Each spike lasted shorter than 10 min, with magnitude less than 1 TECU. These disturbances can be extracted by subtracting the 10-min running average from each TEC time series, thus deriving the DTEC time series, as presented in Figure 6c. With this data-processing method, each spike with magnitude larger than 0.1 TECU can be identified. The consecutive spikes, with durations of tens of minutes to hours, represent the whole structure of $E_s$ traversing through the geostationary satellite-receiver link.

Figure 7. (a–d) The variations of DTEC along the east-west (22.7°N) and north-south (109.0°E, 109.6°E, and 110.5°E) chains of fixed IPPs, as functions of longitude/latitude and time, on 5–6 June 2019. The superimposed green curves in panel a show the $S_4$ index measured at the fixed IPPs of 22.7°N/105.3°E and 22.7°N/111.3°E. The superimposed arrows highlight the westward/southward movements of $E_s$ structures characterized by the consecutive DTEC spikes. (e) The temporal variations of $f_iE_s$ derived from the Sanya PDI and of DTEC at the three fixed IPPs (18.0°N/109.6°E, 19.4°N/110.1°E, and 21.0°N/109.2°E).
In order to investigate the evolution of strong $E_a$ over a large region in detail, we extracted the strong $E_a$ disturbances from TEC data along the EW and NS BD-GEO chains. Figures 7a–7d show DTEC time series from the EW chain of fixed IPPs along 22.7°N and the three NS chains of fixed IPPs along 109.0°E, 109.6°E, and 110.5°E, respectively. Note that the latitudes/longitudes of fixed IPPs were calculated by assuming the $E$-region height of 100 km. Each DTEC curve is offset by the corresponding latitude/longitude of IPPs. In Figure 7a, the superimposed green curves around the longitudes of 105.3°E and 111.3°E show the $S_4$ index time series. The $S_4$ index was generally smaller than 0.2, but at some fixed IPPs, the maximum $S_4$ can be up to 0.4. The magnitude of $S_4$ index was generally larger when DTEC was larger. The spike-like structures of DTEC show apparent westward drifts. In the eastern longitudes, a lot of DTEC pulses consecutively appeared, indicating larger scales of strong $E_a$ structure when they passed over the eastern longitudes. Prior to the most intense $E_a$ structure which disappeared at ~101.4°E (as indicated by the red arrow), several groups of $E_a$ structures were observed drifting westward (as indicated by the gray arrows). Some of the structures were originated after sunrise in the western longitudes. The most intense $E_a$ structure indicated by the red arrow was originated in a farther eastern longitude which cannot be derived from the present data set. Most of the $E_a$ structures traveled across more than 10° in longitude (~1,000 km). The westward drifting velocity is estimated as ~125 m/s.

In the NS chains (Figures 7b–7d), besides the strong $E_a$ structures occurred in morning hours, a group of consecutive DTEC pulses originated in the afternoon (~0900 UT) was observed at lower latitudes below ~22°N. Both the morning and afternoon $E_a$ structures traveled southward (indicated by the arrows in Figures 7b and 7d). The morning strong $E_a$ structure traveled across more than 11° in latitude (from ~29.5°N to ~18.0°N or more with a distance of more than 1,000 km). Some DTEC pulses which were occasionally observed at higher latitudes (e.g., ~34.3°N) did not belong to the structures detected below 30°N. The southward velocity was estimated to be ~70 m/s. Compared to the strong $E_a$ structure originated in the morning hours (~0000 UT), the strong $E_a$ structure originated in the afternoon (~1000 UT) at lower latitudes did not have obvious EW drifts (the observation from the EW chain during afternoon hours is not shown here). The southward velocity of the afternoon $E_a$ structure was estimated to be ~80 m/s. Figure 7e shows a comparison of the top frequency of $E_a$ ($f_t E_a$) derived from Sanya PDI (18.4°N, 109.6°E) with the DTEC obtained from the fixed IPPs 18.0°N/109.6°E, 19.4°N/110.1°E, and 21.0°N/109.2°E. As we can see, the two groups of high $f_t E_a$ value in the morning and afternoon hours, in general, corresponded well with the appearance of consecutive DTEC disturbances at the fixed IPPs. The difference in their durations could be due to the fact that the field of view of ionosonde is very large (~200 km in diameter for beam width 45° in zenith and altitude 100 km), and the DTEC is obtained almost from a single fixed point.

Previous studies have revealed that the preferred elongation directions of $E_a$ structures are EW and/or northwest-southeast (NW-SE) in the Northern Hemisphere, with preferred drifting direction perpendicular to the elongation direction (e.g., Hysell et al., 2009; Maeda & Heki, 2015; Yokoyama et al., 2009). Maeda and Heki (2015) reported that for small- and middle-scale (<500 km) strong $E_a$ structures in the middle-latitude regions, the preferred elongation of morning strong $E_a$ structures is EW, which were band-like frontal structures. For the present large-scale strong $E_a$ structure occurred mainly in low-latitude regions during morning hours, it was detected firstly in the eastern longitudes and then in the western longitudes. The elongation of morning strong $E_a$ structures in our case could be NW-SE. As presented above, the westward and southward velocities of $E_a$ structures were ~125 and ~70 m/s, respectively. The drifting velocity perpendicular to the elongation of morning strong $E_a$ structures was estimated to be ~60 m/s. As for the strong $E_a$ structures originated in the afternoon, since no obvious eastward/westward drift was detected (the DTEC disturbances occurred nearly simultaneously along the same latitude in different longitudes), we surmise that its elongation and drifting direction were E-W and southward, respectively. The drifting velocity was ~80 m/s.

The neutral wind shear theory is widely accepted as the main mechanism for $E_a$ formation (Whitehead, 1989). Many researches have also suggested that their formation and dynamics could be driven by electric fields (e.g., Abdu et al., 2003; Carrasco et al., 2007; Otsuka et al., 2008). The large density gradient produced by wind shear inside the $E_a$ layer can become unstable via the gradient drift instability, thus capable of generating $E$-region plasma irregularities which drift under the effect of neutral wind and/or electric field (Hussey et al., 1998; Patra et al., 2009). By using the low latitude Kototabang (0.2°S, 100.3°E, dip lat. 10.4°S) radar observations, Pavan Chaitanya et al. (2017) reported the westward drifts of daytime $E_a$.
irregularities, ~60 m/s, which were suggested to be driven by electric field. By using TEC observations from the dense receiver network in Japan, Maeda and Heki (2015) reported the northward and southward drifts (30–100 m/s) of $E_s$ patches driven by neutral wind in the morning and afternoon hours. For the present case, the $E_s$ frontal structures drifted southwestward and southward in the morning and afternoon/evening hours. We surmise that the neutral wind could dominate their movements. However, the possible effect of electric field on the southwestward drift of $E_s$ frontal structure cannot be ruled out. This would need simultaneous measurements of $E$-region winds and electric fields. A further statistical analysis of $E_s$ movements using the IONISE data set may be helpful for this issue. On the other hand, regarding the generation of consecutive DTEC spikes within the $E_s$ whole structure, the modulation of gravity waves, which is frequently proposed to be responsible for the morphology of $E_s$ structures (e.g., Chu et al., 2011; Woodman et al., 1991; Yokoyama et al., 2004), might play a role.

6. Detection of Fine-Scale Ionospheric Perturbation and Regional TEC Gradient

Using observations from the two crossed TEC receiver chains, TEC enhancements were observed at different LT, for example, the morning TEC enhancement peaking around ~0200 UT and the sunset TEC enhancement peaking around ~1000–1200 UT. Figure 8 presents a case of TEC enhancement peak occurring in limited longitude/latitude region on 28 February 2019. Figures 8a–8c show TEC from the three EW fixed IPP chains along 28.3°N, 21.7°N, and 17.0°N, respectively. Note that the data periods shown in Figures 8a–8c start from 2000 UT of 27 February 2019.

As shown in Figure 8, there are four peaks of TEC enhancements occurring at ~0200 UT, ~0600 UT, ~1200 UT, and ~1400 UT. The peak of noon TEC enhancement (~0600 UT) occurred near simultaneously at different longitudes and latitudes, which is a normal phenomenon embedded in the TEC daily variation due to optical ionization. The onset of morning TEC enhancement appeared earlier in the eastern longitudes due to the sunrise optical ionization effect (as indicated with red dashed lines) but with the peak magnitude occurring near simultaneously at different longitudes (as indicated with red solid lines). The onset of
sunset (~1200 UT) TEC enhancement, and its peak appeared near simultaneously at different longitudes (as indicated with green dashed and solid lines, respectively). The magnitudes of sunset TEC enhancement peaks, which decreased with increasing latitudes, were generally larger than that of morning TEC enhancement. Along the low-latitude fixed IPP chain of 17.0°N (Figure 8c), the magnitudes of sunset TEC enhancement peaks were even larger than those of noon TEC peaks. Both the morning and sunset TEC enhancement peaks were most significant at the easternmost longitude and were not observed at the westernmost longitude.

We also checked the simultaneous critical frequency of the F2 layer (f0F2) measurements at three ionosonde stations, Wuhan, Shaoyang, and Sanya, respectively (figure not shown here). For the morning TEC enhancement peak around 0200 UT, the f0F2 observed at low-latitude Sanya showed enhancement peak around 0200–0400 UT. Such a peak of morning f0F2 was not seen at the higher latitude stations Shaoyang and Wuhan. For the other three peaks of TEC enhancements around 0600, 1200, and 1400 UT, the corresponding peaks of f0F2 were observed at all the ionosonde stations but with weaker amplitude at higher latitudes. The f0F2 measurements corresponded well with the TEC observations at different latitudes.

For the TEC enhancement shown in Figure 8 which was frequently detected by IONISE, we will leave the detailed discussion in future study by employing more data set to get the statistical behavior. In general, whereas the onset of the morning TEC enhancement was linked with the optical ionization process due to sunrise, which starts earlier in the eastern longitudes, the peak magnitude which was most significant in the eastern longitudes could be due to some extra mechanism, for example, the anomalous enhancements of eastward electric fields near sunrise at limited longitudes (the eastern longitudes in this case). The enhanced eastward electric fields, if occur at one given longitude, can drive the equatorial F layer upward through $E \times B$ and produce TEC enhancement at low latitudes (e.g., Balan et al., 1991, 1994). Similarly, around sunset, the simultaneous presence of TEC enhancement peaks at different longitudes could also be due to the effect of electric fields.

Another noteworthy feature in Figure 8 is the longitudinal difference in the magnitude of noon TEC enhancement (relative to the TEC before sunrise). This enhancement was stronger in the western longitudes than the eastern longitudes. From the TEC curves along the chain of 21.7°N (Figure 8b) which extends more than 24° (~2,500 km) in longitude, we can see that the noon TEC increased about 28 TECU from 0000 UT to 0600 UT in the western longitudes around 96°E, but in the eastern longitudes around 120°E, the noon TEC only increased about 8 TECU from 0000 UT to 0600 UT. At higher latitude around 28.3°N, the longitudinal gradient of noon TEC enhancement was not observed. Previous observations have shown the longitudinal difference of background ionospheric density at midlatitudes of China (Huang et al., 2017; Zhao et al., 2013). Under high geomagnetic activities such as geomagnetic storms, the eastward electric field which was increased by a prompt penetration electric field (PPEF) can produce the longitudinal difference of low-latitude ionospheric density (e.g., Balan et al., 2010; Fagundes et al., 2016). Further, Huang et al. (2017) suggested that the daytime longitudinal gradients at low-middle latitudes were related to electric fields associated with geomagnetic activity. On 28 February 2019, the minimum SYM-H reached $-41$ nT and Kp reached 3+. For the present case, one possibility is that the electric fields caused the longitudinal difference of background ionospheric density.

### 7. General Features of Ionospheric Response During Geomagnetic Storms

The ionosphere is sensitive to geomagnetic activities. For the study of ionospheric response during geomagnetic storms, Lei et al. (2018) and Sun et al. (2017) showed the advantages of BD-GEO TEC owing to the continuity of the TEC data at fixed IPPs. Based on the IONISE data, Li et al. (2019) reported the ionospheric response during a moderate geomagnetic storm with minimum SYM-H of $-86$ nT on 20 April 2018, when the quasiperiodic southward turnings of interplanetary magnetic field Bz could produce multiple short-lived westward PPEFs and thus drive the nighttime low-latitude TEC oscillations simultaneously over a wide longitude range. The results presented the capability of IONISE to capture weak ionospheric perturbations along the same longitude/latitude.

During 25–29 August 2018, a strong geomagnetic storm occurred with minimum SYM-H down to $-206$ nT and maximum Kp up to 7+. Figure 9a shows the geomagnetic index during the storm. The storm initial
phase occurred on 25 August 2018, with SYM-H increased by 30 nT at ~0900 UT, indicating the sudden storm commencement. The positive SYM-H lasted ~9 hr until it turned negative at 1800 UT. The main phase lasted until ~0700 UT on 26 August. During the recovery phase, SYM-H increased rapidly until ~1800 UT but stayed negative between -80 and -30 nT for the next few days.

Figures 9b and 9c show the longitudinal (along the east-west (21.7°N) and north-south (107.7°E) chains of fixed IPPs, as functions of longitude/latitude and time. The red/blue curves in panel (b) represent the TEC increase/decrease compared with that of geomagnetic quiet day (24 August). The superimposed white dots (connected by curves) in panel c represent the crest of EIA. (d–g) The temporal variations of $f_0F_2$ (red curve) and $h_mF_2$ (blue curve) derived from the four ionosondes at Beijing, Wuhan, Shaoyang, and Sanya during 24–29 August 2018.

Figure 9. (a) The temporal variations of SYM-H (red curve) and Kp index (black bar), (b and c) the TEC along the east-west (21.7°N) and north-south (107.7°E) chains of fixed IPPs, as functions of longitude/latitude and time. The red/blue curves in panel (b) represent the TEC increase/decrease compared with that of geomagnetic quiet day (24 August). The superimposed white dots (connected by curves) in panel c represent the crest of EIA. (d–g) The temporal variations of $f_0F_2$ (red curve) and $h_mF_2$ (blue curve) derived from the four ionosondes at Beijing, Wuhan, Shaoyang, and Sanya during 24–29 August 2018.
One generally accepted mechanism for daytime positive storm is the effect of eastward PPEF, which can strengthen the fountain effect (e.g., Kelley et al., 2004; Zhao et al., 2012). An additional effect of eastward PPEF is to expand the EIA to higher latitudes. For the present case, the geographic locations of EIA peak were estimated based on the maximum TEC value. The superimposed white dots in Figure 9c show the latitudes of EIA peak. We can notice that the location of the EIA peak began to migrate toward lower latitudes during the initial phase, reached the lowest latitude of ~19.7°N on 26 August, and then migrated toward higher latitudes in the next days. The results suggest that besides the eastward PPEF, there could be other mechanisms responsible for the positive storm. Lin et al. (2005) and Balan et al. (2010) suggested that storm-generated equatorward neutral winds can play an important role in producing the TEC enhancement at low and middle latitudes. Based on observations of Millstone Hill and Arecibo incoherent scatter radars and Thermosphere-Ionosphere Electrodynamics General Circulation Model simulation, Lu et al. (2008) reported a daytime positive storm case driven by neutral wind only.

To investigate possible mechanisms responsible for the equatorward migration of EIA peak in this case, we examined the observational data from four ionosondes at Beijing, Wuhan, Shaoyang, and Sanya. As shown in Figures 9d–9g, \( f_F2 \) and peak height of the \( F_2 \) layer (\( h_mF_2 \)) are plotted as red and blue lines respectively in each panel. The \( f_F2 \) of four stations all increased on 26 August, which was in accordance with the positive storm observed by TEC measurements from the BD-GEO chains (Figures 9b and 9c). We also notice that the \( h_mF_2 \) on 26 August was generally higher than the prestorm and poststorm days at higher latitude stations but not at the low-latitude station Sanya. For example around 0600 UT on 26 August, the \( h_mF_2 \) at Beijing and Wuhan stations was higher than that on the quiet day (24 August). However, at Sanya, the \( h_mF_2 \) around 0600 UT on 26 August is quite close to that on 24 August. Lu et al. (2008) suggested that in the Northern Hemisphere, the equatorward wind can push the ions upward and hence uplifted the \( F \)-region electron peak height. The present results from the ionosondes at different latitudes support the effect of equatorward wind in contributing to the positive storm and equatorward migration of the EIA peak.

### 8. Summary

Based on the newly developed IONISE, we have presented some preliminary results of ionospheric disturbances with various scales, including EPBs, MSTIDs, strong \( E_n \) structures, TEC enhancements, regional ionospheric gradient, and ionospheric response to geomagnetic storms. The results are summarized as follows:

1. The onset, zonally drifting, latitudinal extension, and disappearance of EPBs over a large longitude region in East/Southeast Asia were tracked by the IONISE. The two EPBs, which were initially observed around 101.4°E, drifted less than ~1,000 and ~400 km in the EW direction before their disappearance.

2. The MSTID traveling from middle to low latitudes during solar minimum and the propagation parameters were identified from the two crossed chains of limited BD-GEO TEC receivers, instead of hundreds of GPS sites. The period, maximum magnitude, phase velocity, and azimuth of the MSTID were estimated to be ~0.5–1.5 hr, ~1.5 TECU, ~85–117 m/s, and ~232–237°, respectively.

3. The strong \( E_n \) structures, which were identified as consecutive spike-like disturbances in TEC time series, were observed traveling more than 1,000 km. With the two crossed BD-GEO chains of IONISE, the drifting parameters of strong \( E_n \) structures observed in the morning and afternoon/evening hours were estimated to be ~60 m/s southwestward and ~80 m/s southward, respectively.

4. Significant peaks of TEC enhancement were detected during morning and sunset periods, which only occurred at limited latitude and longitude regions with large amplitude. Longitudinal difference in the increased amplitude of noon TEC (relative to the TEC before sunrise) was observed at low latitude. One possible factor for the regional TEC enhancements and the longitudinal gradient of noon TEC peak could be the electric fields modulated by geomagnetic activity.

5. The ionospheric response to a strong geomagnetic storm on 26 August 2018 was characterized as a positive storm with the EIA peak moving toward the equator during the main phase. The positive storm was attributed to equatorward wind surge, together with possible eastward PPEF. The equatorward wind surge was responsible for the equatorward migration of the EIA peak.

In general, ionospheric disturbances of various temporal and spatial scales can be directly identified by the IONISE database and extracted with corresponding data processing methods. The multitype instrumentation of IONISE facilitates investigation on ionospheric disturbances in multiple views for the pursuit of...
possible mechanisms and seeding sources. Future aspects on the development of IONISE include the installation of more PDI receivers in the western longitudes of Sanya to capture the F-region bottomside density perturbation for seeding the development of EPIs and of more BD-GEO TEC receivers in Southeast Asia to detect the lower latitude ionospheric perturbations. An ionospheric HF coherent radar at Ledong for observing long-range low-latitude ionospheric irregularities is supported by the Chinese meridian project phase-II. The multi-ongoing development, installations, and construction of IONISE will make it to be a more powerful network. With more data accumulation under routine operation of IONISE, the long-term principles of ionospheric disturbances due to different internal and interplanetary factors will be investigated. We are looking forward to a development of IONISE toward the farther southern and western areas for larger longitudinal and latitudinal extents, which calls for cooperation with relevant institutions and networks in there.

Data Availability Statement

The IONISE data are archived at the Data Center for Geophysics, National Earth System Data Sharing Infrastructure at BNOSE, IGGCAS (http://wdc.geophys.ac.cn/). For the near real-time display of IONISE data, please visit http://ionise.geophys.ac.cn/. The Kp and SYM-H data were downloaded from the World Data Center for Geomagnetism, Kyoto (http://wdc.kugi.kyoto-u.ac.jp/).

References


