

Article

Post-Sunrise Ionospheric Irregularities in Southeast Asia During the Geomagnetic Storm on 19–20 April 2024

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Abstract

We present new insights into post-sunrise ionospheric irregularities in Southeast Asia during the intense geomagnetic storm of 19–20 April 2024. By utilizing Total Electron Content (TEC) and Rate of TEC Change Index (ROTI) maps, along with ionosondes, we identified the emergence of post-sunset Equatorial Plasma Bubbles (EPBs)—plasma depletion structures and irregularities—in western Southeast Asia on 19 April. These EPBs moved eastward, and the irregularities dissipated before midnight after the EPBs covered approximately 10° of longitude. Interestingly, plasma density depletion structures persisted and turned westward after midnight until post-sunrise the following day. Concurrently, an increase in F-region height from midnight to sunrise, possibly induced by the storm's electric field, facilitated the regeneration of irregularities in the residual plasma depletions during the post-sunrise period. The significant increase in F-region height was particularly pronounced in western Southeast Asia. As a result, post-sunrise irregularities expanded their latitudinal structure while propagating westward. These findings suggest that areas with decayed plasma depletion structures from post-sunset EPBs that last past midnight could be sites for creating post-sunrise irregularities during geomagnetic storms. The storm-induced electric fields produce EPBs and ionospheric irregularities at longitudes where the surviving plasma depletion structures of post-sunset EPBs are present.

Keywords: equatorial ionosphere; geomagnetic storm; equatorial plasma bubble; ionospheric irregularities; sunrise irregularities

1. Introduction

In the equatorial and low-latitude ionosphere, nighttime ionospheric irregularities—plasma density fluctuations—are closely associated with the Equatorial Plasma Bubble (EPB) phenomenon. EPBs are areas of plasma density depletion in the nighttime F-region ionosphere, featuring irregularities of various spatial scales [1,2]. These irregularities hold significant importance in space weather research because they can disrupt trans-ionospheric radio signals [3], affecting systems such as L-band Synthetic Aperture Radar (SAR) [4] and Global Navigation Satellite Systems (GNSS) [5].

EPBs form due to the Rayleigh–Taylor instability (RTI) mechanism, which arises from a steep altitudinal plasma density gradient oriented anti-parallel to gravity on the bottom side of the equatorial ionosphere after sunset [6]. These EPB structures originate in the equatorial F-region, expanding simultaneously upward and poleward [7]. A critical factor influencing EPB formation is the pre-reversal enhancement (PRE), during which the enhanced eastward electric field around sunset amplifies RTI growth rates [1]. Strong PRE-driven electric fields can push EPB structures to higher altitudes and latitudes [8], fostering more irregularities in the topside ionosphere while expanding them further poleward [9]. While the zonal electric field significantly increases RTI growth rates, EPB formation may also require an initial seeding perturbation [10], such as an upwelling structure that lifts the bottom side of the equatorial ionosphere [11–15].

EPBs are nighttime phenomena. Under geomagnetically quiet conditions, EPBs typically form during the post-sunset period and drift eastward after the generation, and the latitudinal extension of EPBs is confined to low-latitude regions. Under geomagnetic storm conditions, EPB development significantly differs from its behavior during quiet times. Additionally, the timing of EPB occurrence differs between storm and quiet conditions. Storms introduce global electric fields, i.e., prompt-penetration electric fields (PPEF) and disturbance dynamo electric fields (DDEF) propagating into the low-latitude ionosphere, and disturb thermospheric neutral winds [16,17], which can either enhance or suppress EPB formation. Because of these storm-induced electric fields, EPB behaviors during the storm differ from their behavior during quiet conditions, and the EPB behavior during the main phase of the storm is different from that during the recovery phase. PPEF refers to the rapid penetration of the electric field from high latitudes to the low-latitude ionosphere during the storm. The undershielding PPEF typically occurs during a sudden southward turn of the interplanetary magnetic field (IMF) B_z , while the overshielding PPEF is associated with a sudden northward turn of IMF B_z . During a storm, the westward electric field in the low-latitude ionosphere, which causes post-sunset EPB suppression, can be the overshielding PPEF or westward DDEF, whereas an eastward electric field, leading to EPB enhancement, can be the undershielding PPEF. During the main phase of the storm, the undershielding eastward PPEF can combine with the regular PRE in post-sunset hours, creating “super EPBs” that rapidly extend into mid-latitude regions. During the recovery phase, EPBs may be suppressed in post-sunset hours due to westward DDEF, and after midnight or near sunrise, EPBs can form as a result of eastward DDEF [18–21]. When the storm’s main phase coincides with the sunrise, the storm-driven electric field can generate sunrise EPBs [22]. The overshielding eastward PPEF can also generate fresh EPB near-sunrise [23]. During a storm, the EPB drifts westward, which is opposite to the EPB drifting eastward in quiet conditions.

While storm-induced electric fields play a significant role in EPB formations during both post-sunset and sunrise hours, the necessity of seeding perturbations remains an open question in studies of storm effects on EPB generation. Initial seeding perturbations could be pre-existing conditions needed for EPB formation, even during storm events. Investigating whether the specific locations of storm-driven EPB generation at the seeding

sites are essential, and demonstrating this through observations, is crucial. A storm event on 19–20 April 2024 provided an opportunity to examine the role of initial seeding in sunrise EPB and ionospheric irregularities development under a storm-induced electric field. Panda et al. [24] reported that an intense geomagnetic storm occurred on those days, and post-sunset and near-sunrise EPBs over the Southeast Asian and Indian sectors were observed during this storm. They reported that the overshielding PPEF was a key driver in forming near-sunrise EPBs. Their study also utilized the rate of Total Electron Content (TEC) change index (ROTI) maps derived from the Indonesian GNSS receiver network, archived in the database introduced by Abadi et al. [25]. These ionospheric maps revealed that post-sunset irregularities formed over western Southeast Asia, moved eastward until midnight, and then dissipated. Subsequently, post-sunrise irregularities also emerged over western Southeast Asia and moved westward. Building on these ROTI map observations, we explore factors beyond the storm-driven electric field mechanism that generated post-sunrise irregularities during the 19–20 April storm. We pose a research question regarding why post-sunrise irregularities are exclusively confined to the western side of Southeast Asia. We specifically propose that post-sunrise irregularities originate from the surviving post-sunset EPB structures that are present and then shift westward. Our study examines whether surviving plasma depletions from post-sunset EPBs could serve as potential sites or pre-existing conditions for post-sunrise irregularities and whether storm-induced electric fields create these irregularities in locations where remaining plasma depletion structures exist. To support this proposal, we analyzed TEC and ROTI maps from Indonesia, ionosonde data from Southeast Asia, and the equatorial electric field model, aiming to clarify the role of surviving structures of post-sunset plasma depletion in storm-driven EPB and irregularity formation during sunrise hours.

2. Materials and Methods

This study examines the generation of EPBs in Southeast Asia during the geomagnetic storm of 19–20 April 2024, utilizing ionospheric maps derived from GNSS receivers in Indonesia Continuously Operating Reference Stations (Ina-CORS), managed by the Indonesian Geospatial Information Agency (Badan Informasi Geospasial/BIG). A database of ionospheric maps for EPB research in Southeast Asia has been introduced by Abadi et al. [25]. For this current study, we also utilized TEC and ROTI maps from the publicly accessible database of Abadi et al. [25], available at <https://gatotkaca.brin.go.id/petaionosfer/ionosphericmap/> (accessed on 29 June 2025) (hereafter referred to as the Gatotkaca database). In this database, TEC data were obtained from dual-frequency GPS signals (L1: 1.5 GHz; L2: 1.2 GHz) across the Ina-CORS network receivers with a 30-s resolution, employing software developed by Seemala [26]. ROTI was calculated by assessing the standard deviation of TEC changes over 5 min to identify ionospheric irregularities with spatial scales of a few kilometers. The TEC and ROTI values were then mapped according to geographic coordinates, specifically at an ionospheric pierce point (IPP) altitude of 350 km, using a grid size of 0.25° longitude by 0.25° latitude. The final generation of ionospheric maps involved smoothing the TEC and ROTI data through a boxcar averaging technique across 5 × 5 grids. The temporal resolution of the two-dimensional (2D) ionospheric maps in the database is set at 5 min.

In addition to the initial smoothing, our research applies further smoothing to address missing values in the original TEC and ROTI maps archived in the Gatotkaca database. Specifically, we use a “natural neighbor” interpolation technique to fill the missing values within the specified geographical longitude and latitude intervals of 95°E–140°E and 12°S–8°N. Figure 1 provides a comparative illustration of the original TEC and ROTI maps stored in the database alongside their smoothed counterparts generated via the “natural

neighbor” method. For instance, we evaluate the ionospheric maps dated 27 January 2024, at 12:25 UT. In Figure 1, the red, green, and black solid curves respectively depict the solar terminator (sunset) at altitudes of 110 km (E-region), 350 km (the selected IPP altitude for the ionospheric map), and 650 km (apex altitude of the equatorial F region linked to the ionosphere at 350 km in low-latitude areas). A black dashed line indicates the geomagnetic equator. The original TEC map (Figure 1a) reveals some missing TEC values in specific grids; however, upon applying natural neighbor smoothing, the missing values are interpolated in a notable manner (Figure 1b). The smoothed map enhances TEC depletion for representing EPB locations ($\sim 110^\circ\text{E}$ and 120°E), as indicated by magenta arrows in Figure 1a,b. Similarly, Figure 1c,d exhibit the original and smoothed ROTI maps. The original ROTI map retains missing values, but the smoothed version presents a significantly refined image. Enhanced ROTI values, with a North-South structure (depicted through a color gradient from green to red), indicate areas of ionospheric irregularities, aligning with the TEC depletion locations indicated by magenta arrows in the earlier figures. This research utilizes smoothed maps, achieved through the “natural neighbor” technique, for subsequent data analyses. We indicate the smoothed versions produced using this technique when referring to the TEC and ROTI maps throughout the manuscript.

Furthermore, this current study also proposes the TEC ratio (rTEC) to observe TEC depletion and plasma density perturbation associated with EPB. In Figure 1e, we provide a sample of the rTEC map. In principle, rTEC serves as the parameter indicating the deviation of TEC at specific points relative to the background in a zonal direction. In other words, rTEC is calculated by subtracting the background TEC at specific locations in the TEC map, expressed as follows:

$$\text{rTEC}_{i,j} = \frac{\text{TEC}_{i,j} - \overline{\text{TEC}}_b}{\overline{\text{TEC}}_b} \quad (1)$$

where $\text{TEC}_{i,j}$ represents a TEC value at longitude i and latitude j in the TEC map, and $\overline{\text{TEC}}_b$ denotes the background TEC in the interval of 7° longitudes at a given latitude in the TEC map. $\overline{\text{TEC}}_b$ is the average TEC value from longitudes $i - 3.5^\circ$ to $i + 3.5^\circ$ at latitude j . We adopt the studies of Tulasi Ram et al. [27,28] on the use of rTEC, where the running average of TEC in the zonal direction can be suitable for extracting the plasma density depletions associated with EPB, since the EPB structure has a north-south direction. Also, the rTEC can be suitable for extracting plasma density perturbation as seeding for EPB generation, as the same studies Tulasi Ram et al. [27,28] proposed. The average of TEC in a zonal direction of approximately 800 km (7° in longitude) can be considered a background.

Figure 1e displays the rTEC map on 27 January 2024, at 12:25 UT, where the TEC depletions or EPB (dark or negative rTEC regions) with North-South structures are clearly shown. The magenta dots indicate the locations of irregularities with ROTI values ≥ 0.2 TECU/min. The enhanced value of the ROTI value (≥ 0.2 TECU/min) can empirically indicate the presence of ionospheric irregularities associated with EPB in Southeast Asia [29]. Notably, the $\text{ROTI} \geq 0.2$ TECU/min occurs within TEC depletions at longitudes of $\sim 110^\circ\text{E}$ and $\sim 120^\circ\text{E}$, corresponding to the same TEC depletions in the maps in Figure 1b,c (magenta arrows). In Figure 1e, two additional TEC depletions with North-South structures at longitudes of $\sim 100^\circ\text{E}$ and $\sim 130^\circ\text{E}$ (blue arrows) are also identified. When we examined the rTEC maps for 24 h (no figures shown here), only the TEC depletion generated at longitude $\sim 130^\circ\text{E}$ does not consist of irregularities ($\text{ROTI} \geq 0.2$ TECU/min). However, all TEC depletions generated on 27 January move eastward and survive until sunrise, while the irregularities embedded in TEC depletions also move eastward but decay earlier. In this study, negative or dark rTEC containing irregularities moving together in the same direction are regarded as the TEC depletion associated with EPB. These features are typical of EPB structures; TEC or plasma density depletions, after their generation, contain

ionospheric irregularities that move in the same direction as the motion of the background ionosphere, and the irregularities decay earlier. At the same time, the depletion can survive longer until or even beyond sunrise. In summary, the rTEC parameter derived from the TEC map, along with ROTI values, can effectively detect TEC depletions (EPBs), and these two parameters are utilized to analyze the generation of post-sunrise EPBs on the storm of 19–20 April 2024.

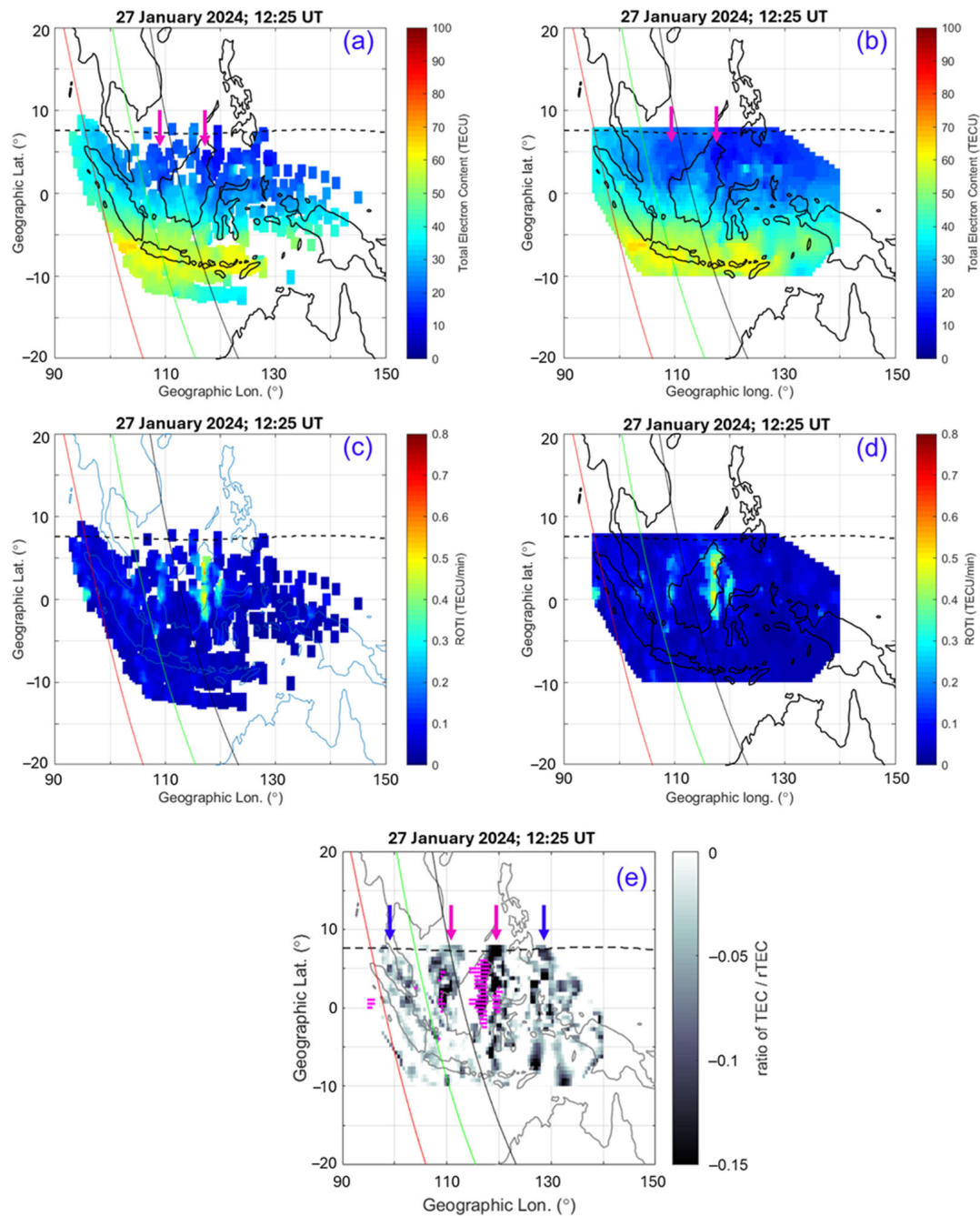


Figure 1. Samples of the original TEC (a) and ROTI maps (c) over the Indonesian sector archived in the Gatotkaca database, <https://gatotkaca.brin.go.id/petaionosfer/ionosphericmap>, correspond with the smoothed TEC (b) and ROTI (d) maps created using the natural neighbor technique. (e) The ratio of the TEC (rTEC) map is derived from the smoothed version of the TEC map, and magenta dots mean the $\text{ROTI} \geq 0.2$ TECU/min. The black dashed curve indicates the magnetic equator. Magenta and blue arrows indicate the locations of TEC depletions or EPBs. Red, green, and black curves indicate the sunset at altitudes of 110 km, 350 km, and 650 km, respectively.

This study utilizes three ionosondes. Two ionosondes, part of the Southeast Asia Low-latitude Ionospheric Observation Network (SEALION) project, are located in Chumphon (99.4°E, 10.7°N) in Thailand and Bac Lieu (105.7°E, 9.3°N) in Vietnam [30]. The other ionosonde is situated on Meiji Island (115.6°E, 9.9°N, dip. Lat: 2.8°), China, as part of the Ionospheric Observation Network for Irregularity and Scintillation in East/Southeast Asia (IONISE) project [31,32]. All three ionosondes are positioned near the magnetic equator. The variation in virtual height of the bottom side F region ($h'F$) from ionosonde observations was used to monitor changes in the height of the F-region ionosphere as a proxy for the zonal electric field variation [33]. We consider that $h'F$ during the nighttime is a reliable indicator of the actual altitude of the base height F region ionosphere; therefore, the vertical change in $h'F$ at night can serve as a proxy for the variation of the zonal electric field in the equatorial ionosphere [30]. We manually scaled ionograms of Chumphon and Bac Lieu ionosondes with a 5-min time resolution to obtain the $h'F$ parameter. Meanwhile, according to the data sharing rule in the IONISE, the $h'F$ parameter from the Meiji ionosonde can be obtained only through automatic scaling with a 10-min time resolution. To complement the investigation of the zonal electric field during storms, we utilize the equatorial electric field variation derived from the Prompt Penetration Electric Field Model (PPEFM) [34]. The PPEFM calculates equatorial electric fields, including both quiet time electric fields and PPEF, with longitudinal and time resolutions of 1° and 5 min, respectively. The PPEFM does not calculate DDEF.

3. Results

Figure 2 displays the zonal (east-west) keogram for the variations of ROTI and rTEC at 0°N latitude, ranging from 95°E to 140°E longitude, alongside the variations of Sym-H, the AE index, and IMF Bz during 18–20 April 2024. The ROTI and rTEC keograms summarize the occurrences of EPB and ionospheric irregularities during these three days. On 19 April, Figure 2a shows the Sudden Storm Commencement (SSC) at approximately 06 UT (marked as red arrow) and two magenta vertical lines within a short time indicating the storm initial phase, which appears as a small positive Sym-H peak before the storm main phase; afterward, the main phase begins and the Sym-H declines to its minimum value (−139 nT) around 19 UT, marking the peak of the main phase or the start of the recovery phase. Subsequently, Sym-H gradually increases within the storm's recovery phase. The storm on 19 April is classified as an intense storm. In Figure 2b, during the main phase, the IMF Bz turns southward, starting before the SSC time and continuing until the peak of the main phase, with a momentary northward direction of IMF Bz observed between 7 and 13 UT. In the recovery phase, IMF Bz turns northward several times from 18 UT to 23 UT before reaching a steady state. The increase in the AE index in Figure 2c indicates auroral Joule heating, with a rise from the SSC time to 23 UT, followed by a sudden increase between 18 and 21 UT, exceeding 500 nT. Figure 2d,e shows the EPB occurrence during quiet (18 and 20 April) and storm (19 April) conditions in the plot of the zonal keogram (longitudinal–UT). Please note that the EPB occurrence timings are related to the solar terminator; therefore, we include sunset and sunrise lines in Figure 2d,e. To help the reader roughly convert UT to LT, $LT = UT + 7 \text{ h}$ at a longitude of 105°E.

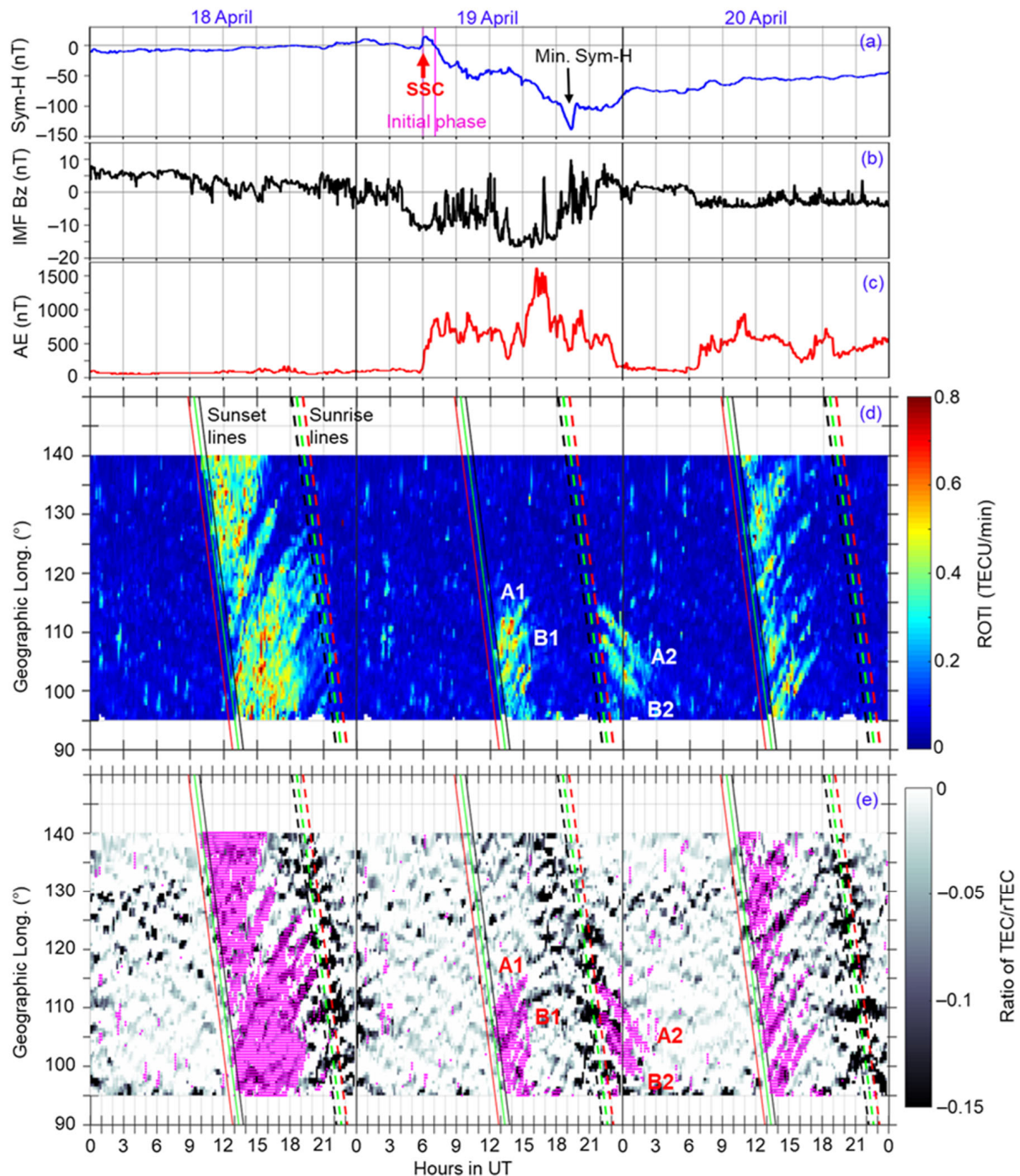


Figure 2. Time variation of (a) Sym-H, (b) IMF Bz, and (c) AE, along with east-west (zonal) keograms of ROTI (d) and rTEC (e) variation at a latitude of 0°N from 18–20 April 2024. In panels (d,e), sunset and sunrise at 110 km, 350 km, and 650 km are indicated by solid and dashed red, green, and black curves. Magenta dots in panel (e) mean the ROTI ≥ 0.2 TECU/min. In panels (d,e), ionospheric irregularity traces for post-sunset hours are labeled by A1 and B1, while A2 and B2 show post-sunrise irregularities.

Figure 2d illustrates the ROTI zonal keogram, showing occurrences of ionospheric irregularities in Southeast Asia during 18–20 April. Typical post-sunset ionospheric irregularities are present on all three nights, as post-sunset EPBs frequently occur during the equinox seasons (March, April, September, and October) in Southeast Asia [35]. On 18 and 20 April, post-sunset irregularities occurred within the 95°E–140°E interval, developing after sunset and moving eastward, nearly reaching the sunrise periods. Notably, the keogram

on the night of 19 April displays both post-sunset and post-sunrise irregularities, with occurrences in both periods generated only at longitudes below 120°E (in the western part). Readers can also refer to Supplementary Information S1 for a more detailed examination of post-sunset and post-sunrise ionospheric irregularities, as shown in the animation of ROTI maps from 09:00 UT on 19 April to 09:00 UT on 20 April, with a 5-min time interval. The EPB and irregularities generated at sunrise are infrequent phenomena unless they occur during a geomagnetic storm. Post-sunrise irregularities on 19 April occurred at 21:20 UT, after the peak of the storm's main phase and during the period when the IMF Bz turned northward. Post-sunrise irregularities moved westward, lasting until 02:40 UT on 20 April. What is particularly interesting is that the irregularities during sunrise hours appear to be connected to those during post-sunset hours, as shown in the irregularity traces A1–A2 and B1–B2 in Figure 2d. The zonal distance between irregularities A1–A2 and B1–B2 is identical, i.e., $\sim 5^{\circ}$ in longitude. Readers can also see the change in the direction of irregularities' travel, from eastward to westward, in the animation of ROTI maps (Supplementary Information S1). After A1 and B1 were generated around 105°E and 110°E in post-sunset hours, they moved eastward approximately 10° in longitude, then disappeared. Notably, the irregularities A2 and B2 were generated at sunrise hours, with their longitudes nearly coinciding with the disappearance longitudes of A1 and B1. Subsequently, post-sunrise irregularities A2 and B2 moved westward, opposite to the movement of post-sunset irregularities A1 and B1.

Figure 2e illustrates the rTEC zonal keogram summarizing the TEC depletions associated with the EPBs. In the figure, magenta dots indicate ROTI values ≥ 0.2 TECU/min, representing the presence of ionospheric irregularities. The irregularities were embedded in negative or dark rTECs (TEC depletions) and moved together. Both negative rTEC and ROTI can be used together to indicate the occurrence of EPB. On 18 and 20 April, it is evident that the TEC depletions (EPBs) and irregularities generated during post-sunset hours moved eastward, with the irregularities decaying earlier while the TEC depletions lasted until and even beyond sunrise. During sunrise, the negative rTEC becomes more pronounced, likely due to the moving average in the rTEC calculation, which results from a sudden increase in TEC from the sunlit area in the east to lower TEC in the nighttime region in the west. TEC values change rapidly at sunrise; using a zonal average of 7° in longitude might exaggerate local depletions, causing bias or artifacts in the negative rTEC during the sunrise transition. Therefore, caution is advised when interpreting rTEC during sunrise, and negative rTEC can be linked to the depletion structures of EPB if the negative rTEC drifts either eastward or westward and is accompanied by ROTI enhancement (irregularities).

Interestingly, Figure 2e shows that the EPBs and irregularities on 19 April, the day of the storm, exhibited unusual characteristics distinct from the typical post-sunset EPBs (18 and 20 April). Apparently, the depletion structures of post-sunset EPBs are connected to the depletion of EPBs during sunrise. As evidence, we observe that the dark rTEC for irregularities A1 and B1 is linked to the dark rTEC for irregularities A2 and B2, particularly the dark rTEC for irregularities B1–B2, which shows a more apparent connection. Focusing on irregularities A1 and B1, the EPB and irregularities generated in post-sunset hours moved eastward together. The post-sunset irregularities decayed after the EPB traveled approximately 10° in longitude, but the TEC depletions (dark rTECs) continued to move slightly east and endured. Subsequently, TEC depletions A1 and B1 turned westward at longitudes $\sim 115^{\circ}\text{E}$ and 120°E , respectively, around 20 UT, and persisted until and beyond sunrise. After sunrise, the irregularities (A2 and B2) reemerged within the same TEC depletions. On the eastern side (above 120°E), one may also notice dark or negative rTEC in post-midnight hours (before sunrise), which could be associated with plasma density perturbations. However, the zonal distance of those initial density perturbations is unclear.

in the pattern displayed and does not match the spatial distance with the zonal distance of A1-B1 and A2-B2. We assert that the similar zonal distance between irregularities A1-B1 and A2-B2 provides strong evidence for the connection between post-sunset and post-sunrise irregularities, along with the continuation of TEC depletion from post-sunset to sunrise hours. In short, we find potential evidence that the regeneration of irregularities at sunrise during the storm may be connected to the earlier plasma depletion structures of EPB generated in the post-sunset hours.

Next, we analyze the latitude-time structure of post-sunrise irregularities during the storm. Figure 3 shows the meridional (North-South) cross-section of ROTI values at longitudes 105–116°E from 9 UT on 19 April to 6 UT on 20 April. From these time and longitude intervals, we can compare the latitudinal development of irregularities during post-sunset and post-sunrise hours on the day of the storm. We have observed that the post-sunset irregularities moved eastward while the post-sunrise irregularities moved westward (Figure 2). Figure 3 illustrates the progression of the latitudinal structure of post-sunset irregularities from 105° to 116°E (eastward). Meanwhile, the latitudinal structure of post-sunrise irregularities can be examined from 116° to 105°E (westward). Post-sunset irregularities extended poleward rapidly after the generation, reaching the southern part of Indonesia. Moving eastward, the latitudinal structure of post-sunset irregularities shortened as these irregularities decayed over time—the post-sunset irregularities completely decayed at a longitude of 116°E by midnight. Afterward, the irregularities reemerged after the E-region sunrise, starting at a longitude of 115°E. The latitudinal structure of post-sunrise irregularities increased as they moved westward, indicating a growing process of irregularities. Again, also referring to Figure 2, it is clear that the growing irregularities at sunrise hour during the 19–20 April storm may have originated from the persistent plasma depletion structures of post-sunset EPBs.

Complementing the analysis of this study, we use ionosondes to investigate the zonal electric field during the storm. Figure 4 shows a sample sequence of ionograms from the Bac Lieu ionosonde collected between 21:00 and 23:00 UT (E-region sunrise occurs around 22:00 UT) on 19 April 2024. In Figure 4, the F region trace moves upward before the occurrence of Equatorial Spread-F (ESF), as marked by the white dashed circles. The rising F region trace from the ionograms can serve as a proxy for the zonal equatorial electric field. Additionally, note that a sudden rise in $h'F$ is not solely storm-induced; it can also serve as a precursor to ESF conditions. The ESF indicates the presence of ionospheric irregularities. Figure 5 illustrates the variation in $h'F$ obtained from all ionosonde observations used in this study, highlighting the zonal electric field's role in the vertical movement of the F region's height. Regarding Figure 5, we analyze the F-region height variation during the storm (orange dots) from 09 UT on 19 April to 06 UT on 20 April and compare it to the height variation under quiet or normal conditions (blue dots). The average F region height variation observed on 18 and 20 April represents the vertical motion of the F region height under quiet conditions. From all ionosondes (Chumphon, Bac Lieu, and Meiji stations), we observed an enhancement of F region height around sunset hours on both storm and quiet days, attributing this uplift of the F region ionosphere to the regular PRE during the equinox season in Southeast Asia [35]. In contrast, from midnight until sunrise, the enhancement of the F region height occurred only on the day of the storm and not under quiet conditions. Notably, the vertical motion of the F region reached its peak at E-region sunrise, while the generation of irregularities (Figures 2 and 3) began just after E-region sunrise. Furthermore, we examined further details concerning the post-midnight rise of the F region height during the storm, noting a larger uplift of the F region confined to the western side. The peak in the sunrise F region uplift increased from the longitudes of Meiji to Bac Lieu and then to the Chumphon ionosondes. The uplift of the F region from

midnight to sunrise during the 19 April storm was caused by the overshielding PPEF linked to the northward turning of IMF Bz, as reported by Panda et al. [24]. While undershielding PPEF under southward IMF Bz appears as eastward electric fields in the dusk sector and westward electric fields in the dawn sector, the overshielding PPEF caused by a sudden northward IMF Bz appears as eastward and westward electric fields in the dawn and dusk sectors, respectively. However, we emphasize that the effects of overshielding PPEF varied in the zonal direction across Southeast Asia on the storm of 19–20 April; the accumulation of the overshielding PPEF that uplifts the F-region height changed with longitude.

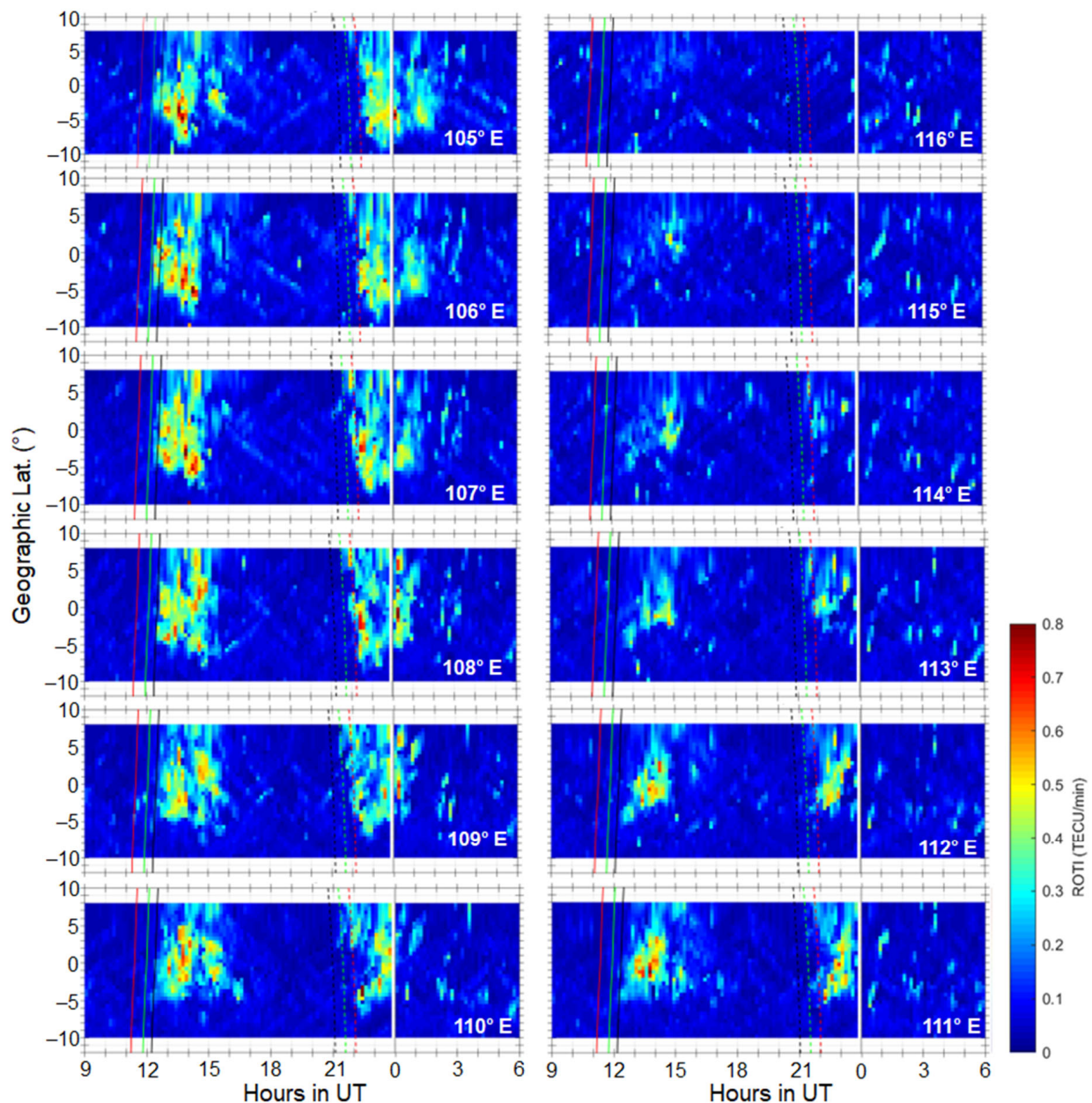


Figure 3. The latitude-time cross-section of ROTI variation at 105–116°E longitude intervals from 9 UT 19 April to 6 UT 20 April 2024. The sunset and sunrise lines at altitudes of 110 km, 350 km, and 650 km are represented by solid and dashed curves in red, green, and black. Conversion from UT to LT: LT = UT + 7 h at 105°E longitude, and LT = UT + 7.73 h at 116°E longitude.

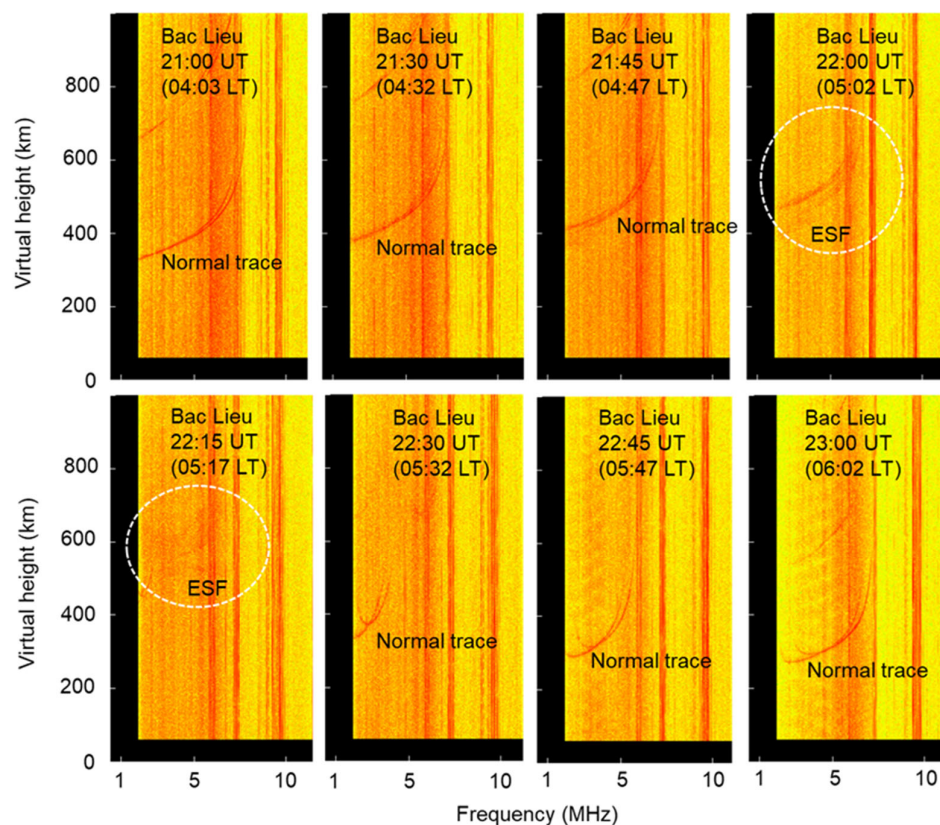


Figure 4. A sequence of ionograms from the Bac Lieu ionosonde recorded between 21:00 and 23:00 UT on 19 April 2024. The dashed white lines indicate the presence of equatorial spread-F (ESF).

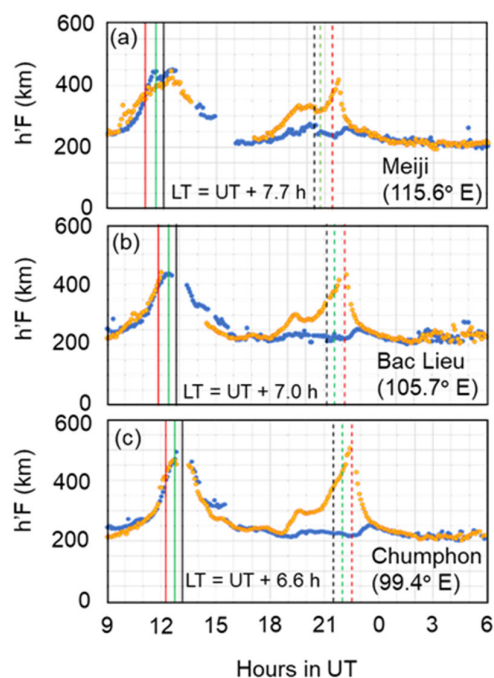


Figure 5. The temporal variations of $h'F$ from the Meiji (a), Bac Lieu (b), and Chumphon (c) ionosondes are shown during the storm, from 9 UT on 19 April to 6 UT on 20 April 2024, represented by yellow dots. Blue dots indicate the average variations of $h'F$ recorded on 18 and 20 April 2024, reflecting quiet conditions. The sunset and sunrise at altitudes of 110 km, 350 km, and 650 km are marked by solid and dashed curves in red, green, and black. Conversion of UT to LT for each station is indicated in each panel.

Here, we discuss the effects of overshielding PPEF on the uplifting F-region height during sunrise across Southeast Asia using the PPEFM. Furthermore, we compare IMF Bz, PPEFM, and the h'F variation (Figure 6) to examine the longitudinal variation of the uplift F region height amplitude during the 19 April storm. In Figure 6a, we again show the IMF Bz variation, the same as in Figure 2b, but with a time interval from midnight to sunrise (17–24 UT) on 19 April. The variation of overshielding PPEF from the model is displayed in Figure 6b. We present the PPEF variation across Southeast Asia (90–140°E) in the zonal keogram or longitude-time cross-section. Figure 6b shows several instances of enhanced PPEF in Southeast Asia during 17–24 UT on 19 April. The E-region sunrise (red dashed curve) and longitudes of Meiji, Bac Lieu, and Chumphon (black lines) are identified in Figure 6b. Figure 6c displays the difference in h'F (dh'F) between storm and quiet conditions from each ionosonde; the dh'F is derived from the orange dots minus the blue dots in Figure 5. The dh'F variation demonstrates nearly identical changes in the vertical movement of F region height at each ionosonde, indicating that the storm-time electric field affected the ionosphere over the three ionosondes almost simultaneously. Note that the h'F increase stopped sequentially at the three ionosonde stations from the east (Meiji) to the west (Chumphon), generally consistent with the local sunrise time.

The marks A, B, C, D, and E in each plot of Figure 6 represent our effort to correlate the northward-turning IMF Bz with the increased PPEF and the rise in dh'F, although the enhanced PPEF at mark B is not reproduced. PPEFM reproduced both undershielding and overshielding PPEFs. The period of Mark B was around the peak of the storm's main phase (~19 UT). The enhanced overshielding PPEF at Mark B could not be reproduced by the model, possibly because of competition between westward undershielding and eastward overshielding PPEFs during the post-midnight period. Nonetheless, we can assert that the periods of increased dh'F and enhanced PPEF generally followed the timing of northward IMF Bz. The northward IMF Bz at mark A indicates the beginning of an increase in dh'F across all ionosondes, and then, the northward IMF Bz at mark D implies a stronger resultant PPEF, which in turn caused a sharp increase in dh'F after 21 UT. Interestingly, the northward turning of the IMF Bz at mark E displays a notable resultant increase in dh'F in Chumphon compared to the other ionosondes. The northward-turning IMF Bz at mark E caused the PPEF around 22 UT before the E-region sunrise at Chumphon, while Bac Lieu and Meiji were already experiencing sunlit conditions. Therefore, only the ionosonde in Chumphon observed a more pronounced vertical motion of the F region height after 22 UT than the other ionosondes. This leads to the conclusion that the ionosphere on the western side of Southeast Asia was more influenced by the overshielding PPEF during the 19 April storm. Consequently, the accumulation of overshielding PPEF resulted in a significant uplift of the F region height during sunrise, confined to the western side of Southeast Asia.

The overshielding PPEF was responsible for the enhanced eastward electric field in western Southeast Asia from midnight to sunrise. When the IMF Bz suddenly turns northward after a steady southward configuration, the Region 2 (R2)-Field Aligned Current (FAC) can be temporarily stronger than the Region 1 (R1)-FAC. This condition is known as "overshielding," and the dominant shielding electric fields penetrate to low latitudes, causing an eastward (westward) polarity of the electric field in the equatorial ionosphere during the night-to-dawn (day-to-post-sunset) sector [23]. In our case, the northward turning IMF Bz occurred between 18 and 23 UT on 19 April, concurrently with the midnight-sunrise times in the western part of Southeast Asia (below 120°E), while the eastern part was already experiencing a sunlit region. Therefore, the effects of the eastward polarity of the overshielding electric fields were exclusively accumulated in the western part of Southeast Asia. Specifically, observations from the Chumphon ionosonde indicate that this site experienced prolonged eastward polarity overshielding PPEF from midnight to

sunrise, resulting in the most significant sunrise uplift of F region height observed above this ionosonde.

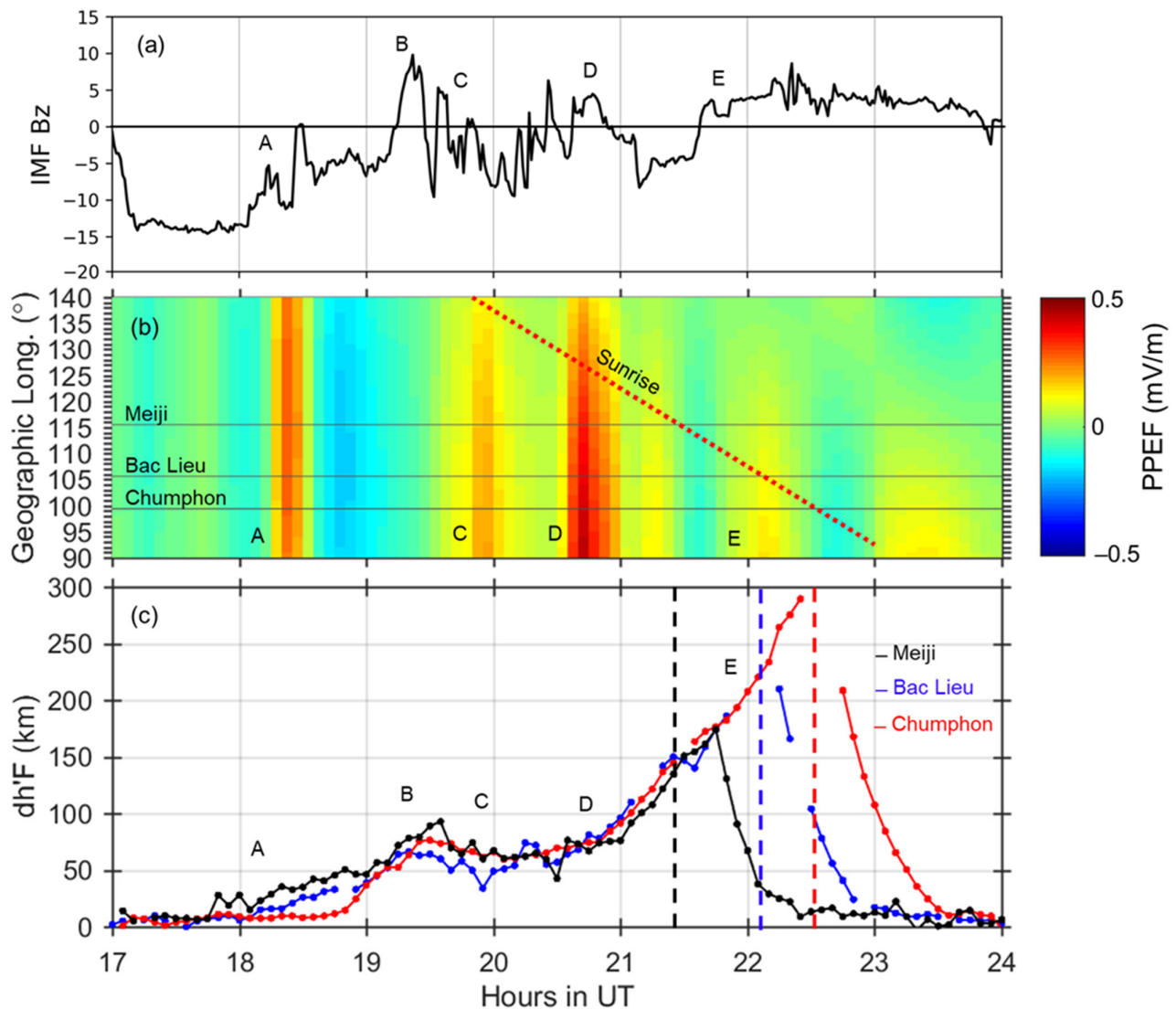


Figure 6. (a) IMF Bz and (b) the longitude-time cross-section (keogram) of equatorial PPEF variation at 90–140°E longitude intervals from 09:00 UT on 19 April to 06:00 UT on 20 April 2024, along with (c) the difference in h'F variation (dh'F) between the storm day (19 April) and the quiet day, derived from the data in Figure 5 for the Meiji, Bac Lieu, and Chumphon ionosondes. Marks A, B, C, D, and E refer to the simultaneously northward IMF Bz, enhanced PPEF, and the increase in dh'F. In panel (b), the E-region sunrise and the longitudes of the Meiji, Bac Lieu, and Chumphon ionosondes are identified. In panel (c), E-region sunrises at Meiji, Bac Lieu, and Chumphon are marked by vertical dashed lines in black, blue, and red, respectively.

4. Discussion

We discuss our findings on the occurrence of post-sunrise irregularities in Southeast Asia during the storm of 19–20 April 2024 and present new insights gained from this study. It is now clearer that linking Figures 2–6, the significant uplift of the F region in the western part of Southeast Asia during sunrise hours (20 April) reemerged the irregularities within the surviving plasma depletions of post-sunset EPBs from the previous night (19 April). The zonal spacing between post-sunrise irregularities mirrored the post-sunset irregularities, clearly illustrating their connection. In this case, the storm-driven electric field primarily promoted EPBs in those distinct locations, where the surviving plasma

depletion structures of post-sunset EPBs persisted past midnight. We consider that the surviving plasma depletion structures after midnight could act as an initial perturbation density in the F region, providing a suitable site for the later formation of ionospheric irregularities driven by storm-induced electric fields (overshielding PPEF). Similar to PRE in the post-sunset hours, the same principle applies to the storm-driven electric field during sunrise: it enhances the growth rate of RTI at the locations of surviving plasma depletion by uplifting the F region. At higher altitudes, the growth rate of RTI increases, leading to the regeneration of ionospheric irregularities at sunrise. As irregularities move westward, the latitudinal structure of post-sunrise irregularities expands due to the uplift in the F region's height, which increases from east to west. To aid understanding, Figure 7 visually connects the elements involved in the occurrence of ionospheric irregularities near or after sunrise during a geomagnetic storm, covering periods of post-sunset hours: post-sunset EPB formation, eastward drifting post-sunset EPBs, decaying irregularities, and persistent depletion structures; and post-midnight: survival depletion structures, uplift of the F-region during sunrise via overshielding PPEF, and the regeneration of irregularities.

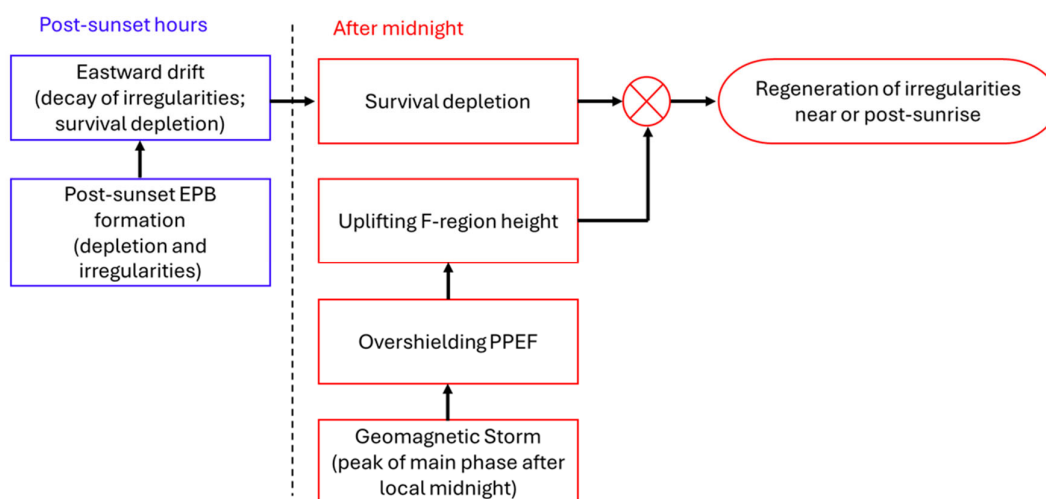


Figure 7. A schematic illustration of the regeneration of ionospheric irregularities within the survival depletion structures of post-sunset EPB around sunrise during a geomagnetic storm. Blue and red boxes represent the processes during the post-sunset and after-midnight periods, respectively.

As emphasized in this study, the surviving plasma depletion structures from post-sunset EPBs can be regarded as potential sites for sunrise EPBs and ionospheric irregularities. Future research should explore the formation of sunrise EPBs in scenarios where post-sunset EPBs do not occur. For instance, during moderate to severe geomagnetic storms that peak in the main phase during local daytime, post-sunset EPBs may not form due to the westward polarity of DDEF, leading instead to post-midnight or near-sunrise EPBs because of eastward DDEF polarity [36]. A notable example is the super geomagnetic storm in May 2024, where the main phase occurred in the local morning in Southeast Asia, resulting in no observable post-sunset EPBs; however, sunrise EPBs appeared in this region [25,37,38]. This raises a compelling question for future research: How does the seeding mechanism operate for sunrise EPB formation without prior post-sunset EPBs? Investigating different pathways in these cases could improve our understanding of ionospheric irregularity development during geomagnetic disturbances. Southeast Asia is particularly relevant for this study due to its proximity to the magnetic equator and the numerous radio wave instruments deployed in the region [39–41].

5. Conclusions

Our research is the first to investigate the connection between post-sunset and post-sunrise ionospheric irregularities during a geomagnetic storm, a topic that has not been previously explored. This is a significant contribution that enhances our understanding of the evolution of sunrise irregularities under storm-time electric fields. We concentrated on the generation of post-sunrise irregularities in Southeast Asia during the storm of 19–20 April 2024. We utilized ionospheric maps across Indonesia, including TEC and ROTI maps and ionosonde data specific to Southeast Asia. Our findings indicate that on the night of 19 April, post-sunset EPBs were generated solely in the western part of Southeast Asia. The post-sunset EPBs formed due to the normal PRE, the enhanced eastward electric field around sunset that raises the F-region height to greater elevations, facilitating the development of EPBs (plasma density structures and irregularities). The post-sunset EPBs drifted eastward, with the irregularities decaying by midnight after the EPBs had traveled approximately 10° in longitude; however, the plasma depletion structures persisted and turned westward from post-midnight to post-sunrise the next day. We observed that irregularities reappeared in the longitudes where the remaining plasma depletion structures were located. The significant rise in the F-region height, caused by the storm's electric field during midnight to sunrise hours, led to post-sunrise irregularities in areas with the remaining plasma depletion structures after sunrise. From the ionosonde observations and equatorial electric field model, the influence of storm-time electric fields exhibited a longitudinal variation, with a greater accumulation of storm-driven electric field effects concentrated in the western part of Southeast Asia compared to the eastern part. The eastward polarity of overshielding PPEF, linked to the northward shift of IMF Bz, was responsible for the post-midnight rise at F-region height in the western part of Southeast Asia. Post-sunrise irregularities demonstrated a growth process, expanding their structure poleward while moving westward. In conclusion, the formation of sunrise EPBs and irregularities depended on the storm-time electric field and locations with initial perturbations. The remaining plasma depletion structures from post-sunset EPBs possibly served as potential locations for the initial perturbations that led to sunrise EPBs and irregularities. The strong electric fields driven by storms raised the F-region during sunrise hours, creating EPBs and irregularities where the initial perturbations occurred.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/rs17162906/s1>, Animation of Supplementary Information S1: Indonesian ROTI Map during storm on 19–20 April 2024.

Author Contributions: Conceptualization, methodology, resources, software, visualization, P.A.; formal analysis, investigation, supervision, validation, writing—review and editing, all authors; data curation, T.N.P.; writing—original draft preparation, P.A.; funding acquisition, project administration, G.L. and P.J. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The ionospheric map over Indonesia is available at the Gatotkaca database (<https://gatotkaca.brin.go.id/petaionosfer/ionosphericmap/>, last accessed 29 June 2025). The prompt penetration electric field model is available at <http://www.geomag.us/models/PPEFM/RealtimeEF.html> (last accessed: 3 June 2025). SEALION ionosondes are managed by the National Institute of Information and Communications (NICT), Japan, and the data can be accessed at <https://aer-nc-web.nict.go.jp/sealion/> (last accessed: 7 June 2025). The parameter of the ionosonde at Meiji Island, as part of IONISE (<http://ionise.geophys.ac.cn/Data.asp>, last accessed 29 June 2025), can be requested by sending an email to geophysdata@mail.iggcas.ac.cn. The contributions

presented in this study are included in the article material. Further inquiries can be directed to the corresponding author.

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Abbreviations

The following abbreviations are used in this manuscript:

EPB	Equatorial Plasma Bubble
TEC	Total Electron Content
ROTI	Rate of TEC change Index
SAR	Synthetic Aperture Radar
GNSS	Global Navigation Satellite System
RTI	Rayleigh-Taylor Instability
PRE	Pre-reversal enhancement
PPEF	Prompt-penetration electric field
DDEF	Disturbance Dynamo Electric Field
Ina-CORS	Indonesia Continuously Operating Reference Stations
BIG	Badan Informasi Geospasial
IPP	Ionospheric Pierce Point
2D	Two-dimensional
rTEC	Ratio of TEC
SEALION	Southeast Asia Low-latitude Ionospheric Observation Network
IONISE	Ionospheric Observation Network for Irregularity and Scintillation in East/Southeast Asia
IMF Bz	Interplanetary Magnetic Field Bz
SSC	Sudden Storm Commencement
AE	Auroral Electrojet
Sym-H	Geomagnetic index derived from the H-component magnetic field: to describe the strength of the geomagnetic storm
UT	Universal Time
LT	Local Time
ESF	Equatorial Spread-F
PPEFM	Prompt Penetration Electric Field Model
R2-FAC	Region 2—Field Aligned Current
R1-FAC	Region 1—Field Aligned Current

References

1. Kelley, M.C. *The Earth's Ionosphere: Plasma Physics and Electrodynamics*, 2nd ed.; Academic Press: San Diego, CA, USA, 2009.
2. Tsunoda, R.T.; Livingston, R.C.; McClure, J.P.; Hanson, W.B. Equatorial plasma bubbles: Vertically elongated wedges from the bottomside F layer. *J. Geophys. Res. Space Phys.* **1982**, *87*, 9171–9180. [[CrossRef](#)]
3. Ishii, M.; Shiota, D.; Tao, C.; Ebihara, Y.; Fujiwara, H.; Ishii, T.; Yoden, S. Space weather benchmarks on Japanese society. *Earth Planets Space* **2021**, *73*, 108. [[CrossRef](#)]
4. Sato, H.; Kim, J.S.; Otsuka, Y.; Wrasse, C.M.; Rodrigues de Paula, E.; Rodrigues de Souza, J. L-band Synthetic Aperture Radar observation of ionospheric density irregularities at equatorial plasma depletion region. *Geophys. Res. Lett.* **2021**, *48*, e2021GL093541. [[CrossRef](#)]

5. Geng, W.; Huang, W.G.; Liu, G.Q.; Liu, S.Q.; Luo, B.X. Assessing the kinematic GPS positioning performance under the effect of strong ionospheric disturbance over China and adjacent areas during the magnetic storm. *Radio Sci.* **2022**, *57*, e2021RS007329. [\[CrossRef\]](#)
6. Ossakow, S.L.; Zalesak, S.T.; McDonald, B.E.; Chaturvedi, P.K. Nonlinear equatorial spread F: Dependence on altitude of the F peak and bottomside background electron density gradient scale length. *J. Geophys. Res.* **1979**, *84*, 17. [\[CrossRef\]](#)
7. Otsuka, Y.; Shiokawa, K.; Ogawa, T.; Wilkinson, P. Geomagnetic conjugate observations of equatorial airglow depletions. *Geophys. Res. Lett.* **2002**, *29*, 43-1–43-4. [\[CrossRef\]](#)
8. Abadi, P.; Otsuka, Y.; Tsugawa, T. Effects of pre-reversal enhancement of $E \times B$ drift on the latitudinal extension of plasma bubble in Southeast Asia. *Earth Planets Space* **2015**, *67*, 74. [\[CrossRef\]](#)
9. Yokoyama, T.; Jin, H.; Shinagawa, H. West wall structuring of equatorial plasma bubbles simulated by three-dimensional HIRB model. *J. Geophys. Res. Space Phys.* **2015**, *120*, 8810–8816. [\[CrossRef\]](#)
10. Retterer, J.M.; Roddy, P. Faith in seed: On the origins of equatorial plasma bubbles. *Ann. Geophys.* **2014**, *32*, 485–498. [\[CrossRef\]](#)
11. Ajith, K.K.; Li, G.; Tulasi Ram, S.; Yamamoto, M.; Hozumi, K.; Abadi, P.; Xie, H. On the seeding of periodic equatorial plasma bubbles by gravity waves associated with tropical cyclone: A case study. *J. Geophys. Res. Space Phys.* **2020**, *125*, e2020JA028003. [\[CrossRef\]](#)
12. Liu, K.; Li, G.; Ning, B. Possible evidence for small-scale wave seeding of equatorial plasma bubbles. *Adv. Space Res.* **2019**, *63*, 3612–3620. [\[CrossRef\]](#)
13. Saito, S.; Maruyama, T. Large-scale longitudinal variation in ionospheric height and equatorial spread F occurrences observed by ionosondes. *Geophys. Res. Lett.* **2007**, *34*, L16109. [\[CrossRef\]](#)
14. Tsunoda, R.T. Upwelling: A unit of disturbance in equatorial spread F. *Prog. Earth Planet. Sci.* **2015**, *2*, 9. [\[CrossRef\]](#)
15. Tsunoda, R.T.; Saito, S.; Nguyen, T.T. Post-sunset rise of equatorial F layer—Or upwelling growth? *Prog. Earth Planet Sci.* **2018**, *5*, 22. [\[CrossRef\]](#)
16. Abdu, M.A.; Batista, I.S.; Bertoni, F.; Reinisch, B.W.; Kherani, E.A.; Sobral, J.H.A. Equatorial ionosphere responses to two magnetic storms of moderate intensity from conjugate point observations in Brazil. *J. Geophys. Res.* **2012**, *117*, A05321. [\[CrossRef\]](#)
17. Blanc, M.; Richmond, A.D. The ionospheric disturbance dynamo. *J. Geophys. Res.* **1980**, *85*, 1669–1686. [\[CrossRef\]](#)
18. Abdu, M.A.; De Paula, E.R.; Batista, I.S.; Reinisch, B.W.; Matsuoka, M.T.; Camargo, P.O.; De Siqueira, P.M. Abnormal evening vertical plasma drift and effects on ESF and EIA over Brazil-South Atlantic sector during the 30 October 2003 superstorm. *J. Geophys. Res.* **2008**, *113*, A07313. [\[CrossRef\]](#)
19. Ma, G.Y.; Maruyama, T. A super bubble detected by dense GPS network at East Asian longitudes. *Geophys. Res. Lett.* **2006**, *33*, L21103. [\[CrossRef\]](#)
20. Sun, W.; Li, G.; Zhang, S.R.; Hu, L.; Dai, G.; Zhao, B.; Perwitasari, S. Regional ionospheric super bubble induced by significant upward plasma drift during the 1 December 2023 geomagnetic storm. *J. Geophys. Res. Space Phys.* **2024**, *129*, e2024JA032430. [\[CrossRef\]](#)
21. Abdu, M.A.; Kherani, E.A.; Batista, I.S.; Sobral, J.H.A. Equatorial evening prereversal vertical drift and spread F suppression by disturbance penetration electric fields. *Geophys. Res. Lett.* **2009**, *36*, L19103. [\[CrossRef\]](#)
22. Fukao, S.; Ozawa, Y.; Yamamoto, M.; Tsunoda, R.T. Altitude-extended equatorial spread F observed near sunrise terminator over Indonesia. *Geophys. Res. Lett.* **2003**, *30*, 2137. [\[CrossRef\]](#)
23. Tulasi Ram, S.; Ajith, K.K.; Yamamoto, M.; Otsuka, Y.; Yokoyama, T.; Niranjana, K.; Gurubaran, S. Fresh and evolutionary-type field-aligned irregularities generated near sunrise terminator due to overshielding electric fields. *J. Geophys. Res. Space Physics* **2015**, *120*, 5922–5930. [\[CrossRef\]](#)
24. Panda, S.K.; Rajana, S.S.K.; Vivek, C.G.; Dabbakuti, J.R.K.K.; Jamir, W.; Jamjareegulgarn, P. Multi-Instrument Analysis of Ionospheric Equatorial Plasma Bubbles over the Indian and Southeast Asian Longitudes During the 19–20 April 2024 Geomagnetic Storm. *Remote Sens.* **2025**, *17*, 1100. [\[CrossRef\]](#)
25. Abadi, P.; Muafiry, I.N.; Pratama, T.N.; Putra, A.Y.; Suraina; Pramono, G.H.; Wibowo, S.T.; Chabibi, F.F.; Ahmad, U.A.; Tresna, W.P.; et al. Leveraging ROTI map derived from Indonesian GNSS receiver network for advancing study of Equatorial Plasma Bubble in Southeast/East Asia. *Earth Planet. Phys.* **2025**, *9*, 101–116. [\[CrossRef\]](#)
26. Seemala, G.K. Estimation of Ionospheric Total Electron Content (TEC) from GNSS Observations. In *Earth Observations, Atmospheric Remote Sensing*; Singh, A.K., Tiwari, S., Eds.; Elsevier: Amsterdam, The Netherlands, 2023; pp. 63–84.
27. Tulasi Ram, S.; Yamamoto, M.; Tsunoda, R.T.; Thampi, S.V.; Gurubaran, S. On the application of differential phase measurements to study the zonal large scale wave structure (LSWS) in the ionospheric electron content. *Radio Sci.* **2012**, *47*, RS2001. [\[CrossRef\]](#)
28. Tulasi Ram, S.; Yamamoto, M.; Tsunoda, R.T.; Chau, H.D.; Hoang, T.L.; Dantie, B.; Wassae, M.; Yatini, C.Y.; Manik, T.; Tsugawa, T. Characteristics of large-scale wave structure observed from African and Southeast Asian longitudinal sectors. *J. Geophys. Res. Space Phys.* **2014**, *119*, 2288–2297. [\[CrossRef\]](#)
29. Olla, A.; Abadi, P.; Srigutomo, W. Investigation of the latitudinal occurrence rate of ionospheric plasma bubble in case of strong and weak pre-reversal enhancement in Southeast Asia. *J. Phys. Conf. Ser.* **2020**, *1523*, 012024. [\[CrossRef\]](#)

30. Maruyama, T.; Kawamura, M.; Saito, S.; Nozaki, K.; Kato, H.; Hemmakorn, N.; Boonchuk, T.; Komolmis, T.; Ha Duyen, C. Low latitude ionosphere-thermosphere dynamics studies with inosonde chain in Southeast Asia. *Ann. Geophys.* **2007**, *25*, 1569–1577. [\[CrossRef\]](#)
31. Li, G.; Ning, B.; Zhao, X.; Sun, W.; Hu, L.; Xie, H.; Ajith, K.K. Low latitude ionospheric TEC oscillations associated with periodic changes in IMF Bz polarity. *Geophys. Res. Lett.* **2019**, *46*, 9379–9387. [\[CrossRef\]](#)
32. Sun, W.J.; Wu, B.Y.; Wu, Z.; Hu, L.H.; Zhao, X.K.; Zheng, J.C.; Xie, H.Y.; Yang, S.P.; Ning, B.Q.; Li, G.Z. IONISE: An ionospheric observational network for irregularity and scintillation in East and Southeast Asia. *J. Geophys. Res. Space Phys.* **2020**, *125*, e2020JA028055. [\[CrossRef\]](#)
33. Bowman, G.G. Some effects of geomagnetic activity and ionospheric height rises on mid-latitude spread-F occurrence. *J. Atmos. Terr. Phys.* **1984**, *46*, 55–64. [\[CrossRef\]](#)
34. Manoj, C.; Maus, S. A real-time forecast service for the ionospheric equatorial zonal electric field. *Space Weather*. **2012**, *10*, S09002. [\[CrossRef\]](#)
35. Burke, W.J.; Huang, C.Y.; Gentile, L.C.; Bauer, L. Seasonal longitudinal variability of equatorial plasma bubbles. *Ann. Geophys.* **2004**, *22*, 3089–3098. [\[CrossRef\]](#)
36. Putra, A.Y.; Irnaka, T.M.; Abadi, P.; Kilowasid, L.O.M.M.; Nuraeni, F.; Rakhman, A. Occurrence of ionospheric scintillation during geomagnetic storms in Indonesia (2003–2024) using superposed epoch analysis. *Earth Planet. Phys.* **2025**, *9*, 966–979. [\[CrossRef\]](#)
37. Sun, W.; Li, G.; Zhao, B.; Zhang, S.-R.; Otsuka, Y.; Hu, L.; Perwitasari, S. Midlatitude plasma blob-like structures along with super equatorial plasma bubbles during the May 2024 great geomagnetic storm. *Geophys. Res. Lett.* **2024**, *51*, e2024GL111638. [\[CrossRef\]](#)
38. Suraina; Rakhman, A.; Abadi, P.; Kilowasid, L.O.M.M.; Putra, A.Y.; Perwitasari, S.; Irnaka, T.M. Pre-sunrise equatorial plasma bubble over Indonesia during the 11 May 2024 super geomagnetic storm. *Earth Space Sci.* **2025**, *12*, e2024EA004152. [\[CrossRef\]](#)
39. Li, G.; Ning, B.; Otsuka, Y.; Abdu, M.A.; Abadi, P.; Liu, Z.; Wan, W. Challenges to Equatorial Plasma Bubble and Ionospheric Scintillation Short-Term Forecasting and Future Aspects in East and Southeast Asia. *Surv. Geophys.* **2021**, *42*, 201–238. [\[CrossRef\]](#)
40. Povero, G.; Alfonsi, L.; Spogli, L.; Di Mauro, D.; Cesaroni, C.; Dovis, F.; Romero, R.; Abadi, P.; Le Huy, M.; La The, V.; et al. Ionosphere Monitoring in South East Asia in the ERICA Study. *J. Inst. Navig.* **2017**, *64*, 273–287. [\[CrossRef\]](#)
41. Povero, G.; Pini, M.; Dovis, F.; Romero, R.; Abadi, P.; Alfonsi, L.; Floury, N. Ionosphere monitoring in South East Asia: Activities in GINESTRA and ERICA projects. In Proceedings of the 2015 International Association of Institutes of Navigation World Congress (IAIN), Prague, Czech Republic, 20–23 October 2015.

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