



## RESEARCH ARTICLE

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## Key Points:

- EPB suppression occurred despite favorable conditions, with vertical drifts exceeding 40 m/s, during the moderate storm
- Post-midnight EPBs developed only in the western sector, highlighting regional differences driven by local ionospheric conditions
- The severe storm produced long-lasting super EPBs, linked to under-shielding PPEF and DDEF effects

## Supporting Information:

Supporting Information may be found in the online version of this article.

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## Space Weather Effects From Moderate to Severe Geomagnetic Storms in October 2024 Over the Latin American Sector

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**Abstract** This study presents a detailed case study of the ionospheric impacts of moderate (G2) and severe (G4) geomagnetic storms over the Latin American sector, with particular emphasis on the formation and suppression of equatorial plasma bubbles (EPBs). The moderate storm of 7–8 October, 2024, presented a rare case of EPB suppression despite favorable conditions, including a pronounced pre-reversal enhancement (PRE), with vertical plasma drifts exceeding 40 m/s. Post-midnight EPBs were observed exclusively in the western side of the Latin American sector. The observed suppressions may be associated with the influence of meridional winds and the presence of an Es layer near the onset time of EPBs. In contrast, the severe storm of 10–11 October, 2024, triggered super and long-lasting EPB across both eastern and western sectors. The enhancement of EPBs during this event is attributed to the combined effects of an undershielding prompt penetration electric field (PPEF) and disturbance dynamo electric field (DDEF). Moreover, the storm's main phase was marked by a pronounced expansion of the Equatorial Ionization Anomaly (EIA) and a significant increase in total electron content (TEC), followed by a decrease during the recovery phase. These findings reinforce the importance of regional and local factors in ionospheric storm-time responses and suggest the need for further statistical studies to improve EPB occurrence forecasts.

**Plain Language Summary** Space weather events, such as geomagnetic storms, impact the entire magnetosphere-ionosphere system. During these storms, a large amount of energy enters Earth's upper atmosphere, affecting regions from the auroral zone to the equatorial region. The main mechanisms by which the ionosphere responds are electric field disturbances, including prompt penetration electric fields (PPEF) and disturbance dynamo electric fields (DDEF). These electric fields can alter the dynamics of various phenomena in the ionosphere. In this study, the ionospheric response to two geomagnetic storms, one moderate (classified as G2) and one severe (classified as G4), is analyzed over the Latin American Sector. The results revealed unusual behaviors: during the G2 storm, a rare suppression of equatorial plasma bubbles (EPBs) was observed, along with post-midnight EPBs on the western side of the region. In contrast, the G4 storm produced super and long-lasting EPBs, along with an expansion of the equatorial ionization anomaly (EIA).

## 1. Introduction

Space weather events have been studied over the decades, particularly the effects of geomagnetic storms on the Earth's ionosphere, which lead to a variety of implications and phenomena. These include enhancements of the Equatorial Ionization Anomaly (EIA) (e.g., Astafyeva et al., 2015; Carmo et al., 2024; Fagundes et al., 2016, 2025), suppression (e.g., Aa, Pedatella, & Liu, 2024; Stephan et al., 2002; Yin et al., 2023) or triggering of equatorial plasma bubbles (EPBs) (e.g., Carmo, Denardini, et al., 2022; Carmo, Pi, et al., 2022; Carmo et al., 2024), traveling ionospheric disturbances (TIDs) (e.g., Carmo et al., 2024; Cherniak & Zakharenkova, 2018), and auroral activity in both the Northern and Southern Hemispheres (e.g., Cherniak et al., 2022; Sieradzki & Paziewski, 2019; Xia et al., 2025), among many others.

Among these phenomena, EPBs are of particular interest in this study. The primary mechanism responsible for the development of EPBs is the Rayleigh–Taylor instability (RTI). Around sunset, the rapid decrease in E-region

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conductivity due to recombination enhances the eastward zonal electric field in the F region, generating an upward  $E \times B$  plasma drift known as the pre-reversal enhancement (PRE). This uplift intensifies the bottomside density gradient of the F layer, making it more unstable and creating favorable conditions for RTI growth, which leads to the development of EPBs (Kelley, 2009; Rishbeth, 2000). Geomagnetic storms can further modulate these conditions.

In addition to these ionospheric processes, the coupling between the magnetosphere and ionosphere also plays a key role. Field-aligned currents (FACs) connect the magnetosphere and ionosphere via two main regions, R1 and R2. During geomagnetic storms, the intensity and dynamics of these currents increase substantially, influencing the coupled system. R1 are associated with magnetospheric convection, while R2 are linked to the ring current (Dai et al., 2024; Sonnerup, 1980). These regions are responsible for the electric field imbalances that lead to penetration electric field into the ionosphere. In a simplified description based on Wei et al. (2015), there are two main mechanisms that create this imbalance: the undershielding prompt penetration electric field (PPEF), which occurs when R1 currents dominate over R2 currents ( $R1 > R2$ ), producing an eastward electric field during the daytime; and the overshielding PPEF, which arises when R2 currents exceed R1 currents ( $R1 < R2$ ), leading to a westward electric field during the daytime. These electric field directions are reversed on the nightside (Fejer, 1991; Fejer et al., 2008; Kelley et al., 1979). Another important mechanism during geomagnetic storms is the disturbance dynamo electric field (DDEF), which is initiated by Joule heating in the auroral region. This heating drives disturbed winds that propagate to low latitudes, producing an electric field with the same direction as the overshielding PPEF (Blanc & Richmond, 1980; Fejer et al., 2008; Richmond & Roble, 1997). These electric field mechanisms significantly impact ionospheric behavior, particularly the vertical plasma drift, the pre-reversal enhancement (PRE), and consequently the formation of EPBs. It is well known that an evening eastward electric field increases the vertical plasma drift and enhances the PRE, which favors EPB generation through a positive growth rate of the Rayleigh-Taylor instability (RTI) (e.g., Aa, Zhang, et al., 2024; Abdu, 2012; Sultan, 1996). Conversely, an evening westward electric field weakens vertical drift, inhibits the PRE, and suppresses the development of EPBs (Akala et al., 2020; Amaechi et al., 2018).

Many studies on geomagnetic storms often focus on the impacts of intense events (Aa, Zhang, et al., 2024; Astafyeva et al., 2015; Carmo et al., 2024; Fagundes et al., 2016, 2025; Singh et al., 2025). However, this work demonstrates that even moderate storms can significantly influence ionospheric dynamics and the generation of EPBs. In particular, it highlights a rare and unexpected case study of EPB suppression, despite favorable conditions such as a strong PRE and an enhanced vertical plasma drift. Additionally, the analysis describes an event in which EPBs developed only on the western side of the Latin American Sector, while no irregularities were observed on the eastern side—suggesting regional differences likely influenced by local drivers such as neutral winds and E-region conductivity (e.g., Abdu et al., 1981; Batista et al., 1986; Rishbeth, 1971). Therefore, the main objective of this case study is to provide a detailed analysis of the ionospheric effects caused by two geomagnetic storms (classified as G2 and G4) over the Latin American sector, thereby extending the existing body of literature to the October 2024 events.

## 2. Data Set and Methodology

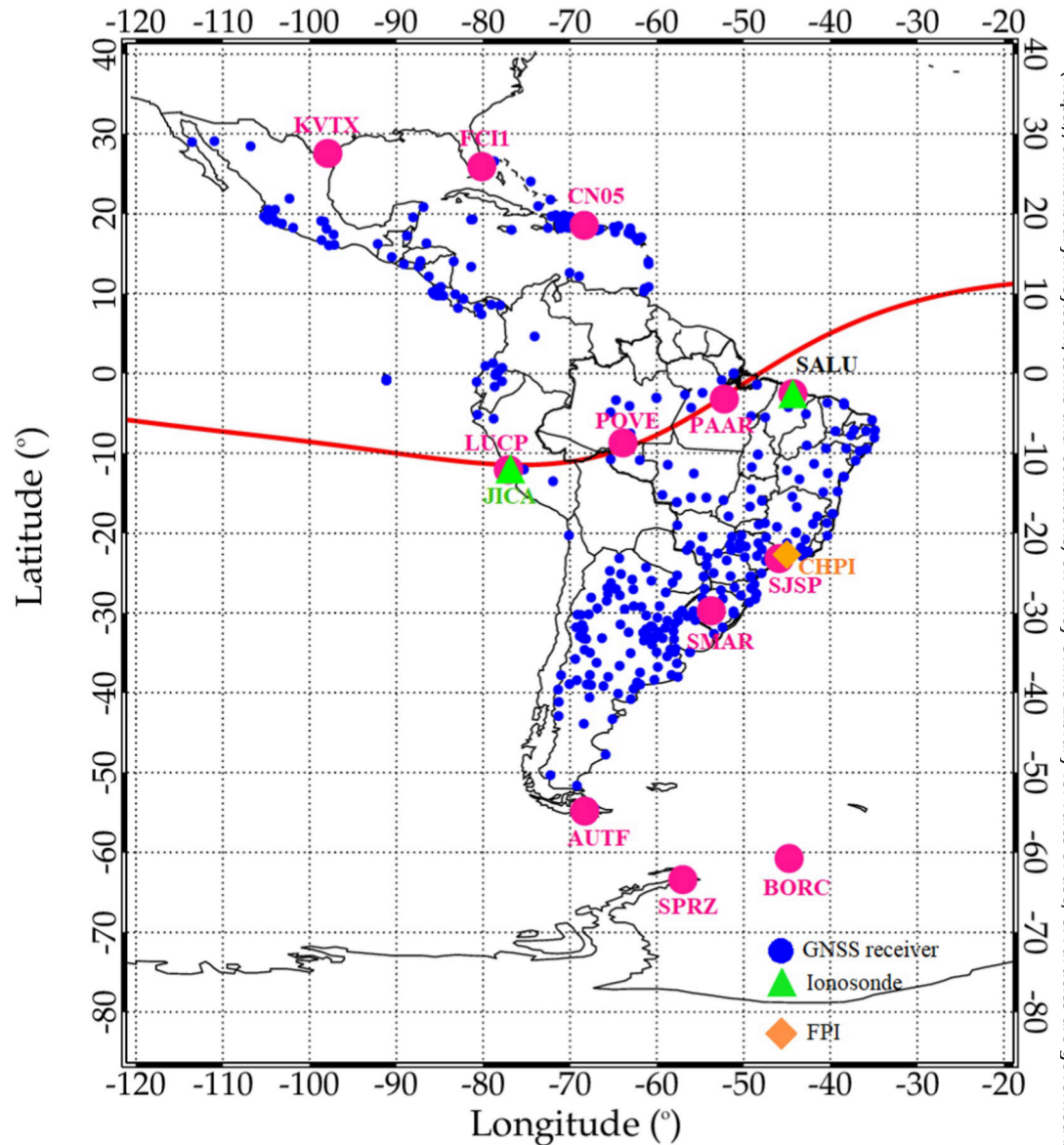
In this study, we used a multi-instrumental approach to analyze ionospheric behavior during geomagnetic storms. Figure 1 shows the locations of all instruments used: GNSS receivers (blue dots), ionosondes (green triangles), a Fabry-Perot interferometer (FPI, orange diamond), and selected GNSS receivers for detailed analysis (pink dots).

The stations used in this study are listed in Table 1 separated according to the instrument, station, latitude category, geographic longitude and latitude, magnetic declination and inclination, and geomagnetic latitude of the stations.

### 2.1. GNSS Receiver, Ionosonde and FPI

The Global Navigation Satellite System (GNSS) receiver is a high-precision instrument used to determine accurate positioning and geolocation by acquiring and processing radio signals transmitted by multiple satellites from various constellations, including the Global Positioning System (GPS, United States), GLObal Navigation Satellite System (GLONASS, Russia), Galileo (European Union), and BeiDou Navigation Satellite System (China). In this study, we used the GPS to investigate ionospheric behavior by calculating the Total Electron Content (TEC), which quantifies the total number of electrons contained in a column of  $1 \text{ m}^2$  cross-sectional area





**Figure 1.** Locations of GNSS receivers (blue dots), ionosondes (green triangles), and the Fabry–Perot Interferometer (FPI, orange diamond). Additional receivers were analyzed in specific case studies (pink dots). The red line represents the magnetic equator for the year 2024, at an altitude of 300 km.

along the signal path between the satellite and the receiver. Initially, the Slant TEC (STEC) is derived from the phase and code measurements of the dual-frequency GPS signals. The STEC is converted to Vertical TEC (VTEC, we call “TEC” in this paper) using a mapping function that projects the slant values to the zenith direction at an ionospheric pierce point (IPP). To derive this parameter, we used the GPS-TEC software (Seemala & Valladares, 2011, version 3.5), which is widely used by the scientific community (e.g., Adewale et al., 2011; Carmo et al., 2021, 2024; Kavacik et al., 2025; Lissa et al., 2021; Ozdemir et al., 2024). The mapping function ( $S(E)$ ) used by the software is given by:

$$S(E) = \frac{1}{\cos(z)} = 1 - \left\{ \left( \frac{R_E \cos(E)}{R_E + h} \right)^2 \right\}^{-0.5}. \quad (1)$$

**Table 1**

*Instrument, Station Name, Latitude Category (Equatorial (EQ), Low or Mid Latitude), Geographic Longitude, Geographic Latitude, Magnetic Declination (D), Magnetic Inclination (I), and Geomagnetic Latitude for All Stations*

| Instrument     | Station | LAT | Longitude (°) | Latitude (°) | D (°)  | I (°)  | Geom lat (°) |
|----------------|---------|-----|---------------|--------------|--------|--------|--------------|
| GNSS           | KVTX    | MID | −97.89        | 27.54        | 3.03   | 56.02  | 35.68        |
| GNSS           | FCII    | MID | −80.14        | 25.90        | −6.82  | 54.06  | 34.92        |
| GNSS           | CN05    | MID | −68.36        | 18.56        | −11.93 | 42.99  | 27.67        |
| GNSS           | LUCP    | EQ  | −77.08        | −12.07       | −3.07  | −1.71  | −2.77        |
| GNSS           | POVE    | EQ  | −63.89        | −8.71        | −13.03 | −1.90  | 0.49         |
| GNSS           | PAAR    | EQ  | −52.21        | −3.21        | −18.29 | −3.33  | 5.47         |
| GNSS/Ionosonde | SALU    | LOW | −44.31        | −2.53        | −19.17 | −10.75 | 5.62         |
| GNSS           | SJSP    | LOW | −45.89        | −23.18       | −20.00 | −38.99 | −14.73       |
| GNSS           | SMAR    | LOW | −53.72        | −29.72       | −14.40 | −39.51 | −20.77       |
| GNSS           | AUTF    | MID | −68.30        | −54.84       | 10.88  | −52.89 | −45.43       |
| GNSS           | SPRZ    | MID | −56.99        | −63.39       | 9.12   | −58.08 | −54.26       |
| GNSS           | BORC    | MID | −44.74        | −60.74       | 0.78   | −57.57 | −52.18       |
| Ionosonde      | JICA    | EQ  | −76.87        | −11.95       | −3.25  | −1.52  | −2.65        |
| FPI            | CHPI    | LOW | −44.99        | −22.67       | −20.36 | −39.19 | −14.29       |

where  $z$  is the zenith angle,  $R_E$  is the radius of the Earth,  $E$  is the elevation angle, and  $h$  is the altitude of 350 km. The GNSS observation data used in this study have a 15-s sampling rate. The software uses satellite elevation angles greater than 20°, but in this study we selected angles greater than 30° to minimize multipath effects.

The absolute TEC values are determined by incorporating the satellite differential biases provided by the University of Bern and the receiver bias, which is estimated by minimizing TEC variations between 2 and 6 LT, more technical detail can be found in Seemala (2023).

Additionally, to study ionospheric irregularities, we calculated the Rate of TEC Index (ROTI), as defined in Equation 2 (Pi et al., 1997).

$$\text{ROTI} = \sqrt{\left\langle \left( \frac{\Delta \text{TEC}}{\Delta t} \right)^2 \right\rangle - \left\langle \frac{\Delta \text{TEC}}{\Delta t} \right\rangle^2}. \quad (2)$$

ROTI was computed with a 5-min resolution. The TEC and ROTI map was obtained using the interpolation method proposed by Takahashi et al. (2016). In addition, we generated ROTI keograms at fixed latitudes to estimate the zonal drift velocity ( $\Delta \text{longitude} / \Delta \text{time}$ ) of the EPBs and other related parameters. This methodology is described in Carmo et al. (2023). In the literature, ROTI thresholds for ionospheric irregularities are classified as  $>0.5$  TECU/min Gao et al. (2023); Pi et al. (1997), intense  $>1$  TECU/min Cherniak et al. (2015), strong  $>3.5$  TECU/min Jacobsen and Dähnn (2014), and very strong  $>5$  TECU/min Jacobsen and Dähnn (2014).

Another instrument used in this study is the Digital Portable Sounder 4D (DPS-4D) ionosonde, a radar operating in the high-frequency (HF) band, capable of measuring several ionospheric parameters, including F layer virtual height ( $h'F$ ), F2 layer peak height ( $hmF2$ ), critical frequencies, among others (Reinisch et al., 2009). In this study, we calculated the apparent vertical drift ( $dH/dt$ ) from the true height corresponding to the average of the critical frequencies at 3, 4, 5, and 6 MHz, according to Carmo et al. (2024) and Abdu et al. (2009). Finally, we also used the FPI, an optical instrument that provides measurements of neutral winds, including both meridional and zonal components (Makela et al., 2011; Meriwether, 2006). To strengthen the robustness of the interpretation, the Horizontal Wind Model 2014 (HWM14, Drob et al., 2015) and the Thermosphere–Ionosphere Electrodynamics General Circulation Model (TIE-GCM 3.0, Wu et al., 2025) were used to compare with the wind observations, using the same altitude as the measurements (250 km).

In this study, the quiet day (Qd) reference used in some analyses corresponds to the three geomagnetically quietest days of the month, as identified by WDC Kyoto (<https://wdc.kugi.kyoto-u.ac.jp/qddays>): 13, 21, and 25 October,

2024. However, 13 October occurs shortly after the recovery phase of a geomagnetic storm, meaning that residual post-storm effects may still have been present and could have influenced the results, even though the day was classified as geomagnetically quiet by WDC Kyoto.

### 3. Results

In October 2024, two geomagnetic storms occurred and will be the focus of this study. The first was associated with a Coronal Mass Ejection (CME) that left the Sun on 3 October, reached Earth on 6 October, according to Space Weather alert from British Geological Survey (BGS, [geomag.bgs.ac.uk/data\\_service](https://geomag.bgs.ac.uk/data_service)). This event was classified as a moderate (G2) geomagnetic storm. The second storm was triggered by the arrival of another CME on 9 October and was classified as a severe (G4) geomagnetic storm.

Figure 2 presents a multi-parameter view of the geomagnetic storm evolution from 6 to 11 October, 2024. Panel (a) shows the interplanetary magnetic field components  $B_y$  (green) and  $B_z$  (pink). Panel (b) displays the Kp index as a color-coded bar plot indicating storm levels from G1 to G4, along with the Dst index in green. Panel (c) shows the Auroral Electrojet (AE) index in orange. Panels (d) and (f) present virtual height ( $h'F$ ) data in green and the average of three quiet days (13, 21, and 25 October) in gray and ROTI values (blue dots) at the JICA/LUCP and SALU stations, respectively. Panels (e) and (g) show the vertical plasma drift ( $V_z$ ) (magenta) for the JICA and SALU stations, respectively.

Figure 2a shows both positive and negative variations in the  $B_z$  component throughout the analyzed period. Notably, on 7 October,  $B_z$  turns southward and remains negative for an extended duration, from 13:00 UT on 7 October to 13:00 UT on 8 October, before returning to oscillate around zero. During this interval,  $B_z$  reaches a minimum of  $-15.8$  nT at 04:00 UT on 8 October. Meanwhile, the  $B_y$  component undergoes a sector change, becoming positive at 22:50 UT on 7 October 2024. In addition, on 10 October, both  $B_z$  and  $B_y$  exhibit rapid fluctuations between positive and negative values, with amplitudes exceeding  $\pm 20$  nT. From 22:30 UT on 10 October to 10:40 UT on 11 October, both components remain negative before returning their oscillations near zero. During this period,  $B_z$  reaches its lowest value of  $-46.49$  nT at 22:40 UT on 10 October.

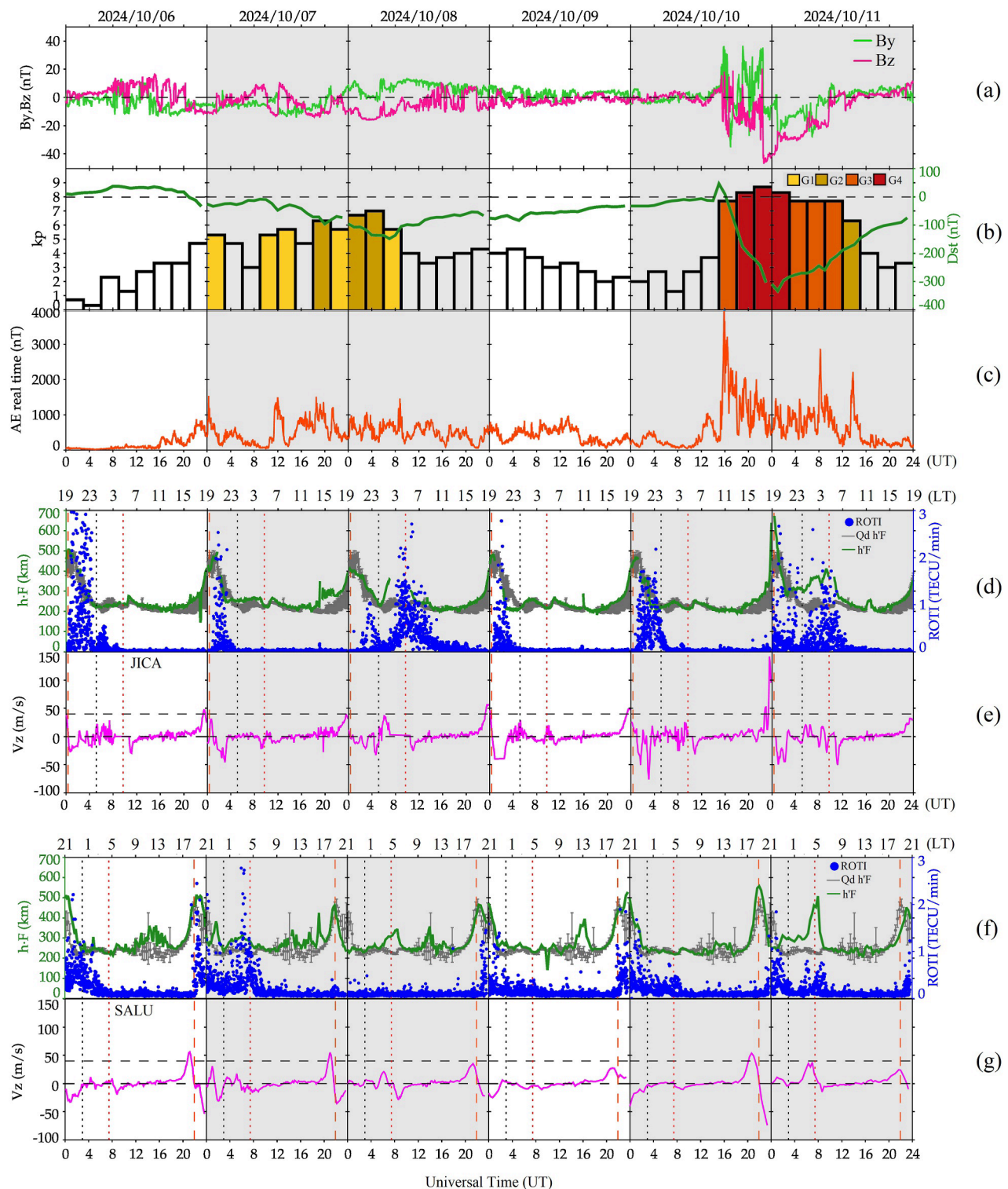
The Kp index (Figure 2b) indicates two geomagnetic storms: a moderate storm (G2) occurring from 7 to 8 October, and a severe storm (G4) from 10 to 11 October. During the first event, the Dst index (green line) reached a minimum of  $-148$  nT at 08:00 UT on 8 October. In the second event, the Dst index dropped to its lowest value of  $-333$  nT at 02:00 UT on 11 October.

The AE index (Figure 2c) indicates intense auroral activity, with values exceeding 1,000 nT from 00:00 UT on 7 October to 16:00 UT on 11 October. The second event, on 10 October, was particularly strong, reaching peak values around 4,000 nT.

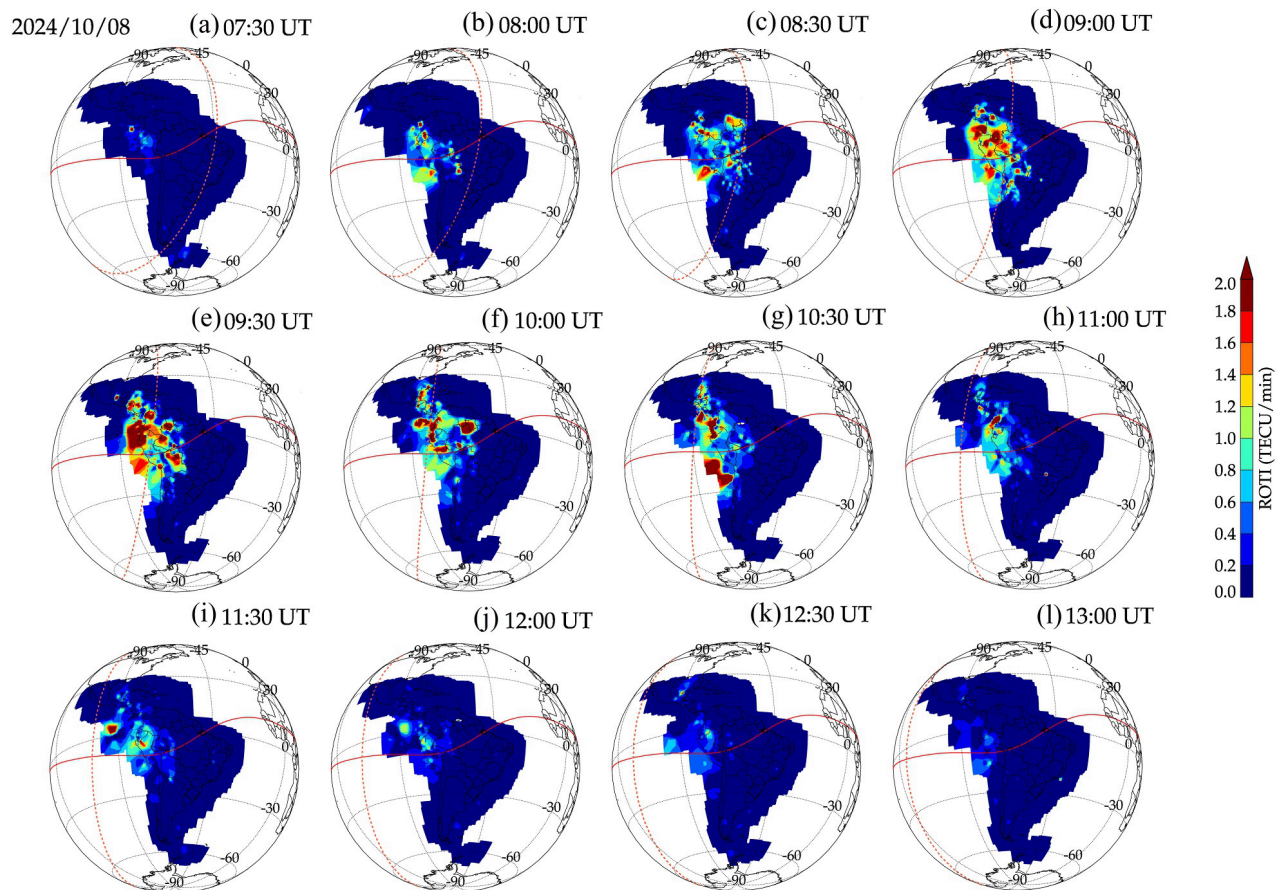
Focusing on the nighttime periods under analysis, at JICA (Figure 2d), the  $h'F$  values were slightly lower (407 km) than the quiet-time reference (436 km) curve at sunset (00:20 UT) on 8 October. However, starting at 05:00 UT, the F-layer began to rise above the quiet-time levels, remaining elevated until 11:00 UT. A small data gap is observed during this interval, due to the occurrence of Spread F, which affected ionosonde measurements. On 11 October, a significant uplift of the F-layer is observed, reaching 673.5 km at 00:20 UT (Qd: 442.3 km). The layer rises again from 04:00 UT to 11:00 UT, peaking at 09:13 UT with 411.8 km. At SALU (Figure 2f), during the sunset hours (21:55 UT) of 7 October, the F-layer remained close to the quiet-time reference (462 km, Qd: 441 km). On 8 October, at 00:00 UT, the F layer height decreased to 238 km, compared to the quiet-time reference of 367 km. It began to rise at 06:00 UT, reaching a peak of 327 km at 08:00 UT. On the night of 10 October, the layer rise above the reference curve, reaching 558 km (Qd: 461 km) at 21:55 UT. A second uplift occurred on 11 October, starting around 02:00 UT and peaking 508 km at 08:00 UT.

At JICA (Figure 2e), the  $V_z$  reaches  $\sim 40$  m/s near 00:00 UT on 8 October, with another similar peak, 37 m/s, around 06:00 UT. During the evening of 10 October,  $V_z$  increases significantly, peaking at 142 m/s at 23:33 UT, followed by smaller peaks ( $\sim 20$  m/s) throughout the night on 11 October. The ROTI values indicate significant ionospheric irregularities between 04:00 and 13:00 UT on 8 October, and again from 00:00 to 11:00 UT on 11 October. At SALU (Figure 2g),  $V_z$  reaches 55 m/s at 21:00 UT on 7 October. Subsequently,  $V_z$  decreased to  $-35$  m/s at 22:10 UT. However, such a post-PRE downward drift is a typical feature, as reported in previous studies (e.g., Abdu, 2005; Fejer et al., 1991). With another peak of 21 m/s at 06:10 UT on 8 October. On 10 October,  $V_z$  peaks again at 54 m/s at 20:40 UT, followed by a second significant peak at 07:00 UT on 11 October,





**Figure 2.** Multi-parameter data: (a) Interplanetary magnetic field components  $B_y$  (green) and  $B_z$  (pink); (b) Kp index represented as a color-coded bar plot indicating storm intensity levels (G1 to G4) and the Dst index (green); (c) Auroral Electrojet (AE) index (orange), (d, f) virtual height ( $h'F$ ) values (green) and the average of three quiet days (13, 21, and 25 October; gray) and ROTI (blue dots) at JICA/LUCP and SALU stations, respectively; (e, g) Vertical plasma drift ( $V_z$ ) (magenta) for the JICA and SALU stations, respectively, with a black dashed line at 40 m/s, from 6 to 11 October, 2024. The period under analysis is marked in gray. The vertical dashed orange lines and dotted red lines are the sunset and sunrise times, respectively, in each station at an altitude of 300 km, and the vertical dotted black lines are the local midnight. The local time (LT) for each station is shown above the x-axis, and the universal time (UT) below.



**Figure 3.** Sequence of ROTI maps from (a–l) 07:30 UT to 13:00 UT on 8 October 2024. The solid red line indicates the magnetic equator, while the dashed line represents the sunrise line.

reaching 38 m/s. ROTI values did not show significant activity during the night of 7 to 8 October, suggesting a possible suppression of ionospheric irregularities in this region. However, on 11 October, ROTI values were significant between 00:00 and 10:00 UT.

The two events under analysis generated EPBs that can be observed in the ROTI maps. Figure 3 shows a sequence of ROTI maps from 07:30 UT to 13:00 UT on 8 October 2024.

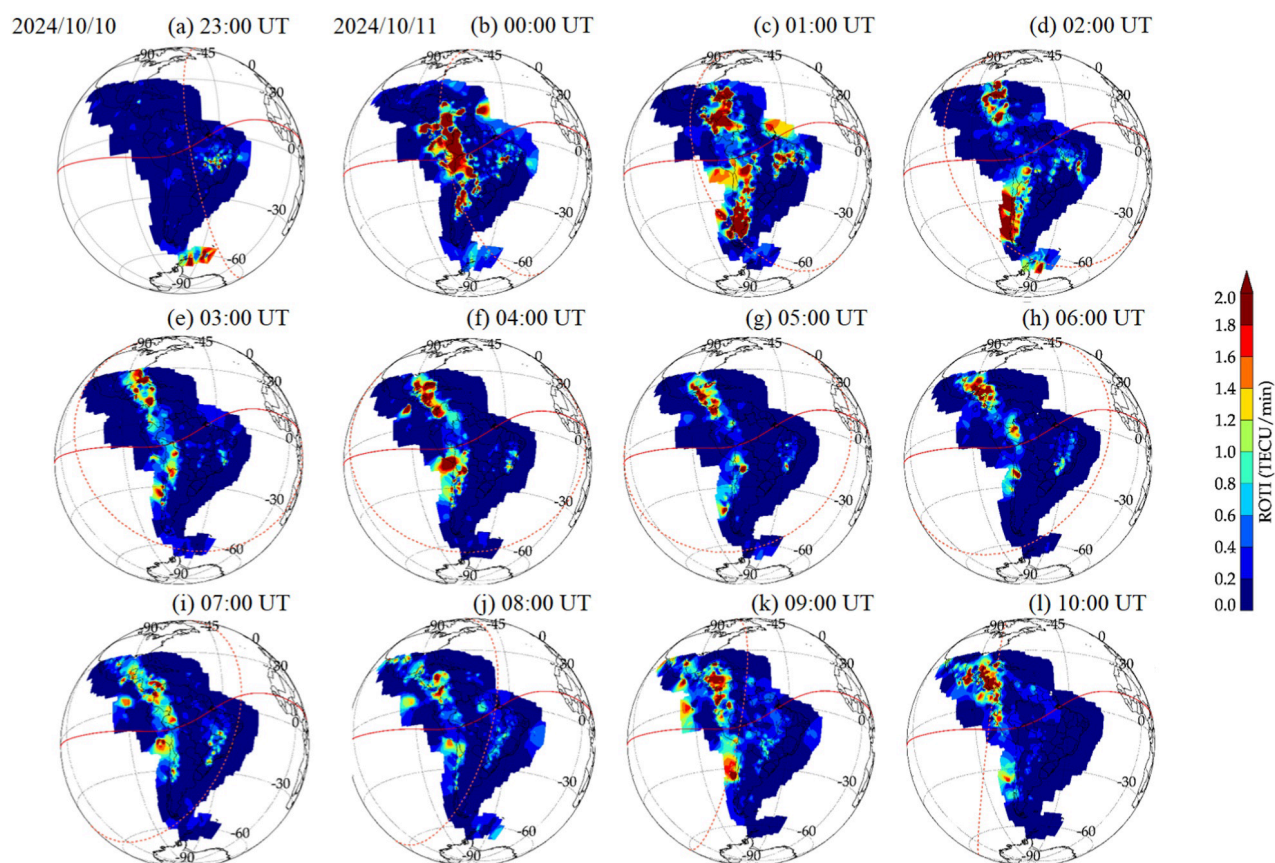
Figure 3 shows the appearance of the EPBs only on the western side of Latin America. We also include radar data from Jicamarca in the Supporting Information S1, supporting that these ionospheric irregularities are indeed EPBs. These irregularities persist even after sunrise, following the passage of the solar terminator (sunrise line), and remain visible at 13:00 UT.

In addition, the same analysis was performed for the second geomagnetic storm. Figure 4 presents a sequence of ROTI maps from 23:00 UT on 10 October to 11:00 UT on 11 October 2024.

Super plasma bubbles can be defined as EPBs that extend to midlatitudes (e.g., Ma & Maruyama, 2006). Figure 4 shows the presence of super EPBs drifting westward over Latin America. These irregularities also persist even after sunrise, following the passage of the solar, and remain visible at 11:00 UT.

Figure 5 shows positive (red shaded) and negative (gray shaded) ionosphere storms, similar to Astafyeva et al. (2015), along with 12 selected GNSS receivers used to analyze details on both the western and eastern sides of Latin America for 7–8 October and 10–11 October (gray shaded), across different latitudinal regions: equatorial, low, and mid-latitudes. The stations include (a) KVTX, (b) FCI1, and (c) CN05 at northern mid-latitudes (NM); (d) LUCP, (e) POVE, and (f) PAAR at equatorial latitudes (EQ); (g) SALU, (h) SJSP, and (i) SMAR at low





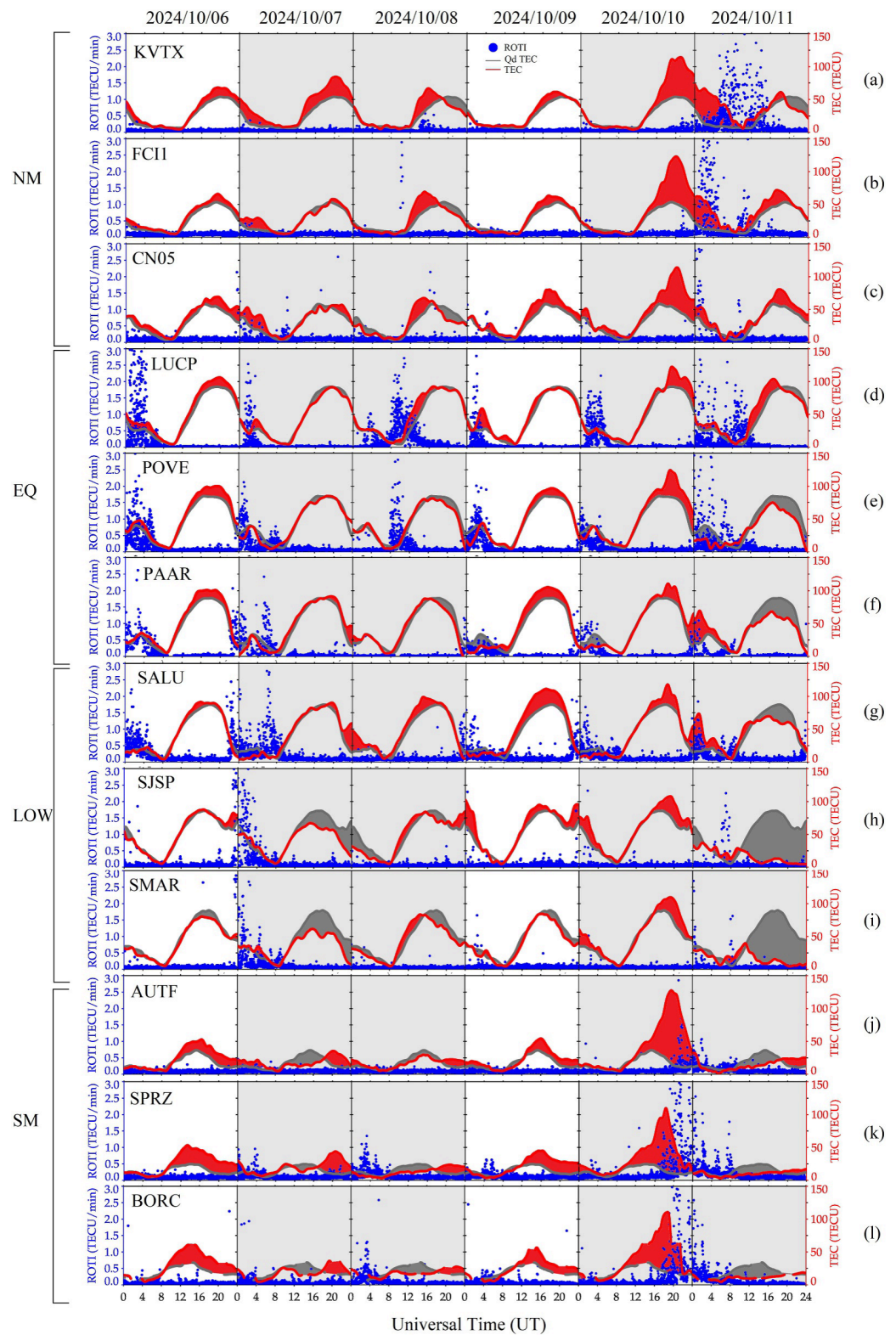
**Figure 4.** Sequence of ROTI maps from (a–l) 23:00 UT on 10 October to 11:00 UT on 11 October 2024. The solid red line indicates the magnetic equator, while the dashed line represents the sunset/sunrise line.

latitudes (LOW); and (j) AUTF, (k) SPRZ, and (l) BORC at southern mid-latitudes (SM). The panels display ROTI (blue dots), TEC (red), and the quiet-time average TEC (gray).

Focusing on the equatorial region, EPBs are known to initiate at the geomagnetic equator and then grow along magnetic field lines, extending to other locations (Kelley, 2009; Rishbeth, 2000). Figure 5 shows that during the first geomagnetic storm (7–8 October), we observe that EPBs were suppressed during the PRE hours at this location, whereas on other days elevated ROTI values were detected during the PRE period. Conversely, at the equatorial stations LUCP and POVE, irregularities occurred later, during post-midnight hours, the same observed in Figure 2. Irregularities of lower intensity compared to other analyzed days ( $<1.5$  TECU/min) were also observed at two southern mid-latitude stations (SPRZ and BORC), indicating possible auroral activity. Additionally, during the second geomagnetic storm (10–11 October), ionospheric irregularities of high ROTI intensity and long duration were observed at nearly all analyzed stations, with the exception of stations on the eastern side (PAAR, SALU, SJSP, and SMAR).

During the first geomagnetic storm (7–8 October), different responses were observed across latitudinal regions. At northern mid-latitudes (KVTX, FC11, CN05), a positive ionospheric storm was observed at KVTX, with TEC enhancements of  $\sim 30$  TECU near 20:00 UT on 7 October, while FC11 and CN05 showed less pronounced responses, remaining close to quiet-time levels. On the following day, all northern mid-latitude stations exhibited a positive ionospheric storm between 12:00 and 16:00 UT, with enhancements of  $\sim 25$  TECU. In the equatorial region (LUCP, POVE, PAAR), TEC values remained near quiet-time averages, indicating no significant storm-time enhancements. At low latitudes (SALU, SJSP, SMAR), a clear negative ionospheric storm occurred on 7 October, with TEC depletions of  $\sim 50$  TECU at SMAR and SJSP. Southern mid-latitudes (AUTF, SPRZ, BORC) experienced a weak positive ionospheric storm, with TEC increases below 30 TECU around 20:00 UT.





**Figure 5.** ROTI and TEC time series for 12 GNSS stations distributed across different latitudinal regions and longitudinal sectors of Latin America. Panels (a–c) correspond to northern mid-latitude stations (KVTX, FCI1, CN05); (d–f) to equatorial stations (LUCP, POVE, PAAR); (g–i) to low-latitude stations (SALU, SJSP, SMAR); and (j–l) to southern mid-latitude stations (AUTF, SPRZ, BORC). Each panel shows ROTI (blue dots), absolute TEC (red line), and the quiet-time average TEC (gray line) during 6–11 October, 2024.

During the second geomagnetic storm (10–11 October), northern and southern mid-latitudes experienced a pronounced positive ionospheric storm on 10 October, with TEC enhancements reaching  $\sim 100$  TECU at 18:00 UT, strongest at mid-latitude stations near the EIA crest. At the same time, equatorial (LUCP, POVE, PAAR) and low-latitude stations (SALU, SJSP, SMAR) showed a positive ionospheric storm with enhancements of  $\sim 30$  TECU. A second positive storm of  $\sim 30$  TECU was observed around 00:00 UT at two stations only (PAAR and SALU). On the following day, a strong negative ionospheric storm occurred, with TEC depletions of  $\sim 75$  TECU at SJSP and SMAR, indicating significant disturbance dynamo effects.

## 4. Discussions

### 4.1. Moderate Geomagnetic Storm (G2)—7 October 2024

Analyzing the moderate geomagnetic storm shown in Figure 2, we observe that  $B_z$  remains predominantly southward throughout most of the analyzed period (from 7 October at 14 UT to 8 October at 12 UT). However, there is a weak northward incursion of  $B_z$  between 21 and 23 UT. It is also important to note that AE values remain elevated during the entire period, indicating continuous energy input into the auroral region. These conditions suggest the possible occurrence of overshielding PPEF during the evening, with the electric field directed westward on the dayside, which typically contributes to a downward movement of the  $F$  layer (Fejer et al., 2008). However, no significant changes in layer altitude were observed during this period. At local sunset,  $h'F$  reached 407 km at JICA, approximately 7% below the quiet-time reference of 436 km, indicating that this variability likely had little impact on the suppression of irregularities. At SALU,  $h'F$  reached 462 km, nearly 5% above the quiet-time reference of 441 km.

Additionally, the observed  $B_y$  reversal during this period may have contributed to reducing the storm-time effects on the  $F$ -layer. This is likely associated with a reduction in magnetospheric convection and, consequently, in the variability of the convective electric field, driven by the combined influence of the  $B_z$  and  $B_y$  components. When these components are purely southward and westward respectively, magnetospheric convection tends to be symmetric, as magnetic flux is deposited uniformly in the magnetotail across both hemispheres. This symmetric convection affects regions from high to low latitudes. However, when the  $B_y$  component becomes significantly positive or negative, in conjunction with southward  $B_z$ , it introduces asymmetries in magnetic flux deposition in the tail region. This leads to an asymmetric magnetotail configuration of the magnetic field lines, which alters plasma circulation and modifies the dynamics of the electric field. These asymmetries can significantly impact ionospheric electrodynamics, including the development and morphology of storm-time disturbances (Grocott et al., 2005, 2008; Grocott & Milan, 2014; Pitkänen et al., 2013, 2018, 2019).

The influence of the  $B_z$  component on the strength of magnetospheric and ionospheric convection is well established (e.g., Dai et al., 2024; Sonnerup, 1980). In contrast, the contribution of the dusk–dawn  $B_y$  component is not yet fully understood. Nonetheless, a non-zero  $B_y$  is known to introduce significant plasma flow asymmetries in the high-latitude ionosphere, leading to distortions of the standard two-cell convection pattern. This occurs because  $B_y$  alters the location and geometry of dayside and tail magnetic reconnection, twisting the polar cap potential pattern. On the nightside, the sign of  $B_y$  largely determines which of the two convection cells—the evening or the morning cell—extends further into the midnight sector. These convection asymmetries exhibit opposite configurations in the Northern and Southern Hemispheres, with the pattern reversed across the noon–midnight meridian (e.g., Heppner & Maynard, 1987; Pitkänen et al., 2024; Reiff & Burch, 1985; Ruohoniemi & Greenwald, 2005). The sign of the  $B_y$  component drives significant asymmetries in high-latitude ionospheric electrodynamics. A non-zero  $B_y$  twists the dayside magnetic reconnection site, unequally loading the magnetotail lobes, which distorts the ionospheric convection pattern. The effects are not directly symmetrical between the hemispheres. Instead, they exhibit a mirror-like reversal: A positive  $B_y$  shifts convection in the Northern Hemisphere toward dawn and in the Southern Hemisphere toward dusk, whereas a negative  $B_y$  produces the opposite pattern.

Hui and Vichare (2021) investigated the influence of  $B_y$  on plasma drifts in the equatorial ionosphere using simulations. They found that this parameter can reduce the PPEF over the equatorial region, with particularly strong effects near the sunrise and sunset terminators. Their results also showed that a strong  $B_y$  component decreases the vertical plasma drift at these local times. Moreover, when  $B_z$  is near zero, a positive  $B_y$  enhances the morning PRE, consistent with our observations, but weakens the sunset PRE, whereas a negative  $B_y$  produces the opposite effect. These findings suggest that  $B_y$  introduces an asymmetric dawn–dusk response in plasma drifts.



Moreover, we can observe that  $h'F$  at JICA and SALU becomes similar to the reference curve, at local sunset,  $h'F$  reached 407 km at JICA (Qd: 436 km) and 462 km at SALU (Qd: 441 km), with the vertical drift at that time showing significant PRE values ( $>40$  m/s). This is particularly intriguing, as such conditions are typically associated with the generation of EPBs during this period and time, but EPBs were suppressed at both stations. Typically, EPB suppression during geomagnetic storms is attributed to the DDEF or overshielding PPEF (Carter et al., 2016; Fejer, 1991; Fejer et al., 2008; Zakharenkova et al., 2019). However, for this mechanism to be responsible, the F-layer would be expected to descend, and the vertical drift should be less than 40 m/s. Yin et al. (2023) investigated a weak geomagnetic storm on 22 November 2020, over the Brazilian sector and found that EPBs were suppressed due to the absence of a significant PRE. Their results indicate that a PPEF caused a downward shift of the F-layer during the sunset hours. Abdu et al. (2006) reported that EPBs can be generated with a PRE  $\geq 38$  m/s. Huang and Hairston (2015) also showed that when the PRE exceeds 40 m/s, the occurrence rate of Spread F irregularities/EPBs is greater than 80%. However, in the analyzed case, although the PRE value was favorable for the generation of EPBs, they were suppressed.

The east–west longitudinal variability may also contribute to the differences observed between these regions due to their distinct characteristics, including local time differences between the western sector (LT = UT – 5) and eastern sector (LT = UT – 2.5), a longitudinal separation of approximately  $33^\circ$  ( $\sim 3,000$  km), variations in magnetic declination angle, and other regional factors. Carmo et al. (2021) reported a longitudinal dependence in the duration of ionospheric irregularities between these two regions during the St. Patrick's Day geomagnetic storm. Geomagnetic declination is the main difference between these regions and plays a crucial role in the evolution and suppression of plasma irregularities (e.g., Abdu et al., 1981; Batista et al., 1986; Tsunoda, 1985). Specifically, JICA exhibits a declination angle of  $-3.25^\circ$ , whereas SALU has  $-19.17^\circ$ , as shown in Table 1. Abdu et al. (1992) demonstrated that geomagnetic declination can modulate the PRE of the zonal electric field, which in turn controls the development of EPBs. They found that the growth rate of plasma irregularities decreases when the solar terminator is nearly aligned with the magnetic meridian, as this reduces the PRE. Conversely, smaller declination angles favor stronger PRE and thus more efficient development of EPBs. These findings indicate that geomagnetic declination contributes to the observed longitudinal differences in EPB occurrence between the two regions. Furthermore, Carmo, Pi, et al. (2022) reported EPBs persisting after sunrise and suggested that magnetic declination may also explain the longitudinal differences in the duration of these post-sunrise events. Additionally, the geomagnetic declination angle plays a crucial role in the seasonality of EPBs across these regions. The seasonality of the PRE has been studied in both sectors and is known to precede the occurrence of plasma irregularities, such as EPBs or spread-F. In the Brazilian sector (SALU), EPBs typically occur from October to March (Barros et al., 2018; Carmo et al., 2023; Sobral et al., 2002), whereas in the Peruvian sector (JICA), their occurrence is concentrated around the equinoxes — March, April, September, and October (Chapagain et al., 2009). Therefore, the present study, conducted in October, falls within the period of highest EPB occurrence for both sectors, allowing a direct comparison under favorable conditions for plasma irregularity development.

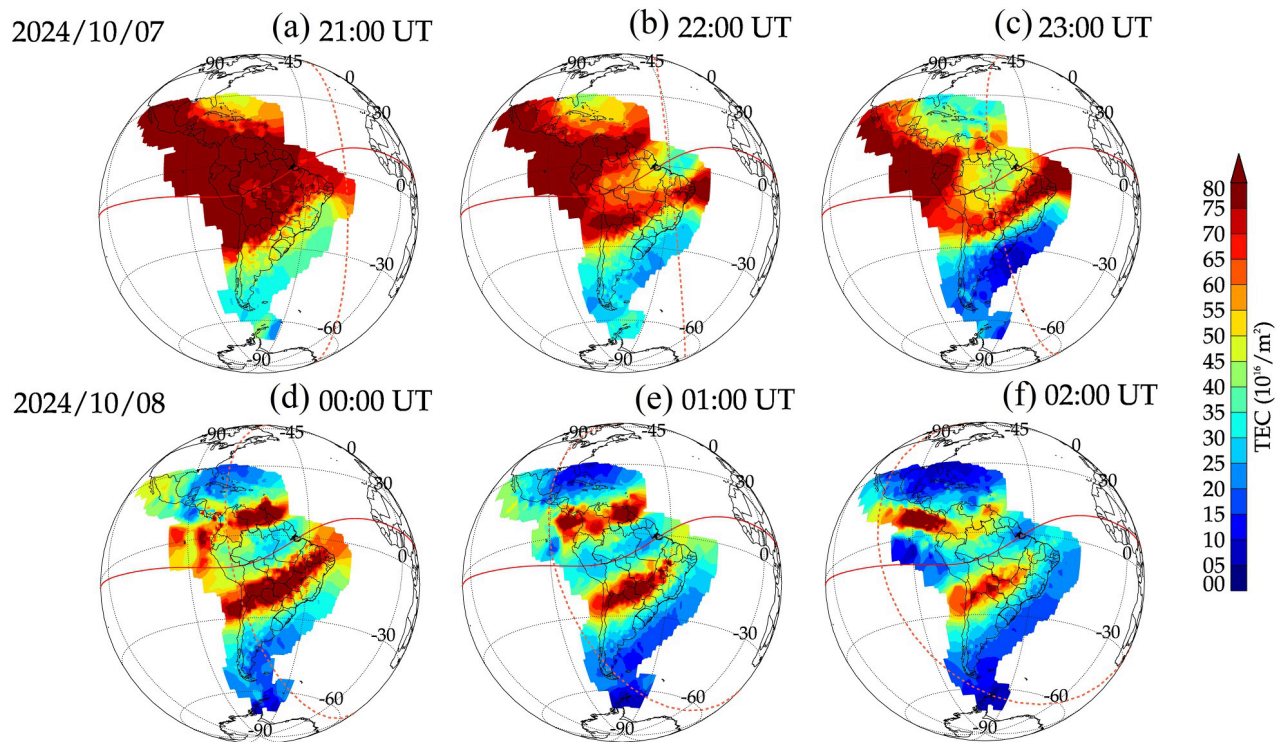
In addition, Rama Rao et al. (1997) studied several factors that contribute to the generation of Spread F/EPBs independently of PRE, including (a) a well-developed EIA, (b) the EIA crest located around  $18^\circ$  latitude, (c) the vertical movement of the F layer, and (d) the direction and magnitude of meridional winds. To thoroughly investigate what contributed to the vertical drift maintaining values favorable for the development of PRE capable of seeding EPBs, we must consider other factors that may have played a crucial role in the lack of irregularity formation. By analyzing the growth rate equation of the Rayleigh-Taylor instability (RTI):

$$\gamma = \frac{\sum_F}{\sum_F + \sum_E} \left( V_z - U - \frac{g}{\nu_{in}} \right) \frac{\Delta n_0}{n} - \beta_T \quad (3)$$

$\sum_F$  and  $\sum_E$  represent the Pedersen conductivity integrated along the magnetic field lines for the E and F layers, respectively.  $V_z$  is the vertical plasma drift,  $U$  is the neutral wind velocity,  $g$  is the gravity,  $\nu_{in}$  is the ion-neutral collision frequency,  $n$  is the plasma density, and  $\beta_T$  is the recombination rate of the major ion species (Kelley, 2009).

Theoretical models of RTI growth rate and conductivities do not capture the day-to-day variability relevant to this case study, as demonstrated in the Supporting Information S1 and corroborated by Vital et al. (2024).





**Figure 6.** TEC map sequence from (a–f) 21:00 UT on 7 October to 02:00 UT on 8 October 2024.

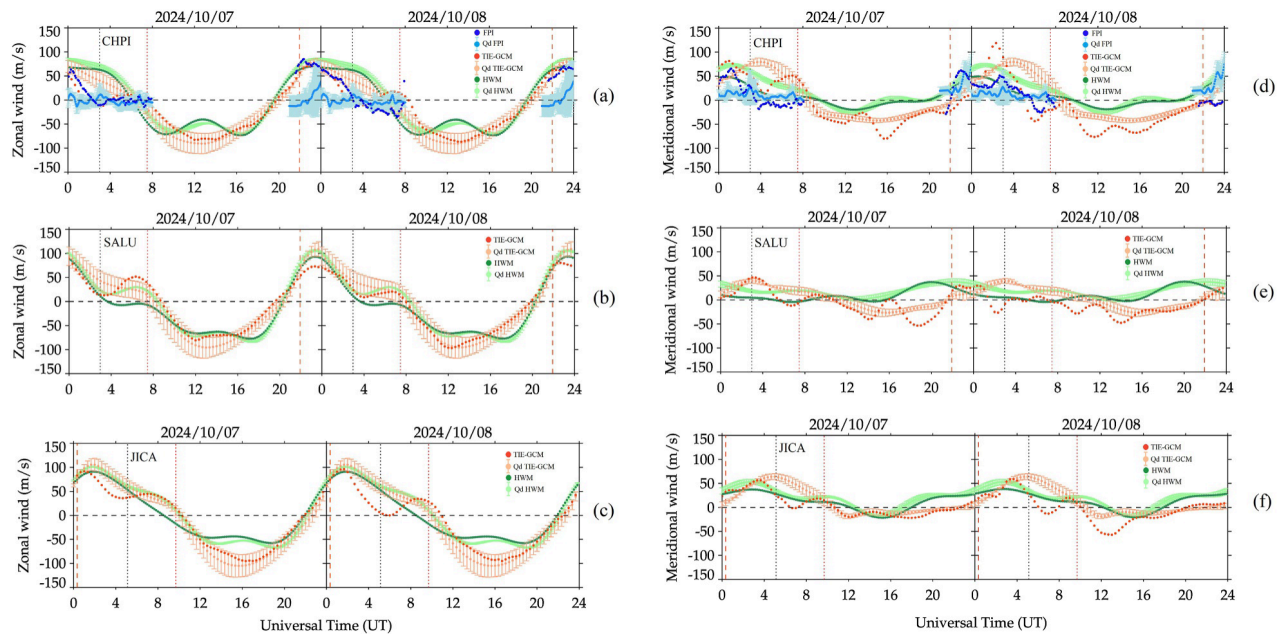
Analyzing Equation 3, we identify the key factors that contribute to the development of EPBs:

- $\gamma$  must be positive ( $\gamma > 0$ ) for irregularities to develop;
- Meridional winds ( $U$ ) can reduce the plasma density gradient along magnetic field lines, leading to a decrease in  $\gamma$ . Additionally, they can enhance both conductivity and the recombination rate, further reducing  $\gamma$ ;
- Zonal winds can intensify the zonal electric field, thereby increasing  $\gamma$ ;
- E-region conductivity contributes to a reduction in  $\gamma$ ;
- An increase in plasma density enhances  $\gamma$ , thereby favoring the growth of irregularities.

As evident, the formation of EPB is not governed by a single factor but rather by the interplay of multiple processes.

By analyzing the parameters of the growth rate equation along with the factors considered by Rama Rao et al. (1997), we observe from Figure 5 that the TEC in the equatorial region did not show any significant increase compared to the quiet-time curve during dusk hours. Additionally, Figure 6 presents a sequence of TEC maps from 21:00 UT on 7 October to 02:00 UT on 8 October, revealing an enhancement of the EIA following the passage of the solar terminator. This behavior is expected under effective PRE conditions (e.g., Astafyeva et al., 2015; Fagundes et al., 2016, 2025). Therefore, neither EIA intensity nor plasma density appear to have contributed to the suppression of EPBs. In contrast, Aa et al. (2022) conducted a study showing that EIA and EPB suppression were associated with a downward  $E \times B$  plasma drift, which reduced the growth rate of the RTI over the American sector following the Tonga volcano eruption. This was the expected outcome, however, in this case, we observed an upward plasma drift along with EIA development, but EPBs were absent.

Winds also play a crucial role in the growth rate of the RTI, and they were analyzed in this case as well. Figure 7 shows the temporal evolution of the neutral winds from 7 to 8 October 2024, separated into zonal (panels a–c) and meridional (panels d–f) components for the three stations: CHPI, SALU, and JICA. This figure compares the FPI observations (blue) with the TIE-GCM (red) and HWM (green) model results, along with their respective wind average of the three geomagnetically quietest days (Qd) of the month (13, 21, and 25 October, 2024) displayed in lighter shades and accompanied by standard deviation error bars.



**Figure 7.** Zonal (panels a–c) and meridional (panels d–f) neutral winds from 7 to 8 October 2024, together with quiet-time reference curves and their associated standard deviations (shown as error bars). The Fabry–Perot Interferometer (FPI) observations are shown in blue, the TIE–GCM model in red, and the HWM model in green. The corresponding quiet-time (Qd) reference curves are indicated by lighter shades of the same colors. They are presented for CHPI (a, d), SALU (b, e), and JICA (c, f). Vertical dashed orange lines and dotted red lines denote the local sunset and sunrise times, respectively, while vertical dotted black lines indicate local time midnight.

Figure 7 shows the variations in zonal and meridional winds with relative to the Qd reference. The zonal wind is initially directed eastward, reaching a maximum velocity of 85 m/s at 22:22 UT, and then shifts to westward around 03:00 UT. Meanwhile, the meridional component begins with a southward flow, registering  $-29$  m/s at 21:34 UT (near sunset), and reverses to a northward direction, peaking 62 m/s at 23:00 UT. Krall et al. (2009) explain that when the meridional wind is uniform and strong, it enhances the field line-integrated Pedersen conductivity, which in turn reduces the growth rate of the RTI, thereby suppressing the development of EPBs. In addition, Huba (2024) reviewed this topic and reported that modeling studies show that ionospheric conductance decreases (increases) when the meridional wind is equatorward (poleward), which suggests that poleward winds suppress irregularities. He has shown that meridional winds exert a conditional influence on the generalized RTI: strong, uniform winds suppress EPB. Conversely, gradients or non-uniform wind structures can enhance the growth rate and favor EPB development. Considering the strong wind near sunset, compared with the quiet-time curve, shown in Figure 7, the post-sunset suppression of EPBs observed on 7 October appears to be consistent with the mechanism reported by Krall et al. (2009) and Huba (2024). Even though the PRE vertical drift ( $V_z > 40$  m/s) was strong, this condition alone was not sufficient to trigger the development of EPBs. Although the thermospheric winds presented in Figure 7 may provide insight into a possible cause of EPB suppression, it is important to acknowledge that these measurements were obtained from a single station (CHPI) and may not capture longitudinal or latitudinal variations in the thermospheric wind field.

The HWM14 and TIE–GCM models were also used to compare with FPI measurements. It is noted that, in this case, the HWM14 does not reproduce the observed wind values at CHPI (panels a and d), and the quiet-time curve shows values very similar to the disturbed conditions. In contrast, the TIE–GCM model exhibits some variability relative to the quiet-time reference curve. The TIE–GCM meridional wind at sunset is consistent with the values measured by the FPI. However, the model does not capture the subsequent reversal and northward intensification observed after this time. At certain intervals, this model reproduces trends similar to the observations, but with amplified magnitudes, as seen in the period shortly before midnight.

Although the models do not fully reproduce the observed conditions at CHPI, at SALU we observe in the TIE–GCM model a pre-sunset intensification of the meridional wind. This enhancement is again evident shortly before midnight relative to the quiet-time reference curve. In contrast, at JICA both models show little or no variation during the analyzed period. Therefore, no robust conclusions can be made for this location.



Additionally, a second key point to highlight during this storm is the development of post-midnight EPBs on 8 October, occurring only on the western side of the Latin American sector. From Figure 2, we observe that after 05:00 UT (local midnight),  $B_z$  remains southward with a brief northward incursion, while  $h'F$  at JICA begins to rise. This suggests the possible influence of an overshielding PPEF or a DDEF—both of which are typically eastward on the nightside and can contribute to the uplift of the F layer. These conditions are commonly associated with the generation of EPBs during these local times (e.g., Carmo, Denardini, et al., 2022; Carmo, Pi, et al., 2022). Although there is a gap in  $h'F$  data shortly afterward, it is evident that the F layer rose compared to quiet-time conditions, with a  $V_z$  of approximately 40 m/s. In contrast, at SALU, the F layer also shows an uplift relative to the quiet reference, but the  $V_z$  only reached 22 m/s, which is not sufficient to trigger irregularities in this case. Carmo, Denardini, et al. (2022) reported an unusual occurrence of EPBs during a moderate geomagnetic storm on 17 February 2015, near 08:00 UT, when  $h'F$  reached 400 km—about 100 km higher than the Qd reference. In the present case,  $h'F$  reached 350 km, also showing a 100 km difference compared to the Qd reference. Although the F-layer rose to a similarly elevated altitude in both cases, EPBs developed in the 2015 event, while in the current case they were absent.

To understand why irregularities developed only on the western side, further analysis of some data sets is necessary. From Figure 7, we observe variations in both zonal (panel a) and meridional (panel d) winds compared to quiet-time conditions during this period (~04:00 UT). This data is from CHPI, located on the eastern side. Also, as mentioned earlier, the TIE-GCM model shows a significant variation in the meridional wind at SALU (Figure 7e) prior to local midnight relative to the quiet-time reference curve. Unfortunately, wind data for JICA is not available for this day, preventing a direct comparison, and the models used do not accurately reproduce the conditions, as shown in Figure 7. Nevertheless, wind remains a crucial factor influencing the growth rate of instabilities and the development of irregularities (Huba, 2024; Huba & Krall, 2013; Huba & Lu, 2024; Krall et al., 2009).

In addition, another important factor to consider is the presence of a sporadic E (Es) layer near the onset time of EPBs. Figure 8 presents ionograms from JICA (a) and SALU (b) during the analyzed hours, and the critical frequency of the sporadic E layer (foEs, green) at JICA (c) and SALU (d) on 7–8 October. At JICA, we observe Spread F (blue arrows), which is associated with the presence of EPBs. In contrast, at SALU, Spread F is not observed. However, we do see sporadic E layers (Es, red arrows). Also, foEs (panels c and d) shows the time intervals when Es layer occurs and the corresponding critical frequency. The gray bars indicate the presence of Spread F at both stations. Carrasco et al. (2005) showed that the Es layer can influence the development of the PRE. According to Stephan et al. (2002), enhancement of the E layer during the evening hours can lead to Spread F suppression, together with a reduction in the vertical plasma drift associated with the PRE. These Es layers presented in Figure 8 may have contributed to enhanced E-region conductivity, which in turn could reduce  $\gamma$  on the eastern side, thereby suppressing irregularity development. Although the present analysis does not focus on evening hours, a similar influence may still be relevant.

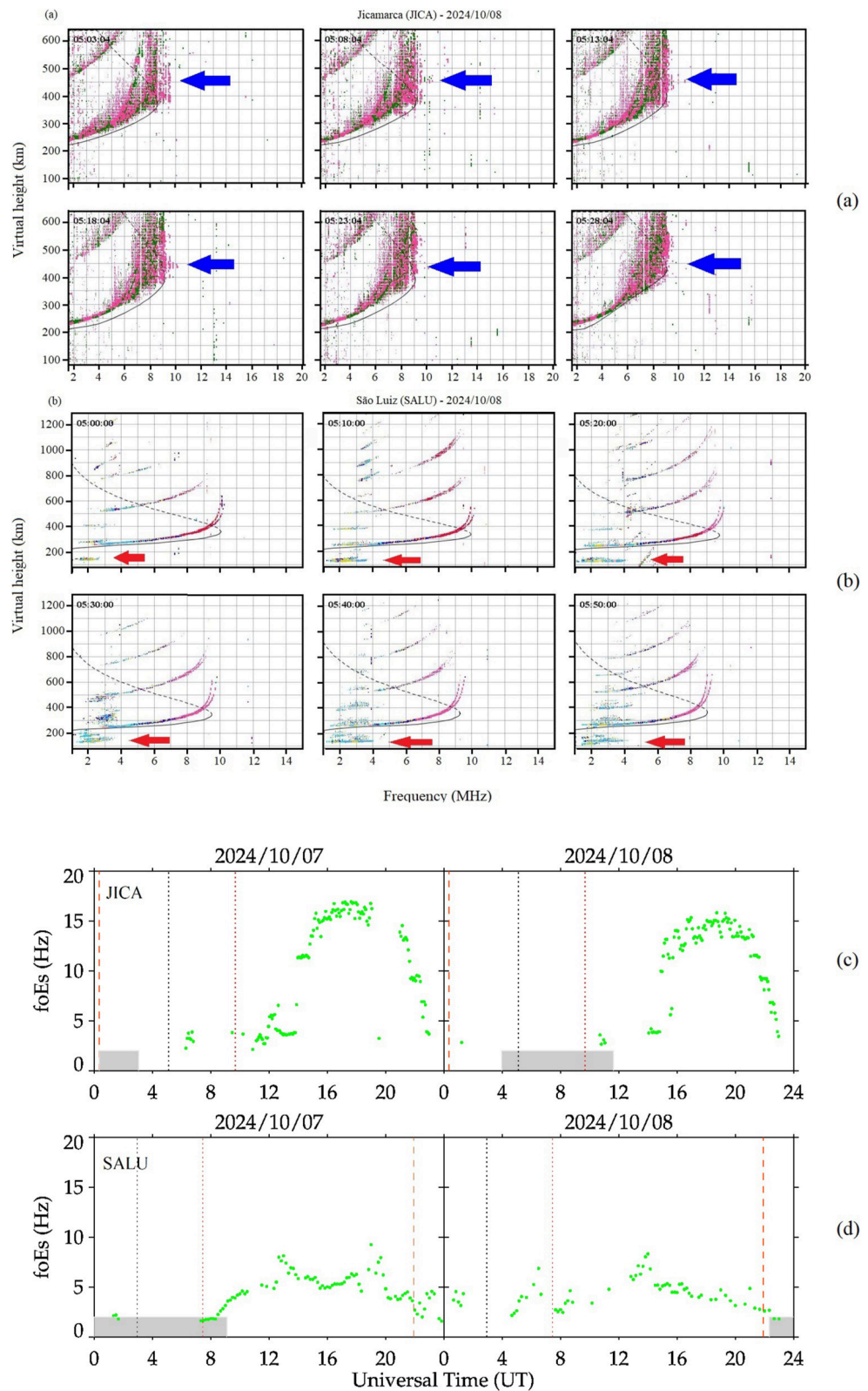
It is also important to note that Es layers are observed during the PRE hours at both stations, which may have contributed to the suppression of EPBs during this period (e.g., Stephan et al., 2002). Therefore, the influence of meridional winds and the presence of Es layers are considered plausible mechanisms for EPB suppression at sunset and on the eastern side near midnight, based on the available observations and models, although further analysis is needed to support and confirm this interpretation.

This moderate geomagnetic storm generated EPBs on the western side of the Latin American sector after local midnight, which persisted after sunrise. The characteristics of these EPBs were analyzed using keogram data. Figure 9 presents ROTI keograms at (a)  $-10^\circ$  and (b)  $-20^\circ$  geographic latitude. The EPBs exhibited a zonal drift velocity of about 80.30 m/s at the geographic latitude of  $-10^\circ$  and 76.62 m/s at  $-20^\circ$ , indicating westward propagation, and a duration of approximately 7h.

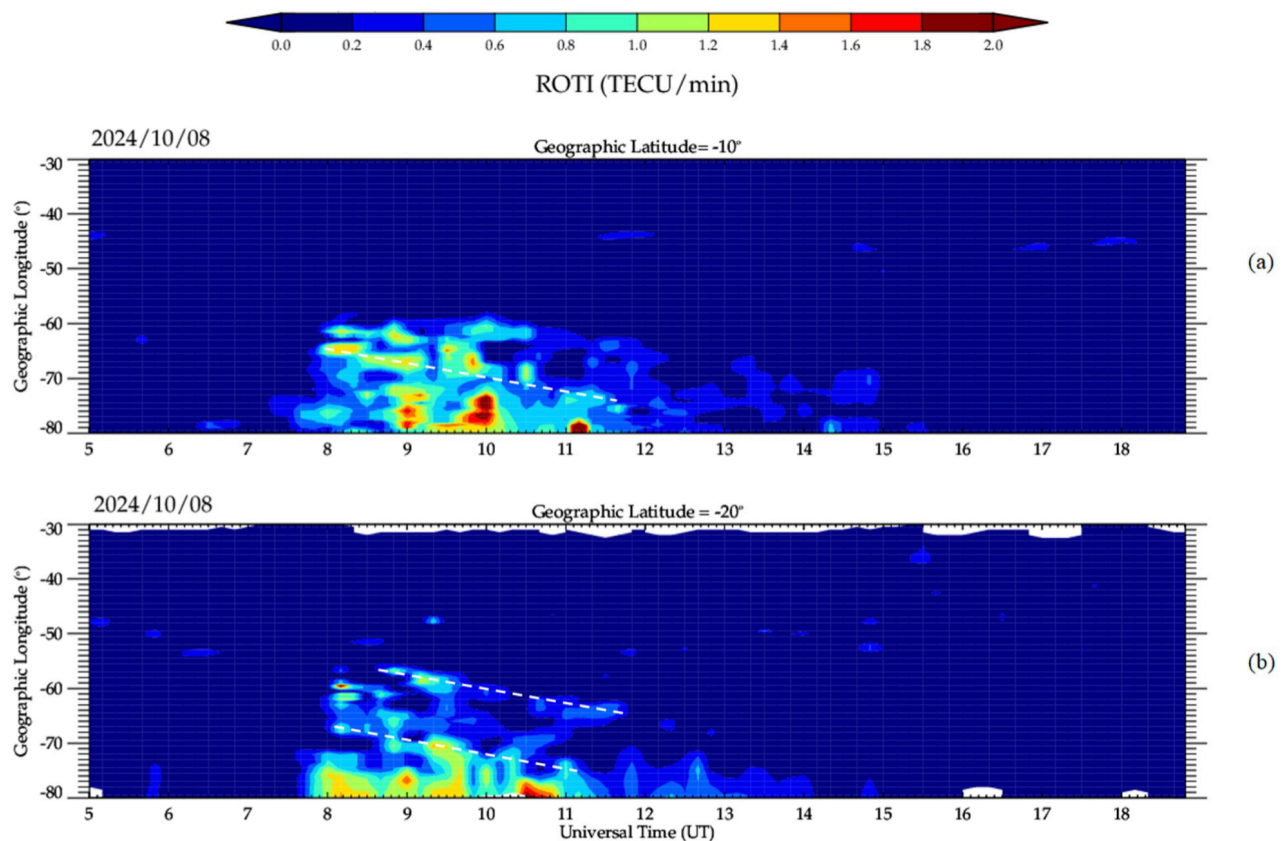
#### 4.2. Severe Geomagnetic Storm (G4)—10 October 2024

The second event analyzed in this article is a severe geomagnetic storm that occurred on 10 October. From Figure 2, we observe that between 16 UT and 22 UT,  $B_z$  fluctuates between southward and northward directions with significant amplitude, and then becomes steadily southward until 10 UT on 11 October, with AE values remaining very high ( $AE > 1,000$  nT), indicating intense auroral activity. Two key moments can be highlighted: first, at the dusk,  $h'F$  at both JICA and SALU shows elevated values compared to the quiet-time reference,





**Figure 8.** Ionograms from JICA (a) and SALU (b) on 8 October, and foEs (green) at JICA (c) and SALU (d) on 7–8 October. Blue arrows indicate the presence of Spread F, while red arrows highlight the occurrence of sporadic E layers (Es), and the gray bars indicate the occurrence of Spread F.



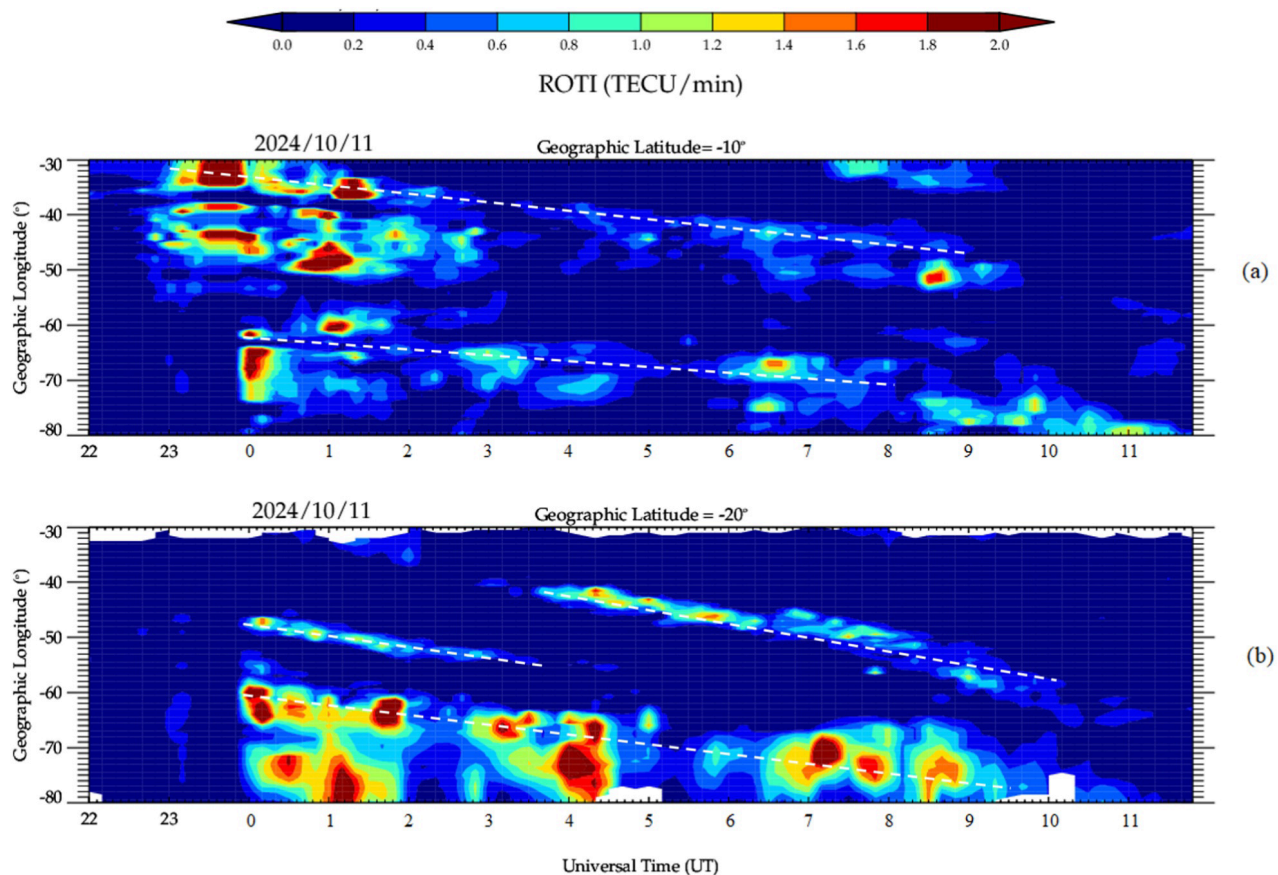
**Figure 9.** ROTI keograms at (a)  $-10^\circ$  and (b)  $-20^\circ$  geographic latitude on 8 October 2024.

consistent with  $V_z > 40$  m/s at both stations; second, after 04 UT on 11 October, the F layer ( $h'F$ ) rises again at both stations relative to quiet conditions. Interestingly, during this second uplift,  $V_z$  at JICA does not show significant values, while at SALU it approaches 40 m/s. The initial uplift is likely associated with an undershielding PPEF, which is eastward on the dayside and promotes upward plasma drift (Fejer, 1991; Fejer et al., 2008). The second (post-midnight) uplift appears to result from a competition between electric fields. The undershielding PPEF, associated with southward  $B_z$  and high AE values at this time, is westward on the nightside and tends to drive the layer downward, however, this downward motion is not observed in the  $h'F$  data. Instead, the observed upward motion of the plasma indicates that the DDEF, which is eastward at night, dominated in this case, compensating for the westward PPEF and allowing the F layer to rise. This interpretation is also supported by Zakharenkova et al. (2025), who studied the same 10 October storm and reported that the second post-midnight EPB was more intense than the one observed earlier in the evening.

As suggested by numerous studies, EPBs are often intensified at dusk by an eastward electric field associated with undershielding PPEF, and can persist after sunrise due to the influence of DDEF effects or overshielding PPEF (e.g., Carmo, Denardini, et al., 2022; Carmo, Pi, et al., 2022; Carmo et al., 2024; Carter et al., 2016; Fejer, 1991; Fejer et al., 2008; Zakharenkova et al., 2019). These EPBs exhibited distinct characteristics, as revealed by the keogram shown in Figure 10. The figure presents ROTI keograms at geographic latitudes of (a)  $-10^\circ$  and (b)  $-20^\circ$ , covering the period from 10 October at 22 UT to 11 October at 12 UT. The EPBs structures are clearly visible in both panels, with a duration of approximately 12 hr. The zonal drift velocity was about 64.25 m/s at the geographic latitude of  $-10^\circ$  and 53.64 m/s at  $-20^\circ$ , indicating westward propagation.

The geomagnetic storm that occurred on 10 May 2024, has been widely studied around the globe (e.g., Ambili et al., 2025; Carmo et al., 2024; Fagundes et al., 2025; Pierrard et al., 2025). In that event, Carmo et al. (2024) reported several characteristics of the EPBs generated, including a zonal drift velocity, propagation direction, duration, latitudinal extension, and apex height, corresponds to 140 m/s, westward direction, lasting for 12 hr,  $-50^\circ$  GLAT ( $\sim 36^\circ$  MLAT), 4,500 km, respectively. In comparison, during the 11 October (severe) geomagnetic





**Figure 10.** ROTI keograms at geographic latitudes of (a)  $-10^{\circ}$  and (b)  $-20^{\circ}$ , from 10 October at 22 UT to 11 October at 12 UT.

storm, the EPBs exhibited a slower drift velocity than those observed during the 10 May (extreme) storm. However, the direction of propagation and duration were the same, along with other similar characteristics. Singh et al. (2025) also reported that, in the October event, the latitudinal extension reached  $-50^{\circ}$  GLAT, corresponding to a comparable apex height, further reinforcing the similarities in EPB development despite the difference in storm intensity. Also, Zakharenkova et al. (2025) reported that super-EPBs during this storm reached apex heights of  $\sim 3,500$ – $4,000$  km ( $40^{\circ}$  MLAT). They further demonstrated that the mid-latitude portions of these structures migrated westward, indicating enhanced westward drifts, consistent with the observations in the present study. Moreover, they attributed the intense post-midnight EPBs, which persisted beyond sunrise, to long-lasting DDEF effects during the storm's recovery phase. They also reported that EPBs on the eastern side were less intense than those on the western side, consistent with our observations (see Figures 2d, 2f and 4). Their model results indicated that the PPEF during the evening hours enhance the PRE. In addition, the main difference between both sectors is the magnetic declination angle, which could contribute to the intensification of the observed irregularities. We also noted that during this storm, the PRE reached a vertical drift of 142 m/s at JICA at 23:33 UT and 53.75 m/s at SALU at 20:40 UT on 10 October.

In addition, the behavior of the EIA can be analyzed using the TEC data shown in Figure 5. During this storm, we observed that on 10 October, TEC increased significantly across all sectors—not only above the anomaly crests. A poleward direction of the EIA crest was also noted, with exceptionally high TEC values reaching up to 125 TECU at mid-latitude stations, representing an enhancement of about 100 TECU compared to the quiet-time reference. This TEC increase is typically associated with an undershielding PPEF, which aligns well with the conditions observed during that period. Additionally, on the following day, we observed a notable decrease in TEC, particularly at equatorial and low-latitude stations. This behavior is characteristic of the recovery phase of a geomagnetic storm and is primarily attributed to the effects of the DDEF (Fagundes et al., 2016). Carmo et al. (2024) reported that during the Mother's Day geomagnetic storm of 2024, the positive ionospheric storm was



three times stronger than that observed during the St. Patrick's Day storm in 2015. The TEC values recorded were very similar to those analyzed in the present study, and both storms exhibited a poleward expansion of the EIA.

Comparing the two storms analyzed here (7 and 10 October, 2024), we observe intriguing differences in vertical plasma drift ( $V_z$ ) values associated with both EPB development and suppression. In the first storm, EPBs were suppressed on the eastern side after midnight, with  $V_z$  around 22 m/s. In contrast, during the second storm,  $V_z$  at Jicamarca (on the western side) reached 27 m/s after midnight, and EPBs were still present at that time. These results suggest that vertical drifts do not necessarily need to exceed 40 m/s to generate EPBs at these times, lower values may still contribute to their triggering under favorable conditions.

Analyzing the severity of the October storms, we observe that geomagnetic indices (particularly AE and Kp) were significantly higher during the severe storm, as expected. The Kp index reflects the intensity and spatial extent of magnetospheric convection, the AE index is also strongly influenced by convection (Thomsen, 2004). Therefore, the intensified magnetospheric convection during the severe storm likely contributed to undershielding PPEFs, which may have facilitated the development of super and long-lasting EPBs.

## 5. Conclusions

Two levels of geomagnetic storms were analyzed (G2 and G4) to investigate their impacts over the Latin American sector as a detailed case study. These events exhibited notably different behaviors. The main findings are summarized below:

Moderate geomagnetic storm (G2):

1. An uncommon suppression of Post-sunset EPBs was observed despite vertical drifts exceeding 40 m/s.
2. The generation of post-midnight EPBs was limited to the western sector of Latin America around 04:00 UT, likely driven by eastward electric fields on the nightside. In contrast, no EPB were observed in the eastern sector.
3. The EPBs suppression at sunset and in the eastern sector after midnight may be associated with the influence of meridional winds and the presence of an Es layer. However, additional observations are needed to further support this interpretation. The wind hypothesis is suggested by the CHPI data but cannot be confirmed at the equatorial stations where EPBs originate.
4. The characteristics of the EPBs included a westward zonal drift velocity of 80.30 m/s (at  $-10^\circ$  latitude) and 76.62 m/s (at  $-20^\circ$  latitude), with a duration of about 7 hr.

Severe geomagnetic storm (G4):

5. An intensification of vertical drift ( $V_z$ ) favorable for EPBs development was observed during the main phase of the storm, likely driven by undershielding PPEF. The persistence of EPBs after sunrise suggests a contribution from DDEF effects during the storm's recovery phase.
6. The characteristics of the EPBs included a westward zonal drift velocity of 64.25 m/s (at  $-10^\circ$  latitude) and 53.64 m/s (at  $-20^\circ$  latitude), with a duration of about 12 hr. Being slower than the EPBs from the extreme storm of May 2024.
7. A significant enhancement of the EIA, including a poleward direction of the anomaly crests, was observed. This behavior is consistent with the presence of undershielding PPEF during the storm's main phase.
8. The significant decrease in TEC during the recovery phase in the equatorial and low-latitude regions suggests the influence of DDEF effects.
9. Stronger magnetospheric convection—reflected in elevated AE and Kp indices—plays a crucial role in generating PPEFs, which in turn can enhance the development and persistence of super EPBs.

This study provides new insights into the behavior of EPBs in response to geomagnetic storms of different intensities. We reveal that EPB suppression can occur even under favorable conditions. These findings enhance our understanding of ionospheric irregularities and suggest promising directions for future research. A statistical analysis of EPB suppression events under high vertical drift conditions could provide valuable insight into the underlying mechanisms and support the development of more reliable prediction models for EPB occurrence.

## Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

## Availability Statement

GNSS receiver data (RINEX) for Brazil was obtained from the Instituto Brasileiro de Geografia e Estatística (IBGE, <https://www.ibge.gov.br/geociencias/downloads-geociencias.html>), and for other stations across Latin America from UNAVCO (<https://www.unavco.org/data/gps-gnss/gps-gnss.html>). Wind data was sourced from the Madrigal database (<https://www.igp.gob.pe>). The models used in this study were the Horizontal Wind Model 2014 (HWM14, <https://ccmc.gsfc.nasa.gov/models/HWM14-2014/>) and the Thermosphere–Ionosphere Electrodynamics General Circulation Model (TIE-GCM 3.0, <https://ccmc.gsfc.nasa.gov/models/TIE-GCM-3/>). Interplanetary medium parameters (Bz, By, Kp, Dst, and AE indices) were provided by OMNIWeb (<https://omniweb.gsfc.nasa.gov>). Ionosonde data was obtained from the Brazilian Studies and Monitoring of Space Weather (Embrace/INPE) website (<https://www2.inpe.br/climaespacial/>). Declination and dip angle values for each station were taken from the IGRF model ([http://geomag.bgs.ac.uk/data\\_service/models\\_compass/igrf\\_calc.html](http://geomag.bgs.ac.uk/data_service/models_compass/igrf_calc.html)). Sunrise information was obtained from <https://www.timeanddate.com/sun/>, and TEC software from <https://seemala.blogspot.com/>.

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