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## RESEARCH ARTICLE

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### Key Points:

- The total electron content and electron density values were higher for the October 2024 than the May 2024 storm
- The two geomagnetic storms triggered and inhibited the occurrence of ionospheric irregularities during the storms' main phase
- There was a reverse longitudinal trend in the percentage occurrence rate of ionospheric irregularities during the two geomagnetic storms

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## Longitudinal Variation of Ionospheric Irregularities and Response of the Ionosphere During 10–13 May and 10–13 October 2024 Geomagnetic Storms

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**Abstract** We examine the response of the ionosphere to the 10–13 May 2024 and 10–13 October 2024 geomagnetic storms, the two recent great geomagnetic storms of solar cycle 25. We identified the occurrence of ionospheric irregularities during the two geomagnetic storms. We used percentage change in vertical total electron content ( $\Delta VTEC\%$ ) computed using VTEC data from three equatorial ground-based global navigation satellite system (GNSS) receivers in the American, African, and Asian sectors, to study the ionospheric response. In order to determine the occurrence of ionospheric irregularities, we employed the rate of change of electron density (Ne) index (RODI) from Swarm-A satellite (Sw-A) and the rate of change of TEC index (ROTI) from the GNSS TEC. Our results revealed a positive ionospheric storm over the African sector during the main phase of May storm; whereas a negative ionospheric response was recorded over the American sector. In contrast, during the October storm, a positive ionospheric storm effect was observed over the American and African sectors and a negative over the Asian sector. Additionally, we identified that the October storm had a higher percentage irregularity occurrence rate than the May storm. During the main phases of the two storms, irregularities were triggered over the African sector and inhibited over the American and Asian sectors. Sw-A showed a longitudinal trend in the occurrence rate of irregularities during the May storm, with America having the lowest rate, followed by Africa and Asia. During the October storm, this longitudinal dependence is reversed.

**Plain Language Summary** We investigated the response of the ionosphere to the two major geomagnetic storms that occurred on 10–13 May 2024 and 10–13 October 2024, which were among the most intense storms of solar cycle 25. Using data from global navigation satellite system (GNSS) receivers and the Swarm-A satellite (Sw-A), we examined changes in total electron content (TEC) and electron density to identify storm time ionospheric responses and occurrence of irregularities. A magnitude of greater than 50% change in VTEC was considered as a significant response. The May 2024 storm produced strong positive ionospheric response over Africa and negative response over the American sector during the main phase while for the October storm the ionosphere responded positively over the American and African sectors, and negatively over the Asian sector. Irregularities were more frequent and intense during the October storm, with the highest occurrence over America, followed by Africa and the lowest over the Asian longitude sectors, though this trend reversed during the May storm. These results provide new insights into how geomagnetic storms influence ionospheric plasma structure and can help improve space weather prediction and modeling.

## 1. Introduction

The Earth's ionosphere responds to both solar and geomagnetic disturbances in a complex way spatially and temporally due to its dynamic nature (Kelley, 2009). The temporary disturbance in the Earth's magnetic field as a result of a space weather phenomenon such as coronal mass ejection (CME), corotating interaction region (CIR)

or solar flare is referred to as a geomagnetic storm (Dessler & Parker, 1959). Geomagnetic storms, which result from enhanced solar wind-magnetosphere interactions, can significantly impact ionospheric plasma, leading to irregularities that disrupt radio communications, navigation systems, and space-based technologies (Kintner et al., 2007; Moldwin, 2008). These storm-induced electric field perturbations redistribute ionospheric plasma, leading to the formation of plasma density irregularities, especially in equatorial and low-latitude regions (Bagiya et al., 2011; Remya et al., 2025). Ionospheric irregularities are often observed as plasma depletions along satellite tracks, scintillations, traveling ionospheric disturbances (TIDs) and variations in the Rate of change of Total Electron Content Index (ROTI) (Aol et al., 2020; Burke et al., 2004; Ondede et al., 2022). They exhibit strong longitudinal and latitudinal dependencies due to geomagnetic field geometry, thermospheric winds, and electrodynamic processes (Yizengaw & Groves, 2018). The knowledge of longitudinal dependence of ionospheric irregularities plays a pivotal role in space weather research since it is necessary for assessing their impacts on satellite communications, global navigation satellite system (GNSS) accuracy, and in identifying the longitudinal input during ionospheric modeling. This is because even at the same latitude, the ionosphere behaves differently at different longitudes as a result of non-uniform geomagnetic field, zonal electric fields, thermospheric winds, and solar terminator effects. The temporal dependence of GNSS cycle slip is related to ionospheric irregularities over the global low latitude region (e.g., Li et al., 2025). Therefore, it is important to study the characteristics and evolution of ionospheric irregularities especially during geomagnetic storms.

The two recent severe geomagnetic storms that occurred on 10–13 May 2024 and 10–13 October 2024 were among the greatest geomagnetic storms since 1957 when Disturbance storm time (Dst) index, an index used to measure the severity of a geomagnetic storm, was first estimated (Campbell, 1996; Krishnendu et al., 2025; Sugiura & Wilson, 1964). The 10–13 May 2024 and 10–13 October 2024 geomagnetic storms reached a minimum Dst index of  $-406$  nT and  $-333$  nT, respectively. Not only did the two geomagnetic storms cause an impact on the Earth's ionosphere that led to adverse effects on the technological systems but also led to the visibility of some beautiful auroras extending to low latitudes. The geomagnetic storms in May and October 2024 were both caused by CMEs from the Sun. The Gannon or Mother's day (10 May 2024) geomagnetic storm was the biggest geomagnetic storm (reaching G5 levels) to hit the Earth in over two decades. The 10–13 May 2024 storm was triggered by multiple CMEs from a large active region (AR 3664) on the Sun, while the 10–13 October 2024 storm was triggered by a powerful X-class solar flare from active region AR 3848 and subsequent CME from another active region. This flare was one of the strongest of solar cycle 25, causing a powerful CME directed toward Earth that led to a geomagnetic storm of G4 levels. The 10–13 May 2024 storm led to increased drag on satellites due to higher density at low Earth orbit altitudes (Parker & Linares, 2024). These two severe geomagnetic storms have gained great attention because of the impact they made on the Earth's ionosphere (e.g., Ahmad et al., 2025; Astafyeva et al., 2025; Chernogor et al., 2025; Danilchuk et al., 2025; Gordiyenko et al., 2025; Jain et al., 2025; Kuai et al., 2026; Lee et al., 2025; Pierrard et al., 2025; Song et al., 2025; Themens et al., 2024; Tulasi Ram et al., 2024; Zakharenkova et al., 2025). However, their distinct temporal and longitudinally localized effects on the Earth's ionosphere have not been highlighted in any study. In addition, the two geomagnetic storms in this study occurred during the same day but in different seasons, though most studies looked at each geomagnetic storm in isolation. For example, Danilchuk et al. (2025) studied the impact of the 10–13 May 2024 extreme geomagnetic storm on the ionosphere and GNSS positioning utilizing ROTI and global ionospheric maps to analyze the ionospheric dynamics. They found that during this geomagnetic storm's main phase the auroral oval expanded down to low latitudes to about  $30^{\circ}\text{N}$  in the American sector and down to  $45^{\circ}\text{N}$  in the European–Asian sector. The ROTI peaked at 2 TECU/min, which was four times as much against the background TEC and the equatorial anomaly crest intensified considerably (up to 200 TECU) resulting into a poleward shift in the American sector (Danilchuk et al., 2025). Pierrard et al. (2025) examined the effects of the two storms on the ionosphere and plasmasphere over Europe, USA, and South Korea. They found that during the two events the plasmasphere was eroded leading to a shift in the location of the plasmapause to lower radial distances smaller than 2  $R_{\text{E}}$  (Earth's radii) in the post-midnight sector. Due to lack of statistics pertaining to the rare occurrence of the extreme geomagnetic storms in addition to their unique differences, it is not feasible to make satisfactory predictions of the effects of such rare but dangerous events (Danilchuk et al., 2025). For example, Lee et al. (2025) investigated the spatiotemporal and altitude variations in ionospheric F-region electron density in response to the superstorm of 10 May 2024 using COSMIC-2, Spire and FengYun-3 radio occultation observations. The authors found out that the electron density decreased globally during the main phase of the storm within the F-region altitude between 200 and 500 km. The peak electron density height increased/decreased during daytime/nighttime in low latitude region. Spogli et al. (2024) studied the effects of the geomagnetic storm

of 10–13 May 2024 on the Mediterranean region with a focus on Italy and found out that the ionosphere over that region responded negatively during the main phase of that storm as indicated by a decrease in critical frequency of the F2 layer ( $f_oF_2$ ) and TEC measurements and were attributed to changes in the neutral composition of the thermosphere. Hence, it is of great interest to study each new extreme storm to add on the existing literature of these rare events. In this study, we examined the two geomagnetic storms in tandem to determine the physical and electrodynamic processes underlying the response of the ionosphere to these two storms.

The similarity and difference in the geomagnetic storms of 10–13 May and October 2024 has not been addressed, given that the two storms occurred in the same solar cycle and different seasons in summer and fall, respectively. Most of the recent studies have been done on the Gannon storm but less on the geomagnetic storm of 10 October 2024. In addition, the longitudinal variability of irregularities that either occurred or were inhibited by the two geomagnetic storms has not been examined to determine the possible mechanisms and dynamics that triggered the two geomagnetic storms. Examining the longitudinal characteristics, particularly their dependence on storm phases, local time (LT), and geomagnetic conditions, is the objective of this study. Such a comparative study of the two storms to analyze their occurrence characteristics, similarity or difference, has not been done to determine whether they had the same driving mechanisms triggered by CME-driven shock. This study investigates the longitudinal variation of ionospheric irregularities during the May and October 2024 geomagnetic storms, two significant space weather events that provided an opportunity to examine storm time dynamics across different regions.

## 2. Data and Methods

In this study, the solar wind and geomagnetic conditions during the two geomagnetic storms were characterized using geophysical parameters and geomagnetic indices. The geophysical parameters and geomagnetic indices were downloaded from NASA Space Physics Data Facility (2020). These parameters included the Plasma speed ( $V_{sw}$ ), Plasma temperature (T), Planetary K ( $K_p$ ) index, Dst index, the auroral indices (AE, AU, AL), and the z-component of the interplanetary magnetic field (IMF Bz). We also computed change in Dst index with time ( $d/dt(\text{Dst})$ ) which gives the history of the Dst index and helps to track the development of the geomagnetic storm.

Data from selected GNSS receivers were used and were downloaded from International GNSS Service (2024). We analyzed the response of the ionosphere and the occurrence of ionospheric irregularities across the three longitude sectors of American, African, and Asian. GNSS receivers São Luís, SALU (2.59°S, 44.2°W geographic, and 0.25°S geomagnetic), Addis Ababa, ADIS (9.04°N, 38.8°E geographic, and 0.18°N geomagnetic), and Guam island, GUUG (13.43°N, 144.8°E geographic, and 5.66°N geomagnetic) represent American, African and Asian sectors, respectively. To check whether the increase in EEJ and vertical  $\mathbf{E} \times \mathbf{B}$  drifts during the local daytime caused a positive ionospheric storm over Jicamarca (JICA), we used a nearby IGS station of Arequipa (AREQ, Peru, 16.47°S, 71.49°W geographic, and 3.61°S geomagnetic). The map in Figure 1 shows the geographic locations of the IGS receiver sites and magnetometer stations used in the current study.

The GNSS data files were downloaded in Receiver INdependent EXchange (RINEX) format. The RINEX data were extracted into readable files using the GPS-TEC analysis software developed at Boston College (Seemala & Valladares, 2011) with vertical TEC (VTEC) and slant TEC (STEC) among the output parameters at a temporal resolution of 30 s. The software uses thin shell approximation at an ionospheric height of 350 km. We averaged VTEC at every hour for all visible satellites at elevation angles greater than or equal to 40° to obtain the final VTEC. This was aimed at reducing multipath effects (e.g., Habyarimana et al., 2023; Rama Rao et al., 2006; Seemala & Valladares, 2011).

The VTEC was used to compute its percentage deviation from the background (taken as the mean VTEC of the five international quietest days at a particular station in a particular month) (e.g., Johnston, 1943; Matzka et al., 2021). The five international quietest days were downloaded from International Service of Geomagnetic Indices (2024). This was then used to reveal the occurrence of positive or negative ionospheric storms during the geomagnetic storms under this study. The percentage deviation in VTEC can fairly approximate the departure of disturbed time VTEC values from quiet mean values (e.g., Dugassa et al., 2020; Dugassa & Habyarimana, 2025; Geleta & Tsidu, 2025; Habyarimana et al., 2023; Immel & Mannucci, 2013; Matamba et al., 2015) and is expressed as Equation 1:

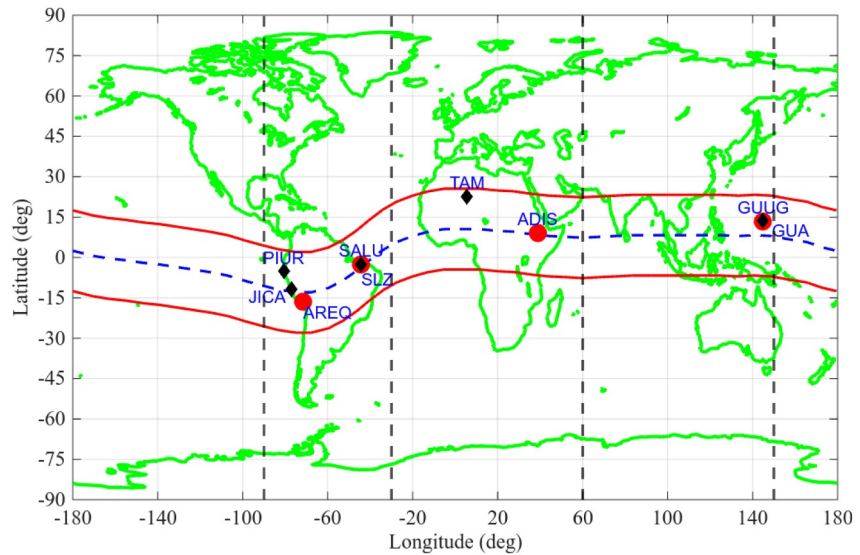


**Figure 1.** Map showing the locations of IGS receivers and magnetometers used in this study. The red dots indicate the locations of the IGS stations of Arequipa (AREQ), São Luís (SALU), Addis Ababa (ADIS), and Guam island (GUUG). The black diamonds show the magnetometer stations of Jicamarca (JICA), Piura (PIUR), São Luís (SLZ), Tamanrasset (TAM), and Guam (GUA). The blue dotted curve represents the geomagnetic equator. The two red solid curves represent the equatorial ionization anomaly region. The black dotted lines indicate the boundaries of the American, African, and Asian sectors.

$$\Delta \text{VTEC}(\%) = \frac{\text{VTEC}_{\text{ob}} - \text{VTEC}_q}{\text{VTEC}_q} \times 100\%, \quad (1)$$

where  $\text{VTEC}_q$  is mean of the five international quietest days in a month and  $\text{VTEC}_{\text{ob}}$  is the VTEC value during the geomagnetic storm day. The threshold for positive and negative ionospheric storm effects was taken to be  $\pm 50\%$ . The STEC was used to compute Rate of change of TEC (ROT) using Equation 2 (Pi et al., 1997):

$$\text{ROT}_{(t)} = \frac{\text{STEC}_{(t+\Delta t)} - \text{STEC}_{(t)}}{\Delta t}, \quad (2)$$

where  $\Delta t$  is the difference between two successive time epochs, usually 30 s for GNSS receivers. We used STEC instead of VTEC for ROT computation because vertical ROT is used to describe irregularities along the zenith of the stations (e.g., Nie et al., 2022). Since the irregularities are highly localized along the actual line of sight, using VTEC to compute ROT index (ROTI) might smooth out some of the small scale fluctuations (Carmo et al., 2021; Sieradzki & Paziewski, 2019). The ROTI is derived from the variance of ROT by finding its standard deviation over a 5 min interval (e.g., Dugassa & Habyarimana, 2025; Habyarimana et al., 2023; Pi et al., 1997), to quantify the intensity of ionospheric irregularities using Equation 3.

$$\text{ROTI} = \sqrt{\langle \text{ROT}^2 \rangle - \langle \text{ROT} \rangle^2}. \quad (3)$$

The ROTI has been widely used to characterize ionospheric irregularities on both local and global scales due to the availability and extensive coverage of GNSS receivers world wide (Blagoveshchensky et al., 2018).

The Swarm-A satellite (Sw-A) in situ electron density (Ne) data were also used to infer ionospheric irregularities associated with the geomagnetic storm events. The Level-1b plasma density data were downloaded from European Space Agency (2024) and converted into a readable format for analysis. We removed data whose Langmuir Probe (LP) Flags were equal to 9 and Ne Flags were greater than 20 or when Ne was negative. This is because Swarm satellite measurements with Ne Flags greater than 20 are considered to arise from low gain probe estimates. On the other hand, measurements when the LP Flags are equal to 9 arise from duplicated harmonic

mode due to an ongoing sweep (e.g., Nielsen, 2021; Okoh et al., 2025). Hence, “good” data were obtained after applying the above two data quality flags. The satellite data were then filtered to retain measurements within the geographic region of interest. The Ne data were organized according to universal time (UT), geographic latitude, and longitude to allow comparison with ground-based observations. Subsequently, the Sw-A tracks were used to identify regions of enhanced equatorial ionization anomaly (EIA) and plasma irregularities. Finally, the processed Sw-A observations were analyzed alongside the GNSS-derived TEC measurements to investigate the response of the ionosphere and occurrence of irregularities during the two geomagnetic storms of 10–13 May 2024 and 10–13 October 2024. This combined approach allowed for a comprehensive assessment of ionospheric variability using both satellite- and ground-based observations. Rate of change of Ne index (RODI) measures the fluctuations in Ne and is defined in a way similar to ROTI with Ne in the place of STEC, and taken as the standard deviation of ROD with a running window of 10 s, or 20 s (Dugassa et al., 2023; Dugassa & Habyarimana, 2025; Jin et al., 2022; Zakharenkova et al., 2016). In this study, we used RODI computed using a standard deviation of 10 s so as to capture small scale fluctuations in Ne.

$$\text{RODI} = \sqrt{\langle \text{ROD}^2 \rangle - \langle \text{ROD} \rangle^2}, \quad (4)$$

with

$$\text{ROD} = \frac{d\text{Ne}}{dt} = \frac{\text{Ne}(t + \Delta t) - \text{Ne}(t)}{\Delta t}, \quad (5)$$

where Ne is the electron density of the ionospheric plasma,  $t$  is the time at which the electron density measurement ( $\text{Ne}(t)$ ) is recorded,  $\Delta t$  is the time interval between two consecutive measurements of electron density computed using the reciprocal of the Sw-A satellite data, and  $\text{Ne}(t + \Delta t)$  is the electron density measured at time  $t + \Delta t$ . The Sw-A RODI data were then filtered to retain measurements within the American, African, and Asian longitude sectors that spanned between  $-90$  to  $-30$ ,  $-30$  to  $60$ , and  $60$  to  $150^\circ$ , respectively.

We used magnetometer data from International Real-time Magnetic Observatory Network, INTER-MAGNET (2024), Low Latitude Ionospheric Sensor Network, LISN (2026), and Estudo e Monitoramento Brasileiro do Clima Espacial, EMBRACE (2026) to support the conclusions about the driving mechanisms that were responsible for the observations on the response of the ionosphere during the two storms. We used data from Jicamarca (JICA, Peru;  $11.95^\circ\text{S}$ ,  $76.87^\circ\text{W}$  geographic and  $0.8^\circ\text{N}$  geomagnetic) and Piura (PIUR, Peru;  $5.2^\circ\text{N}$ ,  $80.6^\circ\text{W}$  geographic and  $6.8^\circ\text{N}$  geomagnetic) to compute EEJ using differential magnetometer approach (e.g., Anderson et al., 2002; Astafyeva et al., 2025; Yizengaw et al., 2014). During this approach, a pair of magnetometers located at the equator and off the equator by  $6$ – $9^\circ$  are used (e.g., Anderson et al., 2004; Yizengaw & Moldwin, 2009). We removed different offsets from the magnetometer data set using nighttime baseline values,  $H_0$  in the H-component of the Earth's magnetic field which were determined by averaging H-component values within 23:00 LT to 03:00 LT. These baseline values were then subtracted from the corresponding magnetometer measurements (e.g., Habarulema et al., 2026; Yizengaw et al., 2014) to obtain  $dH$  values.

$$dH_m = H - H_0, \quad (6)$$

where  $H$  is the H-component of the Earth's magnetic field at the magnetometer station,  $m$  and  $H_0$  is the corresponding nighttime baseline value. The  $dH$  values from the two pairs of magnetometers were then directly subtracted to estimate EEJ, which was used as a proxy of daytime ionospheric vertical  $\mathbf{E} \times \mathbf{B}$  drifts. Hence,

$$\Delta H = dH_{\text{JICA}} - dH_{\text{PIUR}}. \quad (7)$$

The  $\Delta H$  data was then averaged in 1-min bin with 15-min windows to remove small pulses during the storm times and reserve main disturbances suitable for ionospheric storm observations (e.g., Zhang et al., 2024). We note that over the African and Asian sectors there were no two pairs of magnetometer stations with data during the period of the two storms from which EEJ would be computed. We further used the three magnetometer stations of São Luís (SLZ, Brazil;  $2.59^\circ\text{S}$ ,  $44.2^\circ\text{W}$  geographic, and  $0.25^\circ\text{S}$  geomagnetic) collocated with SALU, Tamanrasset (TAM, Algeria;  $22.79^\circ\text{N}$ ,  $5.53^\circ\text{E}$  geographic and  $9.22^\circ\text{N}$  geomagnetic), and Guam (GUA, collocated with GUUG IGS

station) to derive daytime ionospheric currents over American, African, and Asian sectors, respectively during the two storms of May and October 2024. The variation in the H-component of the Earth's magnetic field was previously used by Fathy et al. (2014) and Younas et al. (2021) to estimate ionospheric disturbance currents,  $D_{\text{iono}}$ . The  $Dp_2$  (Ddyn) associated with prompt penetration electric fields (PPEF) (disturbance dynamo electric fields (DDEF)) was extracted from  $D_{\text{iono}}$  using a high pass filter with periods lower than 4 hr (band-pass filter with a diurnal period) (e.g., Fathy et al., 2014; Habyarimana et al., 2023; Teshome, 2026). The vertical drifts were obtained from Jicamarca Unattended Long-Term studies of the Ionosphere and Atmosphere (JULIA) and from the Neural Network Vertical Drift (NNVD) model developed by Habarulema et al. (2026). The NNVD model was downloaded from Habarulema and Okoh (2026).

### 3. Results

#### 3.1. Solar Wind and Geomagnetic Conditions of May and October 2024

Figure 2 shows the solar wind characteristics and the geomagnetic storm indices on 8–15 May 2024 (top panels, (a)–(e)) and 8–15 October 2024 (bottom panels, (f)–(i)).

In Figure 2 (top panels), between 8 and 9 May 2024, the two days were quiet as seen from the Dst and Kp indices (Figure 2c). The Kp and Dst indices were less than 2 and approximately 0 nT, respectively. The plasma speed was between 400 and 520 km/s (Figure 2b). The plasma temperature was about  $1 \times 10^5$  K and the solar flux index (F10.7) during the day of the storm main phase was 218 SFU (solar flux units, Figure 2a). The rate of change of Dst index fluctuated around 0 nT/hr (Figure 2d). There were no data for the auroral indices during these two quiet days (Figure 2e). At the initial stages, while the activity was occurring on the Sun, Earth's magnetosphere and the ionosphere remained relatively calm, the auroral oval shifted equatorward and possibly the network of observatories operating at high latitudes were not able to detect the presence of auroral electrojets flowing in the auroral oval (Valach et al., 2025). The IMF Bz component fluctuated between  $-5$  and 3 nT. On 10 May 2024, the solar wind speed significantly increased from 400 km/s to 750 km/s within less than half a day, while the plasma temperature rapidly increased between  $1 \times 10^5$  to  $1 \times 10^6$  K. Plasma temperature helps to understand the dynamics of geomagnetic storms because it regulates the energy, pressure, and composition of the space plasma surrounding the Earth (Forsyth et al., 2014). The fluctuations in plasma temperature during the storm of May 2024 indicate that the plasma temperature affected the transfer of energy from the solar wind and magnetosphere to Earth's ionosphere, influencing the intensity of the ionospheric storms. The Kp index increased to 9 while the Dst index decreased up to a minimum of  $-406$  nT. The rate of change of the Dst index fluctuated and attained a minimum of about  $-125$  nT. The auroral indices (AU, AL, and AE) fluctuated with positive fluctuations being exhibited by the AE and AU indices while the negative fluctuations by AL index. The AE and AL indices almost reached a maximum and minimum of 2,000 nT and  $-2,000$  nT, respectively while the maximum value of AU index was about 1,200 nT. The IMF Bz fluctuated and reached a minimum of about  $-35$  nT. A series of four shocks were seen during the geomagnetic storm between 10 and 11 May 2024 (e.g., Krishnendu et al., 2025). All these abrupt changes in the indices indicate the storm onset (initial and main phases) which modified the geomagnetic indices. The recovery phase of the storm showed fluctuations in the plasma temperature until when it attained values less than  $2 \times 10^5$  K. The plasma speed reached a maximum value of 1,000 km/s and started decreasing drastically. The Kp index reduced to about 6 and finally to values less than 3. The Dst index kept on fluctuating and did not go to zero, implying that the storm took more than 5 days to recover and attain the quietest conditions. In fact, as the storm was recovering a second storm with a minimum Dst index of  $-100$  nT occurred on 13 May 2024. The impact of this second storm, while still significant, was less severe than the first. The sudden storm commencement (SSC) for this second storm was noted at 21:00 UT on 12 May 2024, marking the onset of the second storm (Krishnendu et al., 2025). The fluctuation in the rate of change of Dst index was close to zero, implying that the index was recovering with time. The auroral indices kept on fluctuating but there was no data for these indices on 15 May 2024. The fluctuations in the IMF Bz were between  $-5$  and 5 nT during the recovery phase.

On October 2024 (Figure 2 bottom panels), the plasma speed (Figure 2g) and temperature (Figure 2f) abruptly increased from 400 km/s to about 750 km/s and from  $1 \times 10^5$  K to  $12 \times 10^5$  K, respectively. This was the initial phase (SSC) of the geomagnetic storm as depicted by an increase in the Kp index (Figure 2h) and a minimum excursion in Dst index reaching a value of  $-333$  nT during the early hours of 11 October 2024. The rate of change of Dst index (Figure 2i) demonstrated fluctuations in the change arising from the occurrence and disturbance in

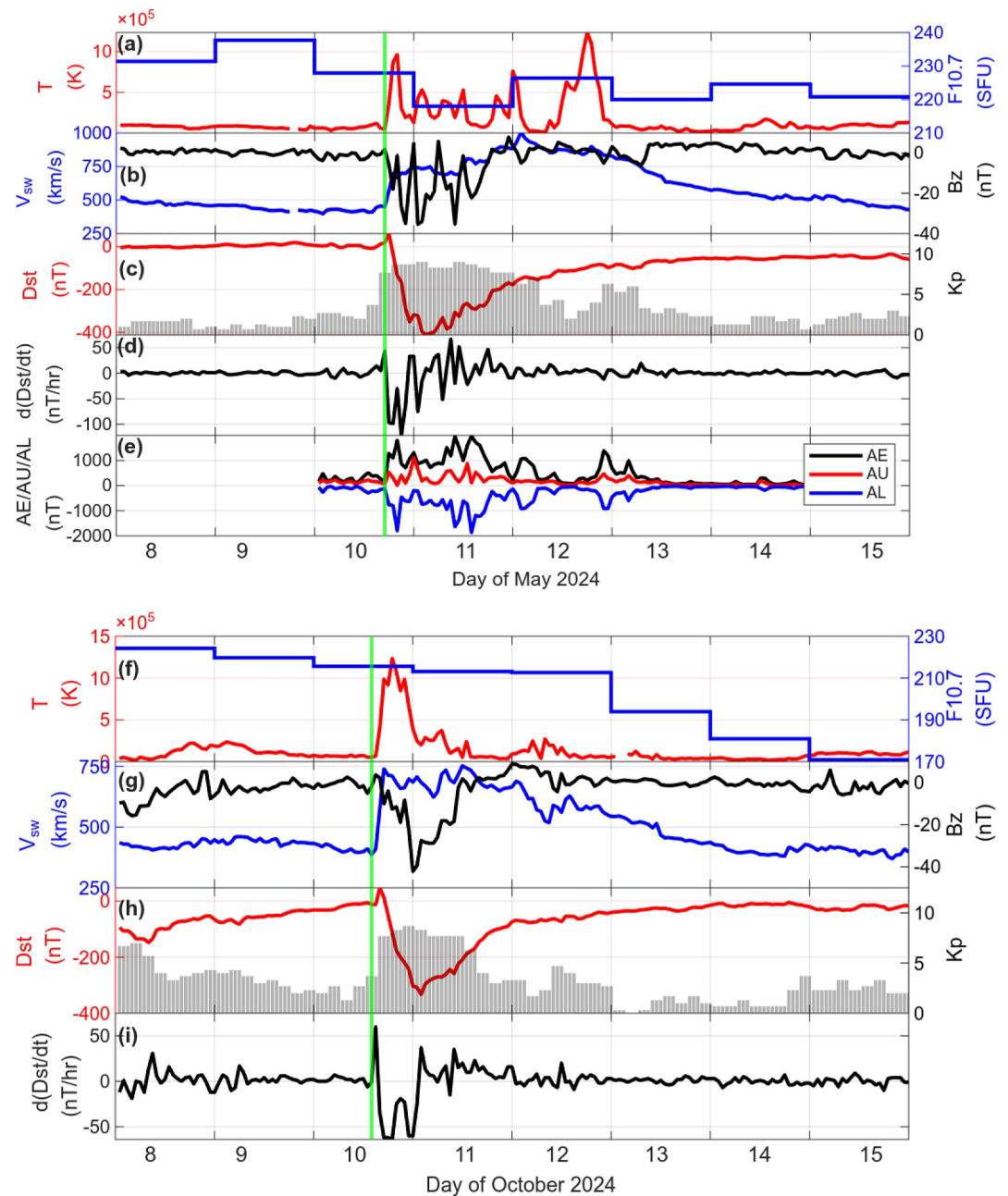


**Figure 2.** Solar wind characteristics for the geomagnetic storms of 8–15 May and 8–15 October 2024. The panels represent the F10.7, Plasma speed, Plasma temperature, Kp index, Dst index, change in Dst index with time, AE, AU, AL indices, and the IMF Bz. The auroral indices were not available for the geomagnetic storm of 8–15 October 2024 and during 8–9 May 2024. The green vertical line indicates the time (in universal time, UT) of sudden storm commencement.

the ring current. The maximum fluctuation occurred at a coinciding time with the time of SSC. The auroral indices had no data possibly due to the effects of the storm. The IMF Bz exhibited a minimum value of about  $-42$  nT during the storm SSC. The F10.7 value during the main phase of the storm was 213 SFU (Figure 2a).

### 3.2. The Response of the Ionosphere to the Two Geomagnetic Storms

Figure 3 shows the variation of VTEC over the three IGS stations during the geomagnetic storms of 8–15 May and October 2024.

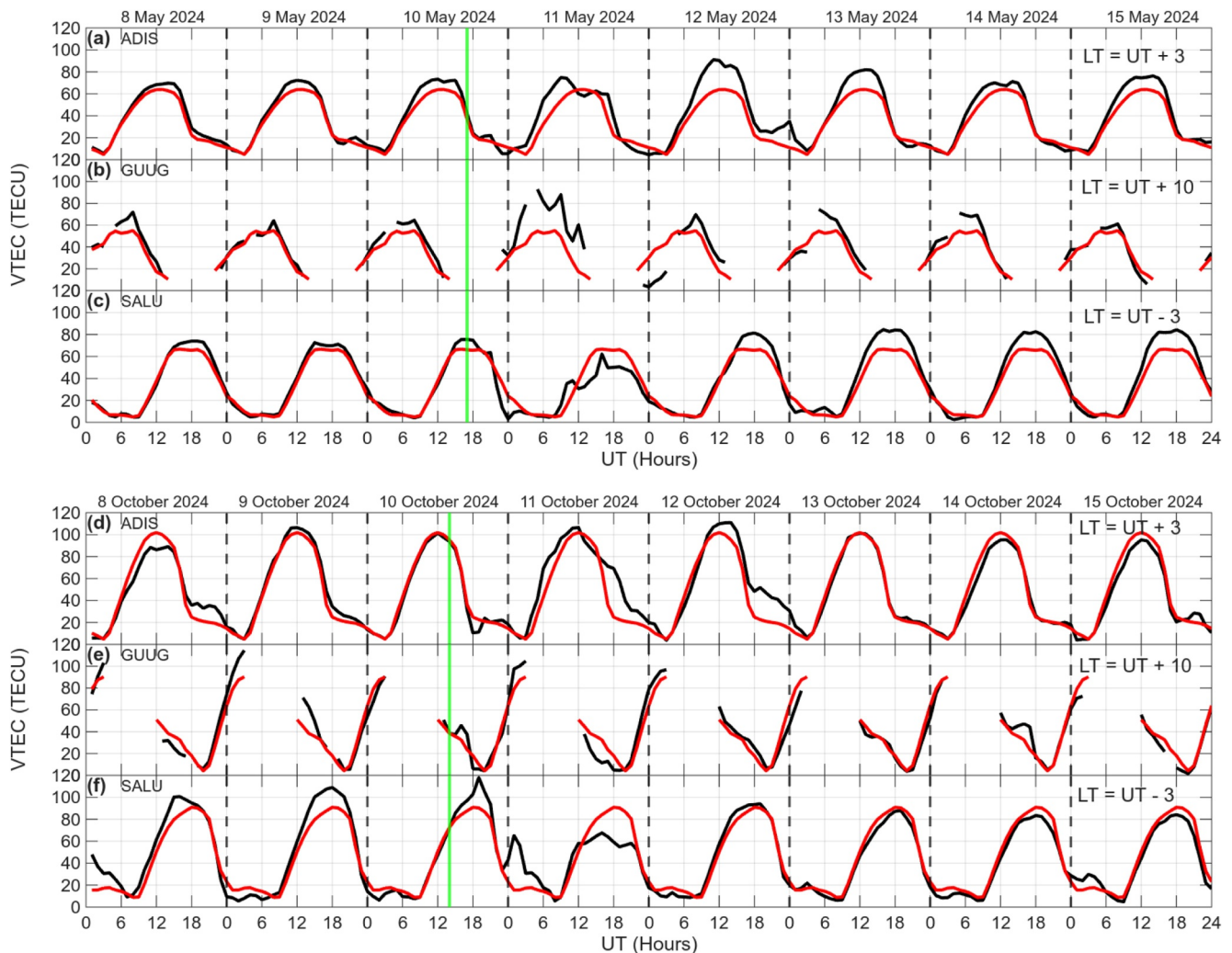


**Figure 3.** Variation of VTEC with time for the geomagnetic storms of 8–15 May 2024 (three upper panels, (a)–(c)) and 8–15 October 2024 (three lower panels, (d)–(f)). The black curve is the actual VTEC data while the red curve is the mean VTEC of the five international quietest days of the month. The green vertical line indicates time of sudden storm commencement.

In Figure 3 (three top panels, (a)–(c)), the black curve is the actual VTEC data while the red curve is the mean VTEC of the five international quietest days of May 2024. The green vertical line indicates time of SSC (17:00 UT), which is the onset time of the storm. The plot shows that during the quiet days of 8–9 May 2024, the variation of VTEC with respect to the mean of the quietest days was regular with VTEC being greater than the mean for the quietest days for the three IGS stations. For the clear observation of local effects of the storm on the ionosphere, UT over American, African, and Asian sectors is converted to LT using  $LT = UT - 3$ ,  $LT = UT + 3$ , and  $LT = UT + 10$  hr, respectively. On 11 May 2024, the geomagnetic storm effects led to a decrease in VTEC over SALU (Figure 3c) while the other two stations of ADIS (Figure 3a) and GUUG (Figure 3b) recorded a significant increase in VTEC, resulting into negative and positive ionospheric storms, respectively. During the recovery phase, the VTEC remained higher than the mean of the quietest days.

The three lower panels of Figures 3d–3f show the pattern of VTEC data together with the mean of the quietest days for the geomagnetic storm of 8–15 October 2024. Between 8 and 9 October 2024, over SALU (Figure 3f), the actual VTEC data was higher than the mean of the quietest days for most of the time. However, over ADIS (Figure 3d), the mean of the quietest days was higher than the actual VTEC on 8 October 2024. Due to the data gap, the patterns of the two data sets are inconclusive over GUUG (Figure 3e). On 10 October 2024, SALU experienced a significant increase in VTEC over the mean of the quietest days. In contrast, ADIS's VTEC and mean of the quietest days were the same for almost the whole day. This observation is similar at GUUG despite

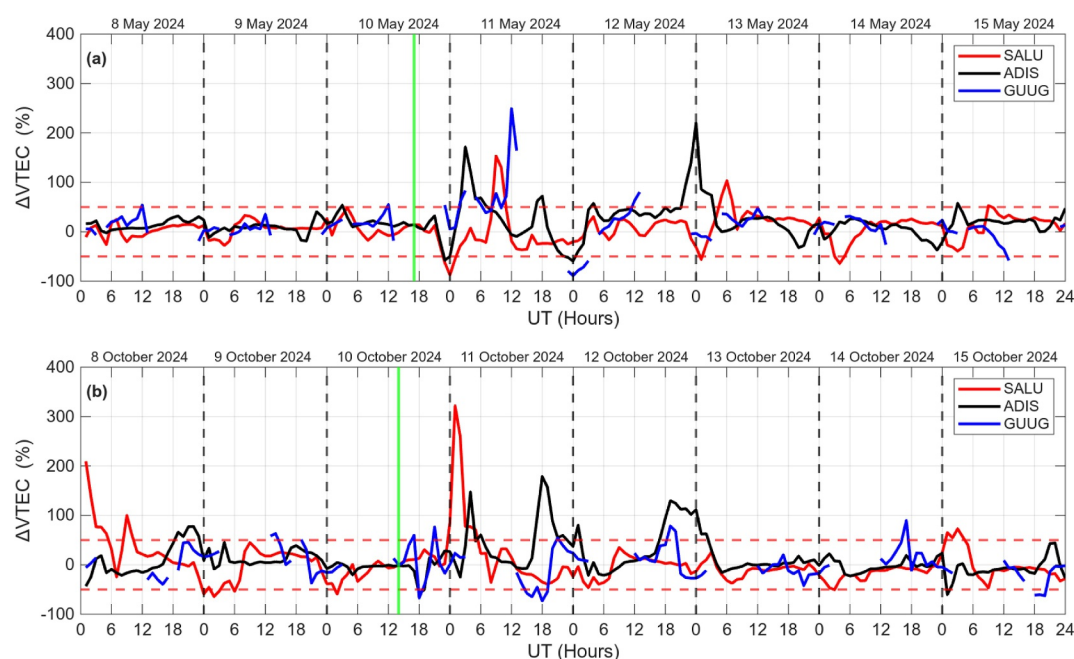


**Figure 4.** Response of the ionosphere to the geomagnetic storm of (a) May 2024, and (b) October 2024. The red dotted lines show the threshold for determining different ionospheric storm effects. The green vertical line indicates the time of sudden storm commencement for each storm that is, 17:00 UT for the May 2024 storm and 14:00 UT for the October 2024 storm.

the data gaps. On 11 October 2024, SALU experienced a significant decrease in VTEC much below the mean of the quietest days. The variation in VTEC over GUUG had several data gaps and hence no conclusion can be made on the patterns of the two curves. The different ionospheric response for the two storms could be due to the LT of the SSC. For May 2024 event, SSC was around dusk/pre-midnight/noon while October 2024 event arrived at evening/pre-midnight/morning over ADIS/GUUG/SALU, respectively.

Figure 4 shows the response of the ionosphere over the three IGS stations to the geomagnetic storms of May and October 2024. It is important to mention that a magnitude of greater than 50% is considered for a significant response of the ionosphere to a geomagnetic storm (e.g., Habyarimana et al., 2023; Matamba et al., 2015). In Figure 4a during the geomagnetic quiet days of 8–9 May 2024, the response over the three IGS stations was not significant except at GUUG where a slight positive percentage deviation at about 12:00 UT (22:00 LT) on 8 May 2024 was observed. GUUG VTEC data had very many data gaps during this month and hence some of the peaks in  $\Delta$ VTEC might not be seen. On 11 May 2024, the three IGS stations recorded significant positive and negative ionospheric storms. For example, on 11 May 2024, at 00:00 UT (21:00 LT on 10 May 2024), SALU recorded a negative ionospheric storm. ADIS also recorded the same but with a slight reduction in the magnitude. During the main phase of the storm, there was a positive ionospheric storm over ADIS at about 03:00 UT. SALU observed a positive ionospheric storm about 6 hr later at 09:00 UT (06:00 LT). During the 8–15 October geomagnetic storm, the response of the ionosphere over the three IGS stations is shown in Figure 4b. The response of the ionosphere to the geomagnetic storm of October 2024 was very significantly positive over SALU on 11 October 2024 at about 01:00 UT (22:00 LT on 10 October 2024). This was a reverse of what was observed over the same station at about the same time during the storm of May 2024, where a negative ionospheric storm effect was seen. ADIS followed suit with a positive response at 04:00 UT (07:00 LT). During the same day, at about 18:00 UT (04:00 LT on 12 October 2024), GUUG recorded a negative ionospheric storm while ADIS recorded a positive ionospheric storm. During the recovery phase, on 12 October 2024, a positive storm effect was observed over ADIS peaking at 19:00 UT (22:00 LT) and 24:00 UT (03:00 LT on 13 October 2024), and over GUUG at 19:00 UT (05:00 LT on 13 October 2024). At 18:00 UT (21:00 LT), both storms showed a positive ionospheric response over ADIS on 11 May and 11 October 2024. Similarly on 12 May 2024 and 12 October 2024 between 18:00 UT (21:00 LT) and 24:00 UT (03:00 LT on 13 October 2024) a positive ionospheric response was depicted at ADIS. This observation indicates that the two storms shared similar dominant physical driving mechanisms especially over the African low latitude regions. The similarity in positive ionospheric responses over the African sector at the same UT

**Table 1**

Summary of the Driving Mechanisms Inferred From IMF Bz Polarity, Interplanetary Electric Field (Ey), and Local Time During the 10–12 October 2024 Geomagnetic Storm, Together With the Corresponding Ionospheric Responses Over the IGS Stations of SALU, ADIS, and GUUG

| Date   | UT | LT      | Station | Bz | Ey | Response | Possible mechanism | Interpretation                                                                                                                  |
|--------|----|---------|---------|----|----|----------|--------------------|---------------------------------------------------------------------------------------------------------------------------------|
| 10 May | 23 | 02 (+1) | ADIS    | S  | E  | –        | Mixed              | PPEF-favorable conditions present, but negative response indicates dominance of DDEF and/or composition-related loss processes. |
| 11 May | 01 | 11      | GUUG    | S  | E  | –        | Mixed              | Daytime negative response despite PPEF-favorable conditions suggests suppression by neutral/compositional effects.              |
| 11 May | 00 | 21 (–1) | SALU    | S  | E  | –        | Mixed              | Pre-midnight eastward field enhanced downward drift; PPEF insufficient, DDEF/neutral effects contributed to depletion.          |
| 11 May | 03 | 06      | ADIS    | S  | E  | +        | PPEF               | Morning eastward field enhanced upward drift, producing a positive storm effect.                                                |
| 11 May | 09 | 06      | SALU    | S  | E  | +        | PPEF (residual)    | Recovery-phase uplift maintained; residual PPEF dominated over DDEF.                                                            |
| 11 May | 09 | 19      | GUUG    | S  | E  | +        | PPEF/PRE           | Evening uplift enhanced PRE, reducing recombination and increasing plasma density.                                              |
| 11 May | 12 | 22      | GUUG    | S  | E  | +        | PPEF               | Pre-midnight uplift consistent with penetration/overshielding-type eastward forcing.                                            |
| 11 May | 18 | 21      | ADIS    | N  | W  | +        | Mixed              | Westward field suppressed fountain; equatorial plasma accumulation due to redistribution and neutral effects.                   |
| 12 May | 01 | 11      | GUUG    | N  | W  | –        | DDEF               | Westward daytime field opposed normal uplift, enhancing recombination and depletion.                                            |
| 12 May | 00 | 03      | ADIS    | N  | W  | –        | Mixed              | Westward field drove downward drift; depletion reflects mixed recovery-phase forcing.                                           |
| 10 Oct | 17 | 03 (+1) | GUUG    | S  | E  | +        | PPEF               | Nighttime penetration; plasma enhancement/retention.                                                                            |
| 10 Oct | 18 | 04 (+1) | GUUG    | S  | E  | –        | Mixed              | PPEF favorable but net depletion dominates.                                                                                     |
| 10 Oct | 21 | 07 (+1) | GUUG    | S  | E  | –        | Mixed              | Morning depletion; competing loss processes.                                                                                    |
| 11 Oct | 01 | 22 (–1) | SALU    | S  | E  | +        | PPEF               | Pre-midnight uplift; reduced recombination.                                                                                     |
| 11 Oct | 04 | 07      | ADIS    | S  | E  | +        | PPEF               | Morning uplift; enhanced upward drift.                                                                                          |
| 11 Oct | 16 | 02 (+1) | GUUG    | N  | W  | –        | Mixed              | Downward drift; recovery-phase depletion.                                                                                       |
| 11 Oct | 18 | 04 (+1) | GUUG    | N  | W  | –        | Mixed              | Continued downward drift; recombination.                                                                                        |
| 11 Oct | 18 | 21 (+1) | ADIS    | N  | W  | +        | DDEF               | Reduced fountain; equatorial accumulation.                                                                                      |
| 12 Oct | 01 | 03      | ADIS    | N  | W  | +        | Mixed              | Redistribution/residual forcing.                                                                                                |
| 12 Oct | 19 | 22      | ADIS    | N  | W  | +        | DDEF               | Pre-midnight accumulation; suppressed fountain.                                                                                 |
| 12 Oct | 19 | 05 (+1) | GUUG    | N  | W  | +        | Mixed              | Dawn enhancement; residual processes.                                                                                           |

Note. S = Southward, N = Northward, E = Eastward, W = Westward, + = Positive ionospheric response, – = Negative response, PPEF = Prompt Penetration Electric Field, DDEF = Disturbance Dynamo Electric Field, PRE = Prereversal Enhancement, (+1) = Local time of the next day, (–1) = Local time of the previous day.

during the two storms indicates that the ionosphere's response is largely driven by global electrodynamic processes (such as PPEF and DDEF effects) that are recurrent when the magnetosphere-ionosphere system experiences comparable solar wind and IMF conditions. This suggests that the African sector exhibits a reproducible storm time uplift pattern when the driving conditions coincide in both UT and LT sectors. Table 1 shows the summary of equatorial ionospheric responses over SALU, ADIS, and GUUG during the 10–12 May 2024 and 10–12 October 2024 geomagnetic storms, showing the relationship between IMF Bz, interplanetary electric field (Ey), and the observed ionospheric response at different local times. The likely electrodynamic mechanisms such as PPEF, DDEF, or mixed effects are inferred based on the polarity, timing, and LT dependence of the electric field. The physical interpretations account for equatorial plasma drift processes, including vertical  $\mathbf{E} \times \mathbf{B}$  drift, fountain effect modulation, and storm time plasma redistribution.

Figure 5 shows the variation of EEJ computed using differential magnetometer approach over JICA and PIUR for the May 2024 storm (Figure 5a) and October 2024 storm (Figure 5b). The red (blue) curve is the EEJ for the disturbed (quiet) day. We used 8 May 2024 and 9 October 2024 as the reference quiet days for the two storms of May 2024 and October 2024, respectively. In Figure 5a, we superimposed the JULIA vertical  $\mathbf{E} \times \mathbf{B}$  drifts data on the EEJ plot to check whether the two approaches agree in identifying the observed physical phenomena. This helped us to infer the observed mechanisms based on EEJ data for the 10–12 October 2024 storm period where no

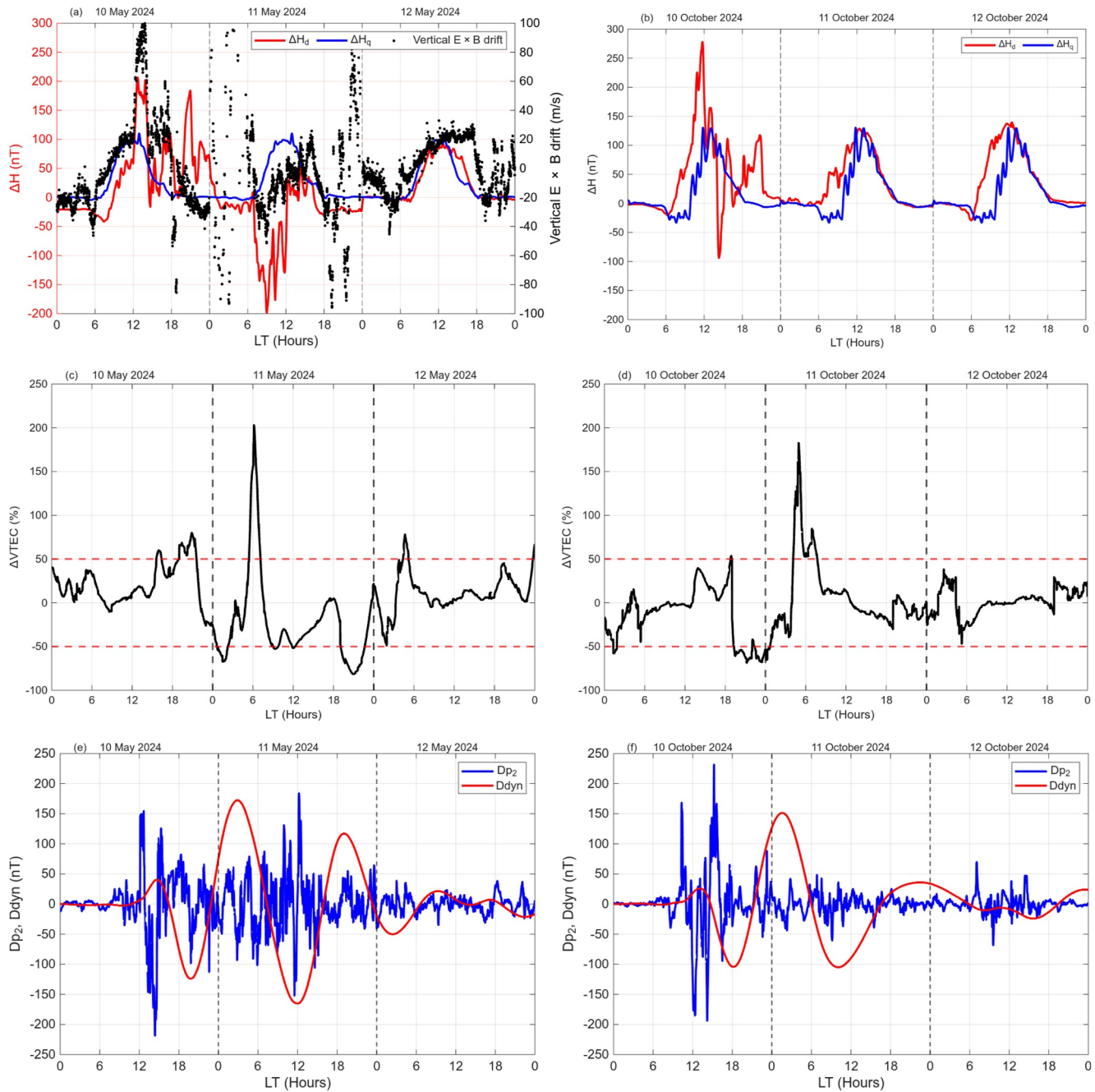


**Figure 5.** Equatorial electrojet over the American sector during (a) 10–12 May 2024, (b) 10–12 October 2024 geomagnetic storms and ionospheric response over AREQ during (c) 10–12 May 2024 and (d) 10–12 October 2024, together with the ionospheric currents over JICA during (e) 10–12 May 2024 and (f) 10–12 October 2024. Positive values correspond to eastward electric fields ( $Dp_2$  and  $Ddyn$ ), upward vertical  $E \times B$  drifts, and an enhanced eastward equatorial electrojet (positive  $\Delta H$ ). Negative values indicate westward electric fields, downward vertical  $E \times B$  drifts, and a weakened or westward equatorial electrojet (negative  $\Delta H$ ).

JULIA data set was available. It is well known that during local daytime, the Incoherent Scatter Radar (ISR) can be used to obtain the 150 km echoes from the JULIA, which can be used as proxies of the F2 region vertical  $E \times B$  drifts (e.g., Anderson et al., 2002; Habarulema et al., 2026). Our interpretations based on magnetometer observations are restricted to local daytime over the American sector because that is the time when magnetometer derived EEJ is reliable. On 10 May 2024 between 06:00 LT and 12:00 LT, the derived EEJ was eastward and significantly increased to values above the quiet time EEJ until it attained a maximum of about 200 nT (Figure 5a). This increase was also depicted by JULIA vertical  $E \times B$  drifts attaining a maximum upward drift of

100 m/s. This was an indication of the presence of PPEF that caused a rapid eastward electric field within the dayside ionosphere resulting into an increase in EEJ and vertical  $\mathbf{E} \times \mathbf{B}$  drifts. The derived EEJ fluctuated between 12:00 LT and 18:00 LT and there was a current reversal from eastward to westward at 14:41 LT. To check whether the increase in EEJ and vertical  $\mathbf{E} \times \mathbf{B}$  drifts during the local daytime caused a positive ionospheric storm over JICA, we used a nearby IGS station of Arequipa (AREQ, Peru, 16.47°S, 71.49°W geographic, and 3.61°S geomagnetic). The positive ionospheric storm on 10 May 2024 at 16:09 LT (Figure 5c) corresponds with the increase in EEJ and vertical  $\mathbf{E} \times \mathbf{B}$  drifts during this time. During this time,  $Dp_2$  was eastward while  $D_{dyn}$  was reversing the direction to westward (Figure 5e). These conditions might have led to the observed positive ionospheric storm effect during the local daytime. Another positive ionospheric storm was observed on 11 May 2024 at 06:00 LT (Figure 5c). During this time, the EEJ over JICA was eastward and there were traces of enhanced upward vertical  $\mathbf{E} \times \mathbf{B}$  drifts from JULIA (Figure 5a).  $Dp_2$  was westward while  $D_{dyn}$  was eastward (Figure 5c). This indicates that the positive response during this time might be attributed to the residual PPEF that dominated DDEF and led to recovery-phase uplift. On 12 May 2024 the EEJ during the quiet and disturbed days followed the same trend during the local daytime. The vertical  $\mathbf{E} \times \mathbf{B}$  drifts followed suit an indication that the ionosphere had returned to its normal background conditions. For the storm of 10–12 October 2024, there was no local daytime ionospheric response during the main phase of the storm. However, on 11 October 2024, there was a positive ionospheric storm at 06:00 LT over AREQ (Figure 5d). This response was also observed using the magnetometer derived EEJ data over the American sector (Figure 5b). The peak in  $\Delta VTEC$  over AREQ at 06:00 LT on 11 October 2024 might be attributed to the increase in  $D_{dyn}$  as a driving mechanism for positive storm effect during nighttime (Figure 5f). Since  $\Delta H$  agrees with vertical  $\mathbf{E} \times \mathbf{B}$  drifts and the computed ionospheric currents when both data sets are available, we used  $Dp_2$  and  $D_{dyn}$  to support our interpretation over locations without pairs of magnetometers for EEJ estimation and vertical drifts. During geomagnetic storms, penetration electric fields associated with SSC can strengthen EEJ or reverse it or modify the daytime dynamo currents (Astafyeva et al., 2025). In such a case, the normal solar quiet (Sq) current system may be temporarily disrupted resulting into a small contribution of Sq to the current system.

Figure 6 shows the corrected horizontal component of the Earth's magnetic field ( $dH_c$ ) after removing the baseline values, the ionospheric currents during the two storm periods of 10–12 May 2024 and 10–12 October 2024 over SLZ, TAM, and GUA, and the vertical  $\mathbf{E} \times \mathbf{B}$  drifts obtained from the NNVD model (Habarulema et al., 2026). It is important to highlight that we should not rely on empirical modeled results to explain the physics, but rather supplement observations with the model. On 10 May 2024, before SSC, the  $dH_c$  over SLZ, TAM, and GUA did not show significant variability. The  $dH_c$  over SLZ increased and attained the highest value of 205 nT at 14:40 LT (Figure 6a). Thereafter, the PPEF turned westward during daytime while DDEF turned eastward as depicted by  $Dp_2$  and  $D_{dyn}$ , respectively (Figures 6b and 6c). The  $dH_c$  over GUA did not show any significant increase on 10 May 2024. During local daytime on 10 May 2024, the vertical  $\mathbf{E} \times \mathbf{B}$  drifts over SALU fluctuated between upward and downward directions until after 12:00 LT where they were downward reaching a minimum value of  $-40$  m/s (Figure 6g). These conditions would ordinarily be expected to produce a negative ionospheric storm effect. However, no significant storm effect was observed (Figure 4a), suggesting that the eastward PPEF present during the pre-main phase counteracted the competing processes that would otherwise have reduced the ionospheric electron content, resulting in a near-neutral ionospheric response. The response of the ionosphere might be attributed to PPEF of magnetospheric origin that spontaneously surged toward the Earth's equator and penetrated the ionosphere. On this day and during the local daytime,  $Dp_2$  changed polarity from westward to eastward while  $D_{dyn}$  was eastward during the early morning hours. This enhanced the PPEF resulting into positive ionospheric storm at this time. Over ADIS, the vertical  $\mathbf{E} \times \mathbf{B}$  drifts were upward during local daytime, while over GUUG, the drifts fluctuated between upward and downward directions. On 11 May 2024 during local daytime, there were significant fluctuations in  $dH_c$  and hence  $Dp_2$  and  $D_{dyn}$  showed fluctuations. On this day, during local daytime over SLZ and GUA, there was a current reversal from eastward to westward between 06:00 LT and 12:00 LT, lasting for over 6 hr. Over TAM, this reversal was observed after 4 hr. This was an evidence of DDEF occurring during the recovery phase of the storm. The vertical  $\mathbf{E} \times \mathbf{B}$  drifts over SALU and ADIS were downward. GUUG had upward vertical  $\mathbf{E} \times \mathbf{B}$  drifts with a maximum of 16 m/s at 14:00 LT.

During the 10–12 October 2024 storm the  $dH_c$  did not show any fluctuation until 12:00 LT (Figure 6d). This led to fluctuations in  $Dp_2$  and  $D_{dyn}$  (Figures 6e and 6f). During 11 October 2024 at 07:00 LT over GUUG (7 hr after SSC), the negative storm effect occurred while  $Dp_2$  was eastward but  $D_{dyn}$  was westward. The modeled vertical drifts were downward indicating that the  $D_{dyn}$ /DDEF contribution likely dominated over the PPEF lowering the

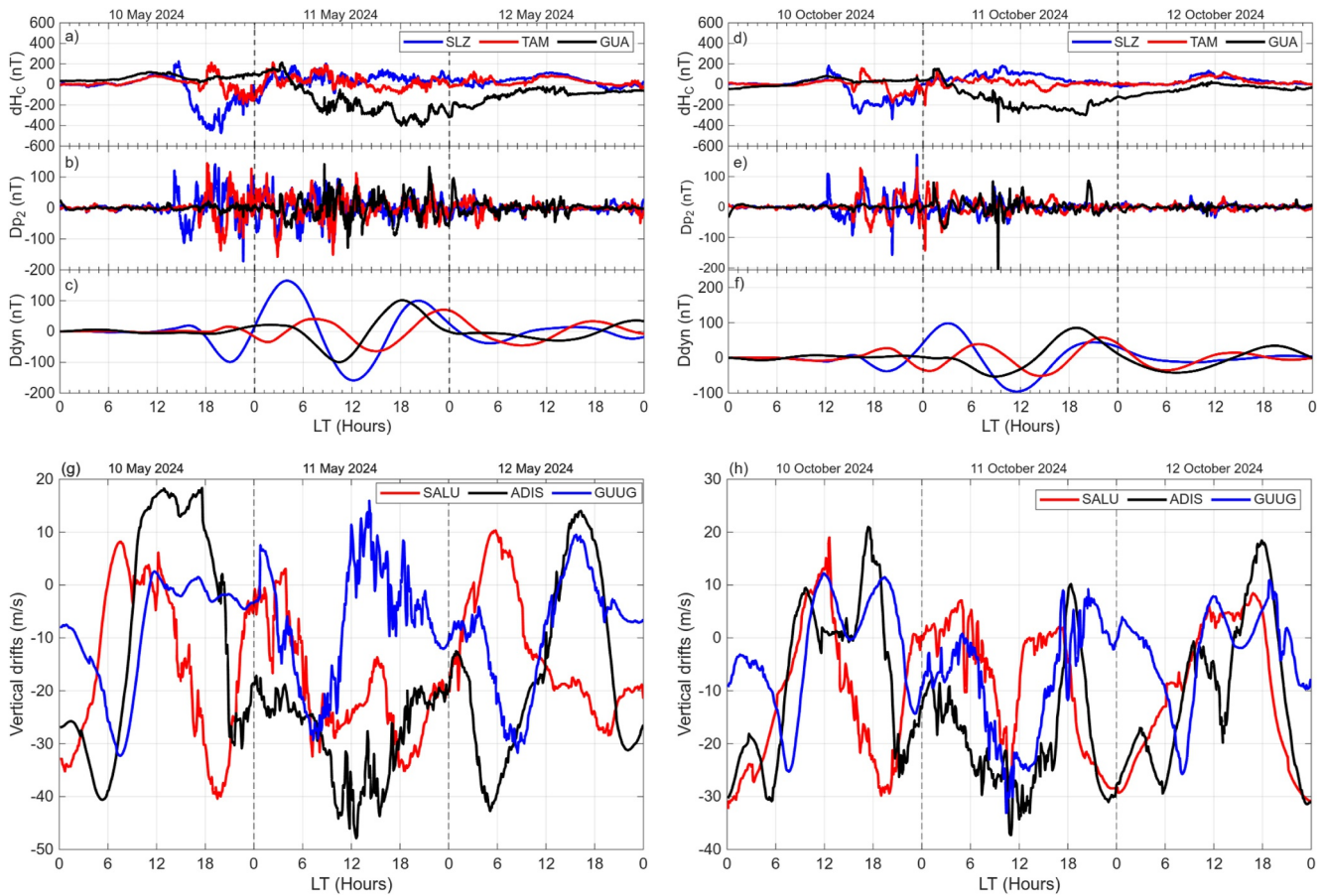


**Figure 6.** Corrected horizontal component of the Earth's magnetic field ( $dH_c$ ) after removing the baseline values, the ionospheric currents during the two storm periods of (a)–(c) 10–12 May 2024 and (d)–(f) 10–12 October 2024 over SLZ, TAM, and GUA. The vertical drifts from Neural Network Vertical Drift model are also plotted in (g) 10–12 May 2024 and (h) 10–12 October 2024.

F region and enhancing plasma loss. Thus, the depletion is consistent with downward vertical  $\mathbf{E} \times \mathbf{B}$  drift and competing loss processes rather than PPEF-driven uplift.

The Sw-A electron density data was also used to check the effect of geomagnetic storm on the ionospheric electron density distribution and on the expansion or contraction/suppression of the EIA. We chose four days to track the changes in the ionospheric parameters during the 9–12 May and October 2024 storms' initial, main and recovery phases. This helps to investigate the behavior of the electron density during the two geomagnetic storms and then make a comparison of their effects as observed by the Sw-A.

Figure 7 shows the cross-section of the daytime electron density profiles, between 6 LT and 18 LT, as a function of latitude and longitude. The red dots indicate the GNSS stations considered in this study to capture the longitudinal dependence of the ionospheric variations during the two geomagnetic storms. On 9 May 2024 (Figure 7a) and 10 May 2024 (Figure 7b), the electron densities within the EIA region were slightly above  $2 \times 10^5 \text{ cm}^{-3}$ , with an expansion of EIA region toward mid latitudes. The EIA region was almost absent especially over the African sector. Over the American sector, the high values of electron density were evident within the northern hemisphere between  $120^\circ\text{W}$  and  $160^\circ\text{W}$ . The electron density started to increase and the EIA region became significant with values of  $N_e$  reaching a maximum of about  $4 \times 10^5 \text{ cm}^{-3}$  on 11 May 2024 (Figure 7c). These observed variations may be attributed to the ionospheric responses brought about by induction of currents as a result of geomagnetic storm activity due to the SSC that was accompanied with an impulse on 10 May 2024. However, on 12 May 2024 (Figure 7d), the characteristic EIA region contracted along the American and African longitudinal sectors. During their study on the impact of the Gannon Superstorm on the EIA

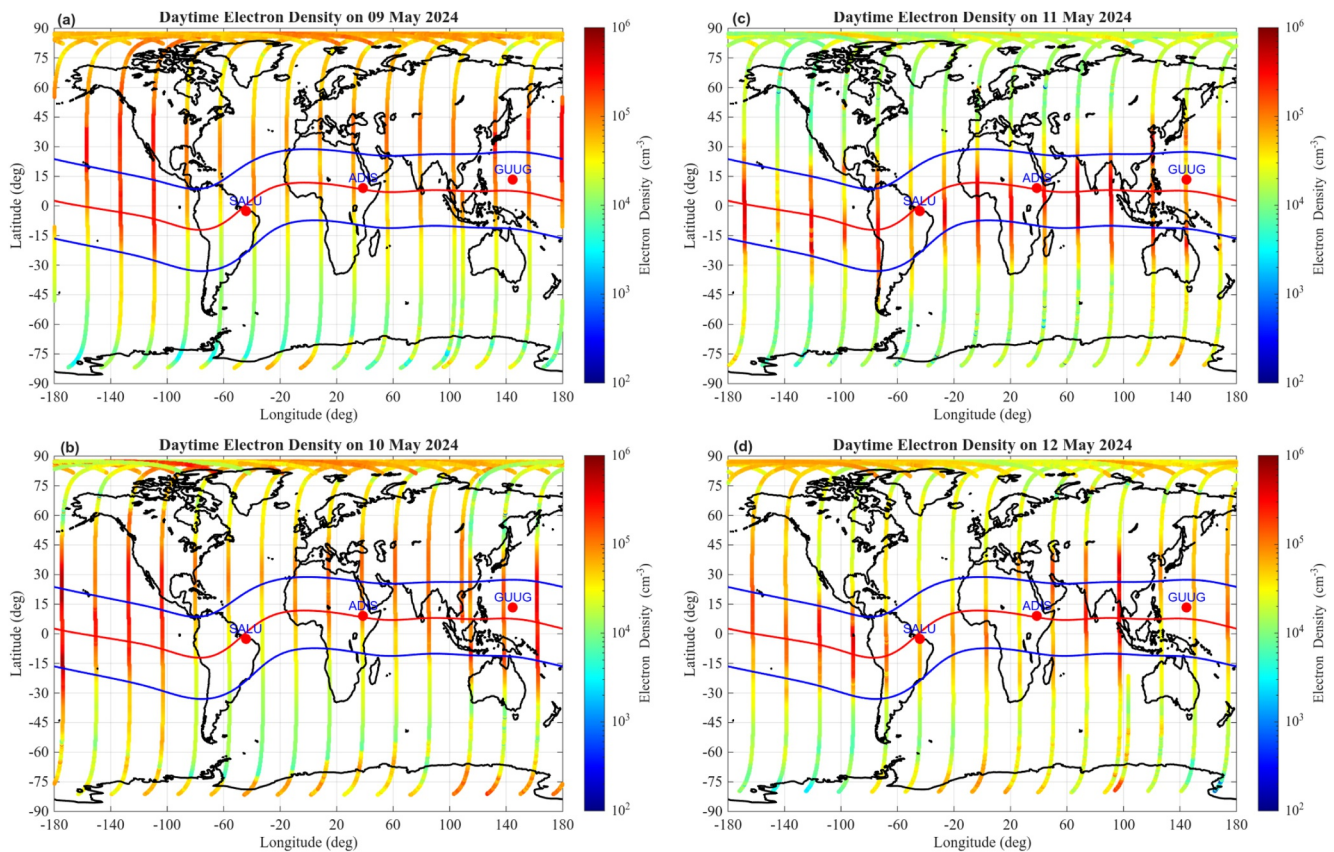


**Figure 7.** Sw-A data for daytime electron density during the geomagnetic storm period between 9 and 12 May 2024. The red solid curve represents the geomagnetic equator. The two blue solid curves represent the equatorial ionization anomaly region.

dynamics during its recovery phase on 11 May 2024, Shimna et al. (2025) revealed a pronounced enhancement in electron density at the equator and a complete disappearance of the EIA crests. They attributed these two features to the presence of equatorward converging meridional winds from both hemispheres and strong daytime Counter Electrojet (CEJ) caused by disturbance dynamo effects, respectively. Vertical  $\mathbf{E} \times \mathbf{B}$  drift was suppressed as a result of this strong CEJ which led to elimination of the fountain effect (Astafyeva et al., 2025; Shimna et al., 2025; Zakharenkova et al., 2025). An expansion of EIA to mid latitude regions is observed at longitudes of 140°W. The intensification of the ring current results in an increase in Ne on 12 May 2024 as a result of the geomagnetic storm's main phase. The maximum values occurred within the Pacific sector at longitudes between 120 and 140°W. Figure 8 is the same as Figure 7 but for a geomagnetic storm period of 9–12 October 2024. A quick look on the magnitude of the Ne values demonstrates that the EIA structure was more pronounced during the October 2024 geomagnetic storm than during May 2024. On careful examination of Figure 7, it can be seen that Ne values at the GNSS stations (considering the close satellite Ne profiles within a 15° interval) were the same, implying that the geomagnetic storm had minimal or no effect on the electron density at the three stations. However, for the storm of October 2024 (Figure 8), a significant increase in electron density during the storm evolution is evident. Overall, the electron density was higher for the storm of October 2024 than the one of May 2024, yet the minimum Dst value for the May geomagnetic storm was lower than that of October 2024. This corroborates that Dst index is a necessary but not a sufficient index to identify, gauge and represent the space weather effects on the atmosphere during a geomagnetic storm (e.g., Borovsky & Shprits, 2017). Throughout the geomagnetic storm of October 2024, Ne values were about  $10^6 \text{ cm}^{-3}$  within the EIA region. On 11 October 2024, there was expansion of the EIA structure to mid latitudes between longitude regions of 100°W–150°W within both the Northern and Southern hemispheres.

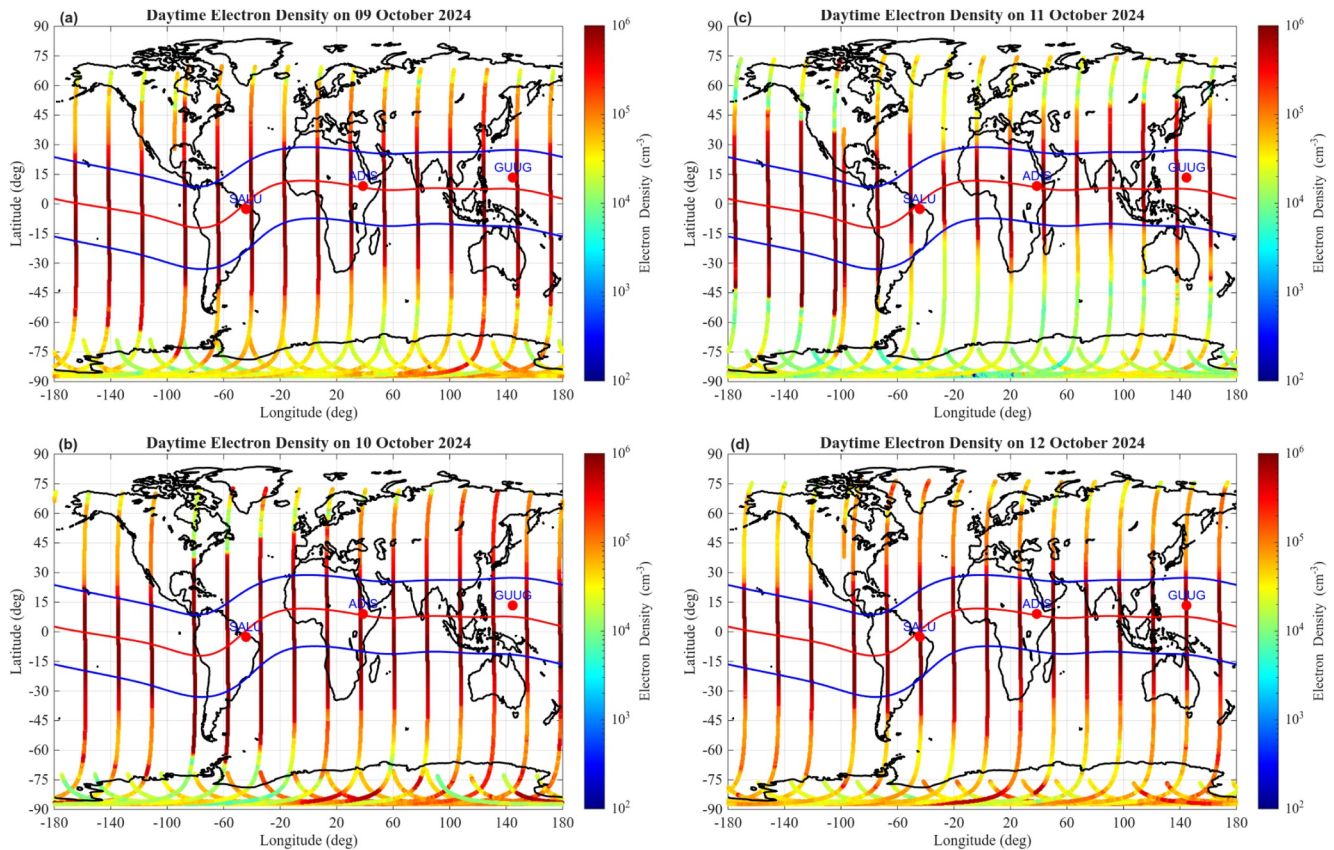


**Figure 8.** Same as Figure 7 but for the period between 9 and 12 October 2024.

### 3.3. Latitudinal Profiles of VTEC During the Two Geomagnetic Storms

To compare the longitudinal differences of the response of the ionosphere to the two geomagnetic storms, we used the latitudinal profiles of VTEC from Sw-A centered at the station longitudes and within  $\pm 7.5^\circ$ . This accounts for the LT differences and considers only satellite passes within the time frame of about 1 hr. In addition, we maintained a latitudinal range of  $\pm 30^\circ$  to constrain our passes within the low latitude/equatorial region, which is the region of focus under study. We note that the Sw-A VTEC data has information for both the topside ionosphere and the plasmasphere. Figure 9 presents the latitudinal profiles for both the morning and evening time sectors during the two geomagnetic storms when the satellite crosses a particular station. The top two rows (Figures 9a–9f) are for the geomagnetic storm of 8–15 May 2024 while the bottom two rows (Figures 9g–9l) are for the geomagnetic storm of 8–15 October 2024. The days are distinguished by the legend at the bottom of the panels for each geomagnetic storm. During 8–15 May 2024 geomagnetic storm, the Sw-A crossed SALU, ADIS and GUUG in the morning (evening) sector at 07:00 LT (19:00 LT). The VTEC profiles showed no apparent rise during the morning sector (dawn). However, small peaks in VTEC profiles were observed during the storm day (11 May 2024) over SALU and ADIS. During the evening sector (dusk) there was an evidence of EIA double crests on 8 May 2024 over SALU and GUUG, 9 May 2024 over ADIS and GUUG, 10 May 2024 over ADIS and 11 May 2024 over GUUG. After 11 May 2024, the double peaks ceased to occur in the VTEC profiles. During the geomagnetic storm on 11 May 2024 there were no visible crests over SALU and ADIS. On the storm day of 11 May 2024, the VTEC profile over GUUG at 19 LT demonstrated an increase in the VTEC values exceeding the previous quiet days. This indicates that the ionosphere over GUUG responded positively to the geomagnetic storm of 11 May 2024 in reference to the quiet day of 8 May 2024. There was a marked enhancement in VTEC profiles over the southern compared to the northern hemisphere, clearly indicating a north-south asymmetry arising from disruption of the fountain effect as a result of the storm.

Figures 9g–9l present the VTEC profiles for the geomagnetic storm of 8–15 October 2024. During this storm, VTEC profiles using Sw-A, were prominent during the morning hours at 06:00 LT. Even though the single peak

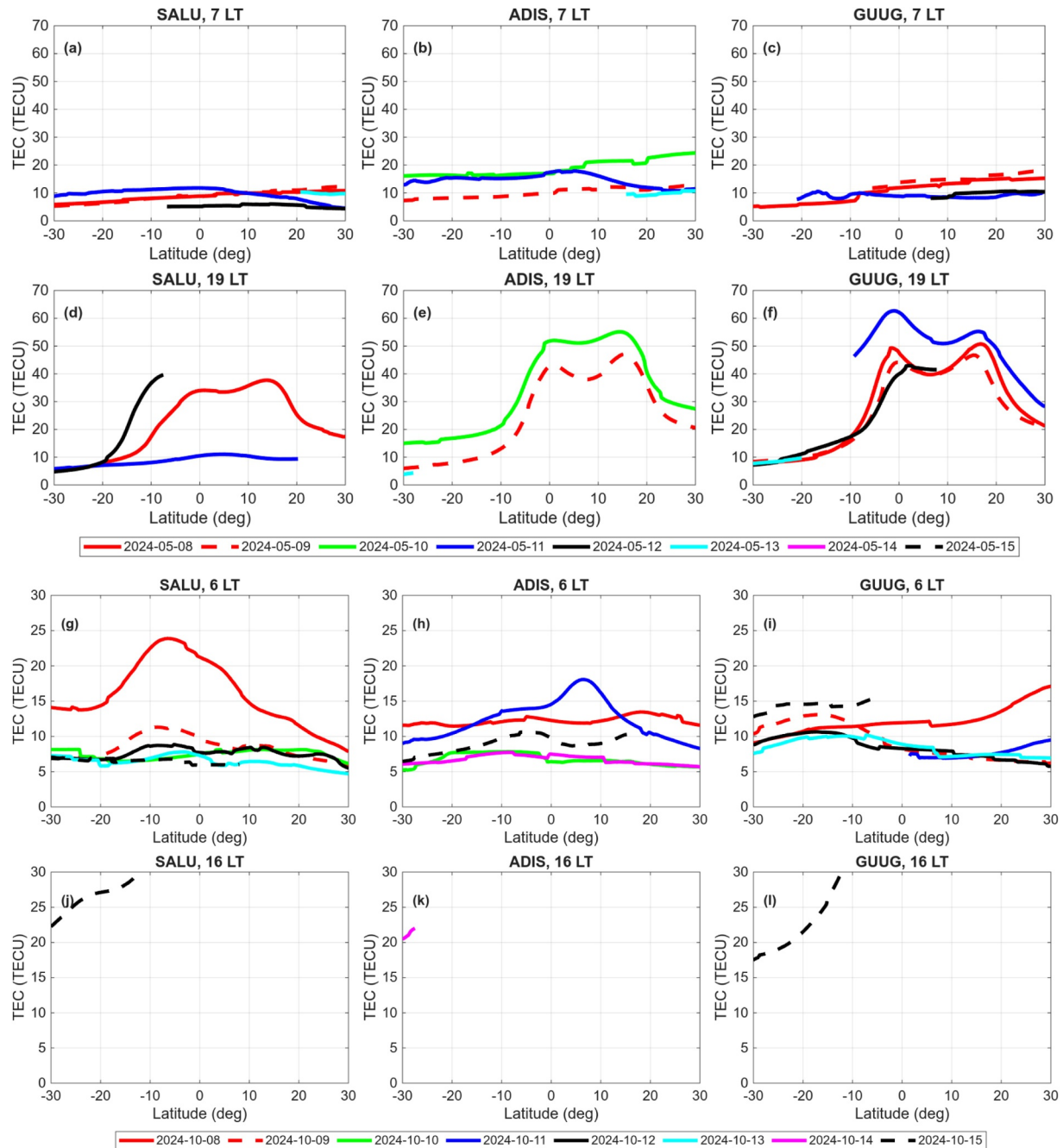


**Figure 9.** Latitudinal profiles of VTEC observed by Sw-A on 8–15 May 2024 (top two rows), and 8–15 October 2024 (bottom two rows). The days are distinguished by the legend at the bottom of the panels for each geomagnetic storm.

in the VTEC profile was not significant over all sectors during this time, there was such evidence over SALU and ADIS especially on 8 October 2024 and 11 October 2024, respectively. Over ADIS, in both the southern and northern hemispheres between  $-15^{\circ}$  and  $14^{\circ}$  latitudes, there was a positive ionospheric response on 11 October 2024 when compared to the reference quiet day of 8 October 2024. However over GUUG, a negative storm effect was observed in the southern hemisphere. Over ADIS, the VTEC profile on 11 October 2024 at 16:00 LT was missing and hence in comparison with 11 October 2024 at 06:00 LT, there was a positive storm effect, and actually a significant one of about 60%. During the evening hours, the VTEC profiles were only partly visible during the recovery phase of the geomagnetic storm at 16:00 LT. For the two storms during the recovery phase, the ionospheric responses were not significant.

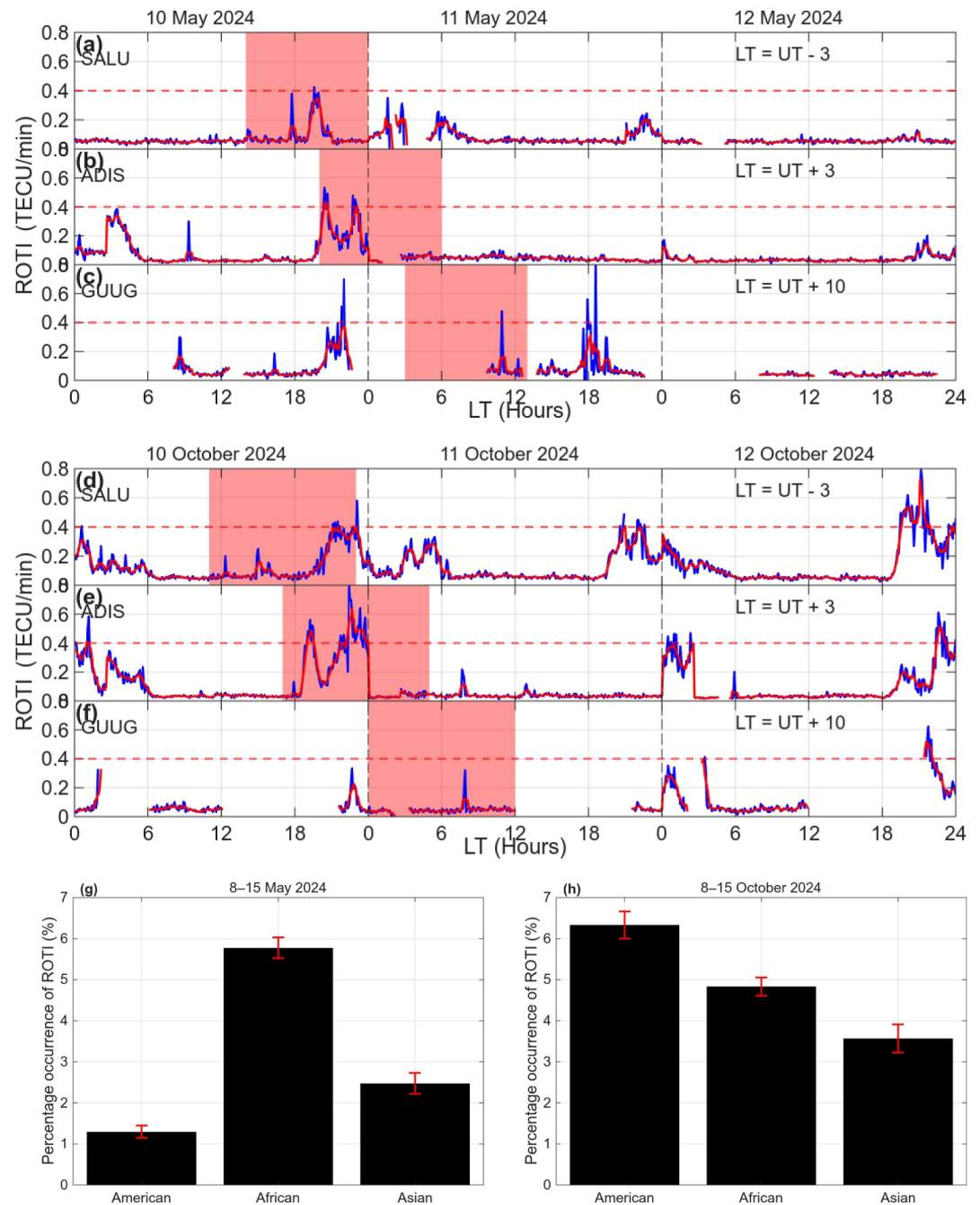


**Figure 10.** Variation in ROTI values during the storm period between 10 and 12 May 2024 ((a)–(c)) and 10–12 October 2024 ((d)–(f)) over SALU, ADIS, and GUUG, and the percentage occurrence rate of ROTI over the American, African, and Asian sectors during the whole storm period of (g) 8–15 May 2024, and (h) 8–15 October 2024. The shaded area shows the main phase of the geomagnetic storm in local time sense from the time of sudden storm commencement to the time of minimum Dst index. The blue curve is the 5-min ROTI while the red curve is the 30-min running average ROTI ( $ROTI_{ave}$ ).

### 3.4. Longitudinal Variation and Occurrence of Ionospheric Irregularities

Figure 10 shows ROTI values for the three IGS stations close to the geomagnetic equator during the storm period between 10 and 12 May 2024 (top rows, (a)–(c)) over SALU, ADIS, and GUUG as a function of LT. The LT conversion for each station using UT is shown on each panel. The blue curve is the 5-min ROTI while the red curve is the 30-min running average ROTI ( $ROTI_{ave}$ ). Previously, studies used 30 s TEC data and showed that the

occurrence of irregularities happens when ROTI is greater than 0.5 TECU/min at scale lengths of a few kilometers (e.g., Ma & Maruyama, 2006; Pi et al., 1997). Later on, using daily irregularity index,  $ROTI_{ave}$ , defined as the average ROTI over half an hour interval for a satellite and then averaging over all satellites in view, it was found out that a threshold of 0.4 TECU/min could be used to detect the occurrence of irregularities (e.g., Dugassa et al., 2019; Oladipo et al., 2014; Oladipo & Schüller, 2013). This modification smooths out short-lived fluctuations in the 5-min ROTI values. This helps to retain persistent ionospheric irregularity activity while using all satellites in view compared to what happens along a single satellite pass. Recently, Cherniak et al. (2022) used ROTI values below 0.2 TECU/min to represent very weak or absence of irregularities. Gao et al. (2023) varied the threshold values of ROTI between 0.2 and 0.6 TECU/min and found out that 0.4–0.45 TECU/min can be used as threshold values to distinguish between weak irregularities and ionospheric background conditions. In this study, we therefore considered ROTI values as significant when above 0.4 TECU/min (Dugassa et al., 2019; Gao et al., 2023; Oladipo et al., 2014; Oladipo & Schüller, 2013). For the rest of this paper, we consider a  $ROTI_{ave}$  value of 0.4 TECU/min as the threshold value for the triggering (above) or inhibition (below) of occurrence of ionospheric irregularities. On 10 May 2024, the SSC was at 14:00 LT over SALU (Figure 10a) while the minimum Dst was reached at 24:00 LT.  $ROTI_{ave}$  values were below 0.4 TECU/min during the main phase over SALU indicating an inhibition of the occurrence of irregularities. Over ADIS (Figure 10b), SSC occurred at 20:00 LT and the minimum Dst was reached at 06:00 LT on 11 May 2024.  $ROTI_{ave}$  was greater than 0.4 TECU/min at 20:55 LT with a maximum value of 0.43 TECU/min. Over GUUG (Figure 10c), the SSC occurred on 11 May 2024 at 03:00 LT while the minimum Dst index occurred at 13:00 LT. All  $ROTI_{ave}$  values were less than 0.4 TECU/min at GUUG between 10 and 12 May 2024. Between 10 May 2024 and 11 May 2024, only ADIS recorded irregularities, with inhibition in irregularity occurrence over SALU and GUUG throughout the whole storm period.

For the storm of October 2024, over SALU (Figure 10d), the SSC occurred at 11:00 LT. All  $ROTI_{ave}$  values were below 0.4 TECU/min during the main phase of the storm. Over ADIS (Figure 10e), SSC occurred at 17:00 LT on 10 October 2024. This was followed by triggering of the occurrence of irregularities observed at 19:20 LT and 22:40 LT on 10 October 2024 during the main phase of the storm. The SSC at GUUG (Figure 10f) was at local midnight on 11 October 2024, and irregularities were inhibited during the storm main phase. This indicates that the two geomagnetic storms triggered the occurrence of irregularities during the main phase over ADIS. Conversely, there was inhibition of irregularities during the main phase of the two storms over SALU and GUUG. During the recovery phase on 12 October 2024, irregularities were triggered over SALU, ADIS, and GUUG during the post sunset hours.

We also computed the percentage occurrence of  $ROTI > 0.4$  TECU/min from the representative GNSS receivers located in the American, African, and Asian sectors using data from visible Pseudo Random Noise codes (PRNs) during the Sw-A passes over the particular longitude sector. This helped us to compare the longitudinal statistics of the percentage occurrences of ROTI with those derived from Sw-A RODI observations. Figure 10g presents the percentage occurrence rate of  $ROTI > 0.4$  TECU/min over American, African, and Asian sectors for the period between 8 and 15 May 2024. During this period, the percentage occurrence rate was 1.29%, 5.77%, and 0.81% over the American, African, and Asian sectors, respectively. This shows that there was no clear longitudinal pattern during the May 2024 storm in terms of percentage occurrence of ROTI. Figure 10h is the same as Figure 10g but for the period between 8 and 15 October 2024. During this period, the percentage occurrence of ROTI was 6.33%, 4.83%, and 3.57% over American, African, and Asian sectors, respectively, clearly depicting a longitudinal asymmetry in the percentage occurrence of ROTI.

The RODI index derived from plasma density recorded by Sw-A was used to study the longitudinal variation of ionospheric irregularities. Figure 11 shows distribution of RODI during the geomagnetic storm of May 2024. Specifically, we considered data between 10 and 12 May 2024 to trace the storm evolution during the initial, main and recovery phases. Throughout these selected days, some RODI values were above the threshold value of  $5 \times 10^3 \text{ cm}^{-3}/\text{s}$ , a clear indication that ionospheric irregularities were triggered during this storm on a global scale (e.g., Jin et al., 2022). Figure 12 is the same as Figure 11 but for the geomagnetic storm of October 2024. As seen from Figures 11 and 12, the ionospheric irregularities as observed by Sw-A were evident but scattered along the satellite paths. Therefore, the two geomagnetic storms of May and October 2024 caused significant irregularities within the ionosphere. This was also evident while using ground based GNSS data in Figure 10 during the different phases of the two geomagnetic storms, especially over ADIS.

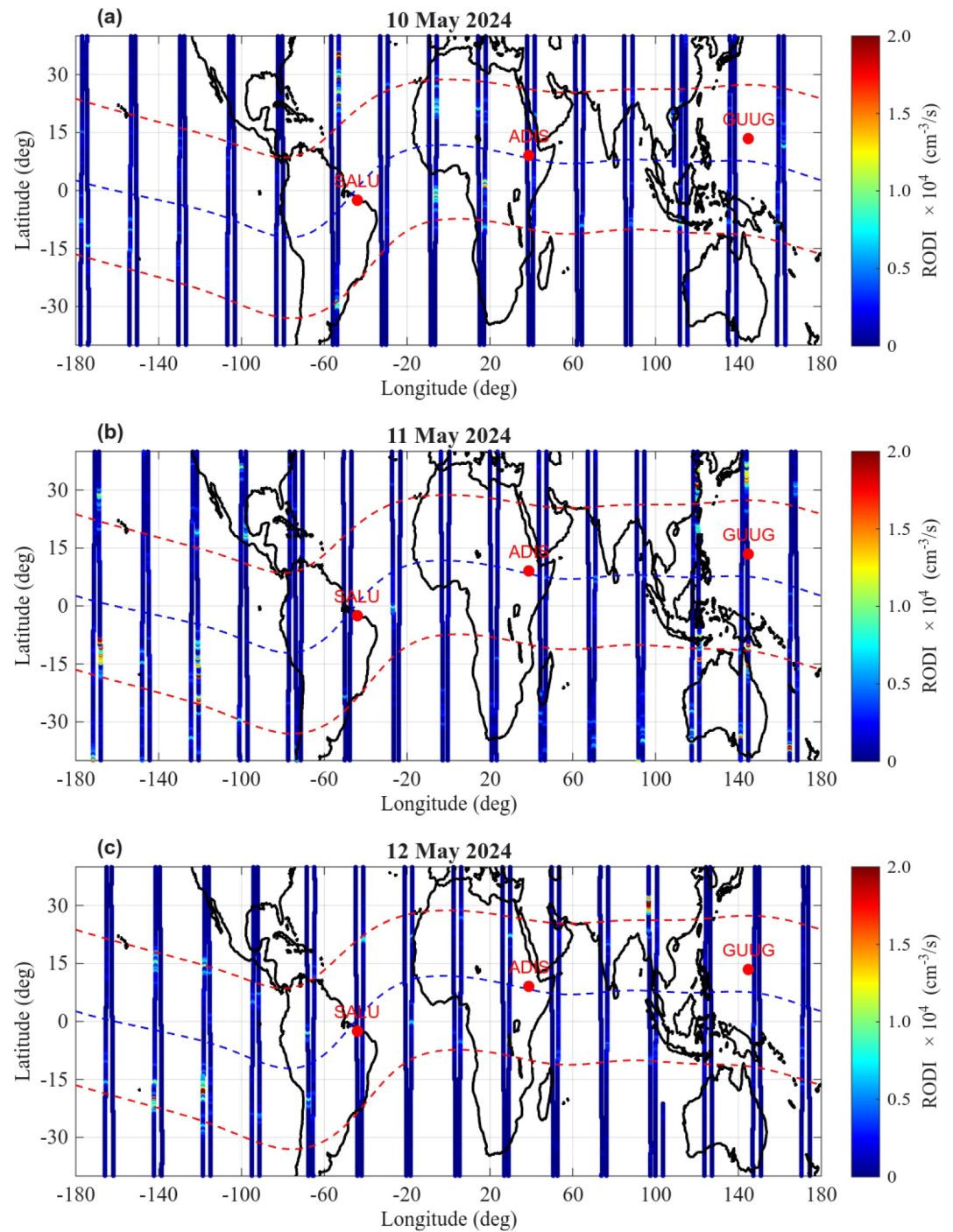


**Figure 11.** Sw-A data for RODI during the geomagnetic storms of May 2024. The blue dotted curve represents the geomagnetic equator. The two red dotted curves represent the equatorial ionization anomaly region.

We further divided the Sw-A data into three longitude sectors: American ( $-90^{\circ}$  to  $-30^{\circ}$ ), African ( $-30^{\circ}$  to  $60^{\circ}$ ) and Asian ( $60^{\circ}$  to  $150^{\circ}$ ). We then restricted the data to low latitudes within  $\pm 30^{\circ}$ . The normalized percentage occurrence rate was then computed by taking a threshold value of  $5 \times 10^3 \text{ cm}^{-3}/\text{s}$  (e.g., Jin et al., 2022). Figure 13 shows the longitudinal variability of the occurrence of irregularities during the two geomagnetic storms using Sw-A RODI data.

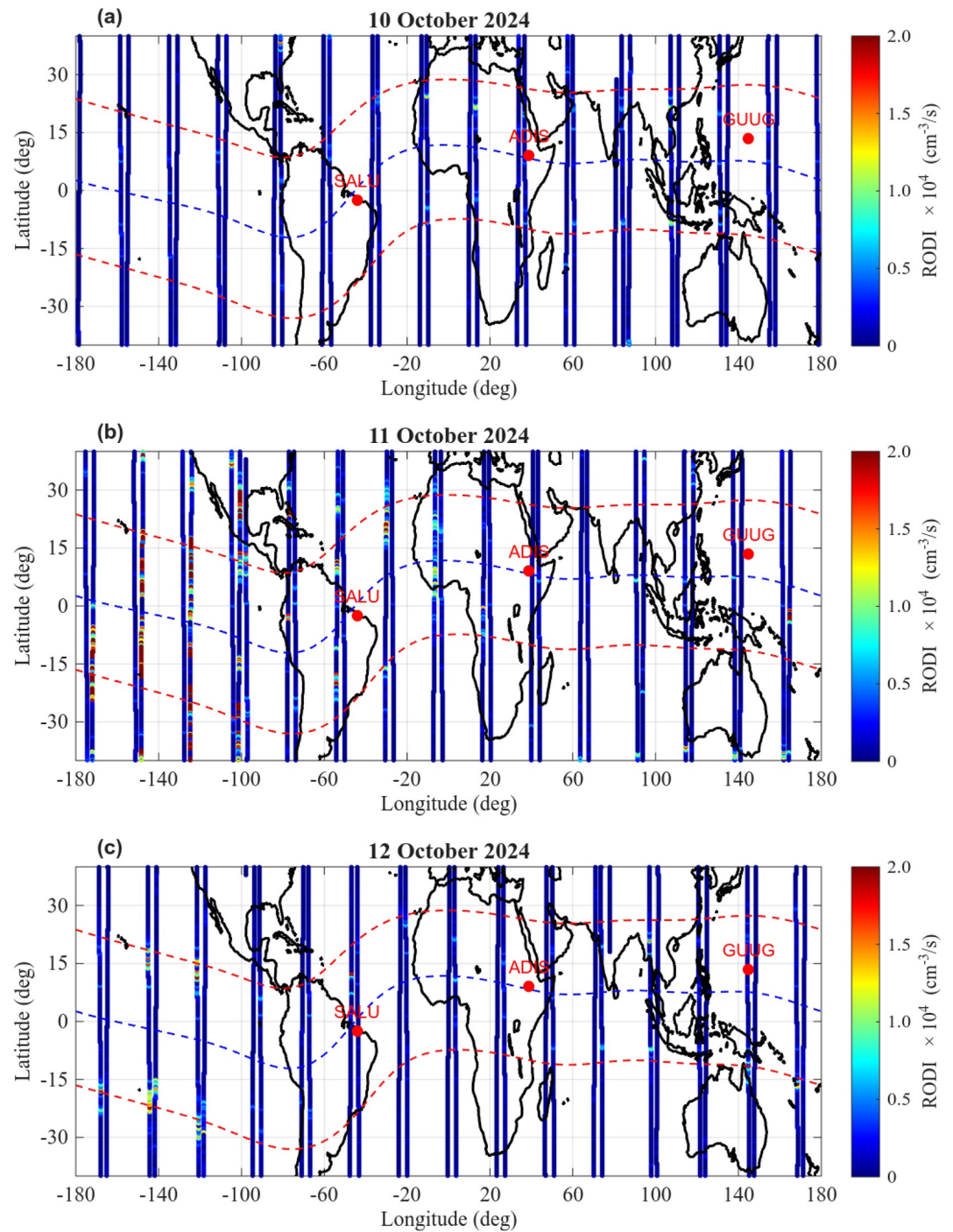


**Figure 12.** Same as Figure 11 but for the geomagnetic storm of October 2024.

Figure 13a shows the percentage occurrence of irregularities above the threshold value of  $\text{RODI} > 5 \times 10^3 \text{ cm}^{-3}/\text{s}$  during 8–15 May 2024. The percentage occurrence of irregularities over the American sector during the post-sunset hours was below 6%, while over the African sector was below 7% and over the Asian sector was below 3%. During the daytime, the percentage occurrence of irregularities of about 7% was evident over the Asian sector, while the other sectors registered irregularity occurrence of about 3%. During the storm of 8–15 October 2024, over the American (African) sector, about 8% (9%) of the irregularities occurred during post-midnight hours. The percentage occurrence over the Asian sector during post midnight hours was below 3%.

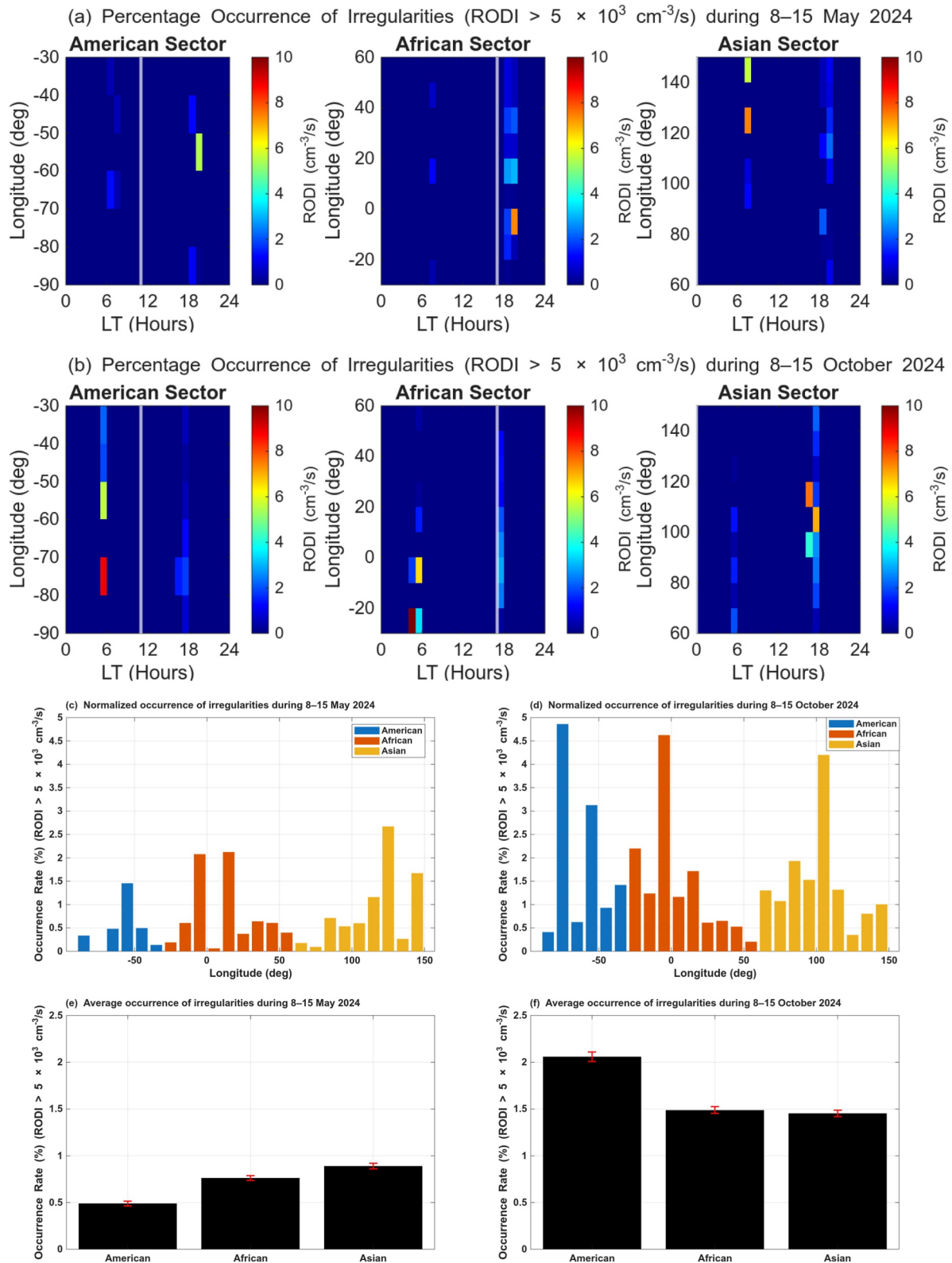


**Figure 13.** Longitudinal variability of the occurrence of irregularities using RODI from Sw-A between 8 and 15 May 2024 (a, c, e), and 8–15 October 2024 (b, d, f). The sectors are distinguished by the different colors on the legend. The white vertical line indicates the local time of the sudden storm commencement during the day of the storm. The red bars on panels (e) and (f) indicate the error bars of the occurrence rates.

For the three sectors, the percentage occurrence of post sunset irregularities was below 3%. Figure 13c shows the normalized occurrence of irregularities from each sector along the low latitude region during 8–15 May 2024. For each sector, we combined the data for all the days under consideration and computed the occurrence rate for each longitude when RODI values were greater than  $5 \times 10^3 \text{ cm}^{-3}/\text{s}$ . Over the American sector, the longitude range between  $-50^\circ$  and  $-60^\circ$  exhibited the highest percentage occurrence rate of 1.46%. Over the African sector, the longitude range of  $10^\circ$  to  $20^\circ$  was the highest with a percentage occurrence rate of 2.12%. On the other hand, over the Asian sector, the longitude range between  $120^\circ$  to  $130^\circ$  exhibited the highest occurrence rate with 2.67%. However, when the different longitude ranges were combined, as shown in Figure 13e, an average occurrence rate over the American sector was the lowest, followed by African sector and the highest over the Asian sector with rates of 0.49%, 0.76%, and 0.89% respectively. Figure 13d shows the normalized occurrence rate of irregularities above the threshold value during the geomagnetic storm of 8–15 October 2024. The percentage occurrence over the American sector was the highest (4.86%) within a longitude range of  $-80^\circ$  to  $-70^\circ$  followed by African sector (4.63%) within the longitude range of  $-10^\circ$  to  $0^\circ$  and the lowest was over the Asian sector (4.2%) within a longitude range of  $100^\circ$  to  $110^\circ$ . When the different longitudes within each sector were combined (Figure 13f), the average occurrence rate was the highest over the American sector (2.06%) followed by the African sector (1.49%) and the lowest was over the Asian sector (1.45%). In general, the percentage occurrence rate was higher during the geomagnetic storm of October 2024 than during the geomagnetic storm of May 2024, with an observed reverse trend of the highest occurrence rate for the different sectors. During the storm of May 2024, the occurrence rate was the lowest in American, followed by African and then Asian sectors, but during the storm of October 2024, this trend was reversed though the occurrence rate was still higher for the sector with the lowest occurrence rate in October 2024 than the highest in May 2024 (Asian). The error bars indicate that the computed occurrence rates were precise with low variability. These findings agree with those of ground-based ROTI especially during the period between 8 and 15 October 2024 in Figure 10h. The discrepancy between the percentage occurrence rates for the ground- and space-based measurements during the period between 8 and 15 May 2024 may be attributed to the inhibition of irregularities over the region caused by the strong negative ionospheric storm (see Figure 4a) that might have reduced the vertical plasma drift and weakened the EIA formation (e.g., Astafyeva et al., 2025). This might have led to suppression of Rayleigh-Taylor instability responsible for irregularity generation. Over the Asian sector, a lot of data gaps might have led to the low percentage occurrence.

We again checked the validity of the reverse occurrence rate of ionospheric irregularities for the two geomagnetic storms of 8–15 May 2024 and 8–15 October 2024 by only selecting the occurrence rate when the RODI values from Sw-A were greater than the threshold value. The RODI values were then binned into  $2.5^\circ \times 5^\circ$  latitude  $\times$  longitude bins. Figure 14 shows the longitudinal variability of the occurrence of RODI greater than  $5,000 \text{ cm}^{-3}/\text{s}$  along the low latitude region.

Important to note from Figure 14 is that most of the RODI values were found along the equatorial anomaly region within  $\pm 15^\circ$  geomagnetic latitude, with the highest occurrence rate in the American sector. The occurrence rate was higher during the October 2024 storm (Figure 14b) than the May 2024 storm (Figure 14a), possibly attributed to the difference in the strength of the storms and the seasons of the year.

#### 4. Discussion

This study investigated the longitudinal variation of ionospheric irregularities and the storm time response of the ionosphere during the geomagnetic storms of May and October 2024. The analysis revealed pronounced longitudinal asymmetries, with the African and American sectors exhibiting stronger irregularity activity compared to the Asian sector during the October 2024 storm and a vice versa in May 2024. Moreover, the October storm generated enhanced irregularity occurrence and prolonged disturbances compared to the May storm. These results confirm that storm time ionospheric dynamics are highly dependent on longitude, storm intensity, seasonal occurrence, and LT of the station at SSC onset (Mendillo, 2006; Schunk & Nagy, 2009). Importantly, the precise ionospheric responses to storm conditions are highly variable across longitude sectors due to differences in solar LT, geomagnetic declination, and regional electrodynamics. The specific LT of the storm onset further modulates how storm induced neutral winds and composition disturbances interact with local VTEC and Ne variability across sectors, underscoring the need for sector-specific analysis to refine current predictive ionospheric models (Fuller-Rowell et al., 1994).

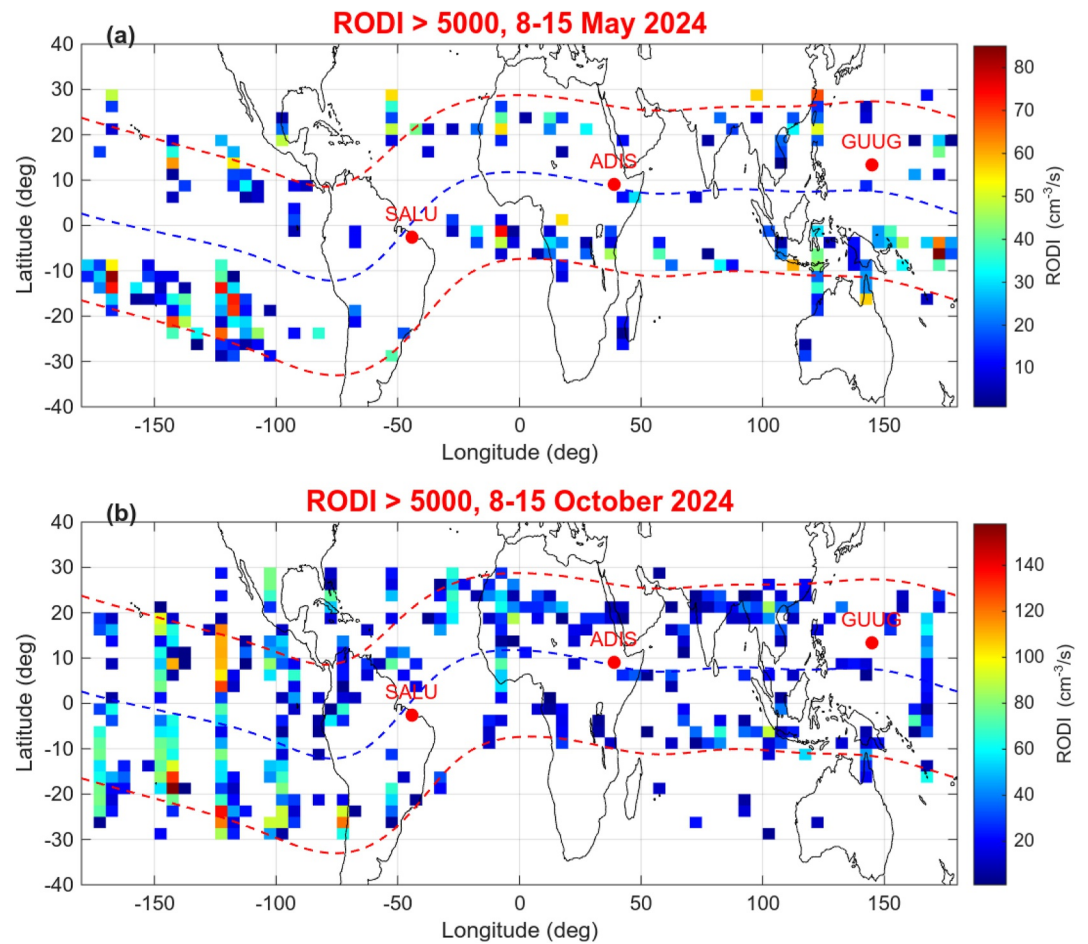


**Figure 14.** Longitudinal variability of the occurrence of irregularities using  $\text{RODI} > 5,000 \text{ cm}^{-3}/\text{s}$  from Sw-A between (a) 8–15 May 2024, and (b) 8–15 October 2024.

Previous studies have extensively reported longitudinal differences in ionospheric responses to geomagnetic storms, attributing these variations primarily to LT dependencies, neutral wind dynamics, and the variability of electric fields across longitudes (e.g., Astafyeva et al., 2020; Balan et al., 2012; Sharma et al., 2011). Their observations demonstrate that the ionospheric disturbances not only vary in intensity between the storms but also display marked differences from one longitudinal sector to another. The longitudinal variations reflect differences in the geomagnetic field geometry, local electrodynamics, and thermospheric wind patterns across the regions (Zhang et al., 2018). The results from Figure 4 demonstrate that the geomagnetic storms of May and October 2024 produced significant disturbances in the equatorial and low-latitude ionosphere, with clear longitudinal asymmetries in the occurrence of irregularities as shown in Figures 10 and 13. Notably, the African and American sectors showed enhanced irregularity activity compared to the Asian sector, with stronger effects observed during the October 2024 storm, which was characterized by a more prolonged main phase and higher geomagnetic activity levels (See Figure 13). Our findings are consistent with previous studies that have reported strong longitudinal dependence of storm time ionospheric responses (e.g., Atıcı & Sağır, 2020; Basu et al., 2002). We observe that the African sector is particularly vulnerable to post-sunset irregularities during storm times as shown in Figures 13a–13b. However, unlike studies that emphasized primarily pre-midnight enhancements, our analysis also shows significant post-midnight activity, especially during the October 2024 storm in the American and African sectors (See Figure 13b). This discrepancy may be linked to differences in storm intensity, solar flux levels, and seasonal effects. The observed longitudinal asymmetries can be explained by several mechanisms. First, the storm time PPEF likely played a critical role in modulating the equatorial ionosphere, enhancing the pre-reversal enhancement (PRE) and thereby creating favorable conditions for irregularity growth in certain longitude sectors. For example, for the American sector, the IMF Bz was southward between 17:00 UT (14:00 LT) on 10

October 2024 and 11:00 UT (08:00 LT) on 11 October 2024 (Figure 2g). Between 18:00 UT (15:00 LT) on 10 May 2024 and 18:00 UT (15:00 LT) on 11 May 2024, the IMF turned southward but fluctuated with its orientation turning northward at 00:00 UT (21:00 LT on 10 May 2024) and 06:00 UT (03:00 LT) on 11 May 2024 (Figure 2b). This indicates that PPEF was eastward during the southward IMF Bz instances that occurred during the daytime resulting into triggering of ionospheric irregularities. Second, DDEF which typically suppress irregularity development, may have contributed to the reduced activity in the Asian sector. The role of thermospheric winds and storm-induced TIDs cannot be excluded, as these processes are known to redistribute plasma density and alter instability conditions (e.g., Han et al., 2025; Zhang et al., 2025). The background conductivity of the ionosphere plays a critical, complex, and multifaceted role in the generation of ionospheric irregularities, which are caused by plasma instabilities. Conductivity can either suppress or enhance these irregularities, depending on the specific instability, location, and time of day. During daytime when the E-region conductivity is strong, ionospheric drivers such as neutral winds and electric fields and their fluctuations cannot win in producing irregularities in the ionosphere. But after sunset when the E-region conductivity becomes weak, the drivers can generate plasma irregularities of various scale sizes (Balan et al., 2018). During both May and October 2024 storms, prompt penetration of magnetospheric electric fields likely enhanced the eastward equatorial electric field in the PRE period, favoring plasma uplift and irregularity growth (Fejer et al., 2008; Kelley, 2009). The stronger irregularities in the African and American sectors suggest that PPEFs were more effective in these regions, possibly due to sectoral differences in the LT of storm onset and conductivity conditions. Additionally, DDEFs driven by storm time thermospheric circulation during the later stages of the storms (Blanc & Richmond, 1980; Fuller-Rowell et al., 2002) may have suppressed PRE and reduced irregularity growth, particularly in the Asian sector during the main phase of 10–13 October 2024 geomagnetic storm (Figure 10f). This mechanism is consistent with the lower irregularity occurrence observed there. Thermospheric winds and composition changes also contribute to the differences in the observed irregularity occurrences over the three longitude sectors. Storm-time equatorward winds and altered neutral composition (enhanced O/N<sub>2</sub> ratios) redistribute plasma density and modify instability growth conditions (Balan et al., 2013). The stronger irregularity activity in Africa may be linked to enhanced equatorward winds over this longitude, as also suggested by observations from the CHAMP and Sw-A (Lühr et al., 2004; Zheng et al., 2018). Storm-time TIDs excited by enhanced high-latitude energy input, can propagate equatorward and modulate equatorial instability conditions (Hernández-Pajares et al., 2006; Jonah et al., 2016). The extended post-midnight activity during the October storm is likely connected to large-scale TID activity, which would modify local ionospheric conditions even after the decay of PPEFs.

Figures 10–12 demonstrate the role of geomagnetic storms in influencing ionospheric irregularities during storm time conditions. The findings are broadly consistent with prior investigations of storm time irregularities in low latitudes. Basu et al. (2002), and Abdu (2012) reported that geomagnetic storms frequently trigger post-sunset equatorial spread F and plasma bubbles, with the strongest activity in the African and American longitudes. Nishioka et al. (2017), and Atıcı and Sağır (2020) also highlighted significant sectoral differences, attributing them to variations in electrodynamic drivers and background ionospheric conditions. Our results support these earlier conclusions but extend them by showing enhanced post-midnight irregularities during the October 2024 storm, contrasting with the dominant pre-midnight activity reported by Huang (2015), and Spogli et al. (2016). The observed storm time differences between May and October 2024 storms (Figures 7 and 8) can be related to different seasons and hemispheric asymmetries in ionospheric electron density observed by the Sw-A. Numerous studies have noted that equinoxes provide favorable conditions for storm time electrodynamic coupling due to alignment of geomagnetic and geographic equators (e.g., Balan et al., 2013; Fuller-Rowell et al., 1994; Mendillo, 2006). The October 2024 storm, occurring under equinox conditions, likely benefited from these enhanced coupling mechanisms, thereby producing stronger irregularities compared to the May 2024 event (Figures 10–12).

The ionospheric response to a geomagnetic storm varies with season, LT, longitude, latitude, and the relative contributions of storm-time electrodynamic and thermospheric processes, including PPEFs, DDEFs, neutral winds, and changes in thermospheric composition. The additional electrodynamic observations provide a consistent interpretation of the storm-time ionospheric responses. During the 10 May 2024 storm, the enhanced daytime EEJ was accompanied by increased JULIA upward  $\mathbf{E} \times \mathbf{B}$  drifts, indicating the presence of an eastward PPEF that strengthened the equatorial fountain and contributed to the observed positive ionospheric storm over AREQ. The agreement between the magnetometer-derived EEJ and JULIA vertical drifts demonstrates that the differential magnetometer approach reliably captures daytime electrodynamic variability and can therefore be

used to infer vertical plasma transport during periods when ISR observations are unavailable. Following the storm commencement, fluctuations and polarity reversals in EEJ, together with the evolution of  $Dp_2$ ,  $D_{dyn}$ , and  $dH_c$ , reveal the transition from PPEF-dominated conditions during the initial phase to increasing DDEF influence during the recovery phase. Although the NNVD model indicated predominantly downward vertical  $\mathbf{E} \times \mathbf{B}$  drifts during parts of the recovery phase, the persistence of positive ionospheric storm effects suggests that residual PPEFs locally compensated for or exceeded the disturbance dynamo contribution. By contrast, during the 10–12 October 2024 storm, the absence of significant daytime EEJ enhancement and the occurrence of downward vertical drifts were consistent with weaker electrodynamic forcing and the generally subdued ionospheric response. Collectively, the EEJ,  $dH_c$ , ionospheric disturbance currents, and vertical  $\mathbf{E} \times \mathbf{B}$  drifts provide complementary evidence that the balance between PPEFs and DDEFs governed the observed storm time TEC variability. The negative storm effect observed over GUUG at 07:00 LT is consistent with the combined electrodynamic signatures. Although the  $Dp_2$  component indicated an eastward PPEF, the westward  $D_{dyn}$  component was sufficiently strong to produce net downward  $\mathbf{E} \times \mathbf{B}$  drifts. The suppression of the EEJ and the absence of a significant enhancement in  $\Delta H$  further suggest weakened eastward equatorial electric fields, leading to a lowering of the F region, enhanced recombination, and reduced TEC. The agreement between the current systems, modeled vertical drifts, and the observed TEC depletion provides a coherent explanation for the storm-time ionospheric response.

In summary, this study has shown that the May and October 2024 geomagnetic storms produced strong but distinct ionospheric responses across longitude sectors. The African and American longitudes were particularly susceptible to storm-induced irregularities, while the Asian sector showed relatively suppressed activity during October 2024 storm and vice versa during May 2024 storm. These differences can be explained by the combined action of PPEFs, DDEFs, thermospheric winds, and TIDs, modulated by seasonal and conductivity conditions. These results reinforce the critical role of electrodynamic and neutral processes in shaping the storm time equatorial ionosphere, and they underscore the importance of expanding multi-longitude monitoring and modeling efforts for improved space weather prediction. The findings underscore the importance of considering longitude-dependent electrodynamic drivers in global storm time models (Richmond et al., 2003; Scherliess & Fejer, 1997).

## 5. Conclusions

In this study, we examined the response of the ionosphere to geomagnetic storms of May and October 2024, the two recent great geomagnetic storms of solar cycle 25. We identified the occurrence of ionospheric irregularities during the two geomagnetic storms. We used percentage change in TEC ( $\Delta VTEC\%$ ) and rate of change of VTEC or electron density (Ne) index (ROTI or RODI) to study the ionospheric response and presence of ionospheric irregularities, respectively. We used data from ground-based GNSS receivers in South America (SALU, São Luís, Brazil, 2.59°S, 44.2°W geographic, and 0.25°S geomagnetic), Africa (ADIS, Addis Ababa, Ethiopia, 9.04°N, 38.8°E geographic, and 0.18°S geomagnetic), and Asian (GUUG, Guam island, 13.43°N, 144.8°E geographic, and 5.66°N geomagnetic). In addition, we used data from Swarm-A satellite (Sw-A) to extract Ne, and RODI, and examined the presence of ionospheric irregularities in the in situ data during the two geomagnetic storms. Overall, the electron density was higher for the storm of October 2024 than the one of May 2024, yet the minimum Dst value for the May geomagnetic storm was lower than that of October 2024. This corroborates that Dst index is a necessary but not a sufficient index to identify, gauge and represent the space weather effects on the atmosphere during a geomagnetic storm. We divided the Sw-A data into three longitude sectors: American (−90° to −30°), African (−30° to 60°) and Asian (60° to 150°). We then restricted the data to low latitudes within  $\pm 30^\circ$ . The normalized percentage occurrence rate was computed by taking a threshold value of  $5 \times 10^3 \text{ cm}^{-3}/\text{s}$ . Throughout the two storm periods, at some instances, the RODI values were above a threshold value, a clear indication that ionospheric irregularities were triggered during the two storms on a global scale. The percentage occurrence of ionospheric irregularities followed a reverse longitudinal trend with higher occurrences during the geomagnetic storm of October 2024 than during the geomagnetic storm of May 2024 at the different sectors. It can be seen that during the geomagnetic storm on 11 May 2024 the crests were larger over the American sector, followed by African sector and then Asian sector, clearly demonstrating a longitudinal dependence of TEC profiles. There was a marked enhancement in TEC profiles over the southern than the northern hemisphere, clearly indicating a north-south asymmetry arising from disruption of the fountain effect as a result of the storm. The findings of this study have contributed to a better understanding of the mechanisms governing storm time

plasma structuring and may improve space weather prediction models through data assimilation and incorporating longitude dependency into the models. The use of a single GNSS station per longitudinal sector may limit the ability to resolve intra-sector variability and may introduce biases due to local ionospheric conditions, satellite geometry, and magnetic field configuration. Future work may incorporate multiple GNSS stations within each longitudinal sector and other ground- and space-based instrumentation such as ionosondes, magnetometers, and radio occultation data to provide a more comprehensive characterization of storm time ionospheric variability and help distinguish true longitudinal differences from local observational effects. Sensitivity analysis to evaluate different ROTI thresholds (0.3–0.7 TECU/min) may be performed to ascertain whether the observed longitudinal reversal and enhanced irregularity occurrence during the October storm remain consistent across different threshold values of ROTI.

## Conflict of Interest

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

## Availability Statement

All data used in this study are publicly available. GNSS data were downloaded from International GNSS Service (2024). GNSS data processing and analysis were performed using the GPS-TEC analysis software developed by Seemala and Valladares (2011). The implementation used in this study was GPS-TEC Analysis Program version 3.5, while the underlying algorithm is described by Seemala (2023). The Dst and Kp indices were downloaded from NASA Space Physics Data Facility (2020). Geomagnetically quietest days of the month were obtained from International Service of Geomagnetic Indices (2024). The Sw-A observations were downloaded from European Space Agency (2024). All data sets used in this study have been archived and published by Habyarimana et al. (2026). The NNVD model can be downloaded from Habarulema and Okoh (2026). The magnetometer data were obtained from INTERMAGNET (2024), Low Latitude Ionospheric Sensor Network, LISN (2026), and Estudo e Monitoramento Brasileiro do Clima Espacial, EMBRACE (2026).

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