Coordinated ground-based and space-based observations of equatorial plasma bubbles

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Key Points:

- Combined GOLD/UV spectrograph images and ground-based TEC data revealed EPB features and development over a large geographic area
- Bottomside F-layer oscillations and travelling ionospheric disturbance were observed by ionosonde and detrended TEC results
- Atmospheric gravity waves likely play an important role in seeding the R-T instability and the development of this EPB event

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Abstract

This paper presents coordinated and fortuitous ground-based and space-borne observations of equatorial plasma bubbles (EPBs) over the South American area on 24 October 2018, combining the following measurements: Global-scale Observations of Limb and Disk (GOLD) far-ultraviolet emission images, Global Navigation Satellite System (GNSS) total electron content (TEC) data, Swarm in situ plasma density observations, ionosonde virtual height and drift data, and cloud brightness temperature data. The new observations from the GOLD/UV imaging spectrograph taken at geostationary orbit provide a unique opportunity to image the evolution of plasma bubbles near the F-peak height over a large geographic area from a fixed longitude location. The combined multi-instrument measurements provide a more integrated and comprehensive way to study the morphological structure, development, and seeding mechanism of EPBs. The main results of this study are as follows: (1) The bubbles developed a westward-tilted structure with 10°– 15° inclination relative to the local geomagnetic field lines, with eastward drift velocity of 80–120 m/s near the magnetic equator that gradually decreased with increasing altitude/latitude. (2) Wave-like oscillations in the bottomside F-layer and detrended TEC were observed, which are probably due to upward propagating atmospheric gravity waves (AGWs). The wavelength based on the MSTID signature was consistent with the inter-bubble distance of ∼500–800 km. (3) The AGWs that originated from tropospheric convective zone are likely to play an important role in seeding the development of this equatorial EPBs event.

Plain Language Summary: This study presents multi-instrument observations of equatorial plasma density depletions occurred on 24 October 2018 by using Global-scale Observations of Limb and Disk (GOLD) far ultraviolet images, Global Navigation Satellite System (GNSS) total electron content (TEC) data, electron density measurements from Swarm satellite, ionosonde measurements, and cloud temperature data. This multi-instrument study generated an integrated and detailed image revealing both large-scale and meso-scale structures of the equatorial plasma depletion. Our results also suggest that atmospheric gravity waves originating from tropospheric convection activity could play a significant seeding role in the development of equatorial plasma bubbles.

1 Introduction

Equatorial plasma bubbles (EPBs) refer to irregular structures of plasma density depletion that are usually observed in the equatorial and low latitude F-region during postsunset period. Typical density irregularities within EPBs can have different scale sizes of several to hundreds of kilometers, and EPBs can cover a broad altitudinal range from the bottomside ionosphere up to ∼1,000 km (Cherniak, Zakharenkova, & Sokolovsky, 2019; Lühr, Xiong, Park, & Rauberg, 2014). One of the top research priorities in the global space weather community is to better understand the generation mechanisms and the dynamic features of EPBs, because they can severely disrupt the amplitude and phase of trans-ionospheric radio waves so as to cause adverse effects on relevant communication and navigation systems. It is generally accepted that EPBs are triggered under a favorable condition of the generalized Rayleigh-Taylor (R-T) instability at the bottomside of the F layer, where a steep vertical density gradient forms after the E layer disappears post-sunset due to high recombination rate. During quiet times, the prereversal enhancement (PRE) of the zonal electric field is responsible for the enhanced upward $\mathbf{E}\times\mathbf{B}$ drift after sunset, which elevates the ionospheric height and subsequently amplifies the growth rate of R-T instability (Abdu, 2005; Carter, Zhang, Norman, Kumar, & Kumar, 2013; Fejer, Scherliess, & de Paula, 1999; Kil, 2015; Woodman & La Hoz, 1976). Thus, initial density perturbations at the bottomside F-layer can then evolve into EPBs and develop nonlinearly after rising to the topside ionosphere.

The morphological features and spatial/temporal variability of EPBs have been widely investigated via case studies and statistical analysis using different observational methods. For example, the structure of EPBs can be observed from irregular traces of range-type equatorial spread F (ESF) in ionograms (Abdu, 2012; Hysell, 2000; Li et al., 2018; Tsunoda, 2015). The spatial variation of EPBs can be derived from the dark streaks of emission depletion in optical observations from ground-based all-sky imagers (ASIs) or space-based ultraviolet imaging spectrographs (e.g., Comberiate & Paxton, 2010; Hickey et al., 2018; Kelley et al., 2003; Kil, Heelis, Paxton, & Oh, 2009; Makela, 2006; Martinis et al., 2015; Otsuka, Shiokawa, Ogawa, & Wilkinson, 2002; Shiokawa, Otsuka, Lynn, Wilkinson, & Tsugawa, 2015). In addition, the altitudinal information of irregularities embedded within EPBs can be examined through observations of plume-like structures from coherent backscatter radar or incoherent scatter radar measurements (Ajith et al., 2015; Jin et al., 2018; Li et al., 2013; Rodrigues et al., 2018; Tulasi Ram, Ajith, Yokoyama, Yamamoto, & Niranjan, 2017; Yokoyama & Fukao, 2006). Furthermore, the temporal variation and occurrence distribution of irregularities/bubbles can be extracted from in situ satellite observations, such as the Defense Meteorological Satellite Program (DMSP) constellation (Burke, Gentile, Huang, Valladares, & Su, 2004; Burke, Huang, Gentile, & Bauer, 2004; C. Y. Huang, Burke, Machuzak, Gentile, & Sultan, 2002), Communications/Navigation Outrage Forecasting System (C/NOFS) satellite (C.-S. Huang et al., 2014; Smith & Heelis, 2017), and Swarm constellation (Xiong et al., 2016; Zakharenkova, Astafyeva, & Cherniak, 2016). Moreover, with the fast-growing and global availability of ground-based Global Navigation Satellite Systems (GNSS) measurements and space-based radio occultation data, the evolution characteristics of EPBs can be monitored continuously on both global or regional scales (e.g., Aa et al., 2018; Barros, Takahashi, Wrasse, & Figueiredo, 2018; Buhari et al., 2014, 2017; Cherniak, Krankowski, & Zakharenkova, 2014; Cherniak & Zakharenkova, 2016; Katamzi-Joseph, Habarulema, & Hernández-Pajares, 2017; Ma & Maruyama, 2006; Nishioka, Saito, & Tsugawa, 2008; Takahashi et al., 2015).

Although EPBs have been extensively studied for several decades, there are still some important and challenging tasks that need to be performed to improve current understanding of their detailed spatial/temporal structures and seeding mechanisms. In this regard, different instruments have their own advantages and limitations in analyzing EPBs: (1) Coherent/incoherent scatter radars can monitor irregularities at high spatial resolution, but their location and field-of-view (FOV) limit their coverage range. (2) Optical measurements of ASIs are limited with their field-of-view, and their availability depends on weather conditions. For this reason, multiple ASIs are usually required to get a complete evolution of EPBs structures. (3) Low-Earth orbiting (LEO) satellite observations can produce in situ density profiles or ultraviolet radiance images of irregularities at high spatial resolution, but they can only sample a narrow swath of the EPBs structures along the track of the satellite. (4) Global/regional GNSS total electron content (TEC) observations can monitor ionospheric variability continuously; however, the small-scale structures characteristic of EPBs will sometimes be smoothed out because of the integrating nature of the TEC calculation, not to mention huge data gaps which still exist over receiver-sparse areas, such as oceans.

For these reasons, collective analysis of multi-site and multi-instrument measurements provides an effective way to generate an integrated and comprehensive image for specifying both large-scale and mesoscale features of plasma bubbles (e.g., Aa et al., 2019; Cherniak et al., 2019). Recently, with the successful launch and deployment of NASA's Global-scale Observations of Limb and Disk (GOLD) mission, an excellent opportunity exists to use the unique data-set from the GOLD far ultraviolet (FUV) imaging spectrograph to monitor equatorial ionospheric structure. In this paper, we present coordinated ground-based and space-borne observations of an EPBs event which occurred on October 24, 2018. Our analysis uses multi-instrument measurements: GOLD/UV imaging spectrograph, TEC from GNSS receiver networks, Swarm in-situ density observations, ionosonde measurements, and cloud temperature data. We use these observations

120 to implement a comprehensive analysis of the structural evolution and relevant seeding
121 mechanisms of EPBs.

2 Data Description

123 The GOLD mission was launched on 25 January 2018 and started its operational
124 observations in October 2018. The main scientific objective of GOLD is to understand
125 the "weather" response of the Earth's thermosphere and ionosphere system to forcing
126 from above and below, and the formation and evolution of equatorial plasma bubbles
127 is a primary scientific question (Eastes et al., 2017, 2019). Operating at geostationary
128 orbit (GEO) over the longitude of 47.5°W, GOLD has an unparalleled advantage of "star-
129 ing" at the American region from a fixed geographic location for extended periods of time,
130 providing an exact time-evolving map that can unambiguously specify the spatiotem-
131 poral variability of Earth's thermosphere and ionosphere system. The GOLD instrument
132 is a far-ultraviolet imaging spectrograph that measures Earth's airglow emissions from
133 132 to 162 nm, which can be used to infer thermospheric temperature and composition
134 on the dayside disk as well as equatorial ionospheric structures on the nightside. The night-
135 time disk images of atomic oxygen 135.6 nm emissions, which have a spatial resolution
136 ∼100 km in the longitudinal direction and ∼50 km in the latitudinal direction, will be
137 used in this study to derive valuable information on the low latitude ionosphere.

138 Gridded TEC products from the Madrigal distributed data system are also used
139 to study EPBs structures. TEC data are produced and provided through the Madrigal
140 distributed data system developed at the Massachusetts Institute of Technology (MIT)'s
141 Haystack Observatory by using dense networks of worldwide GNSS receivers, and have
142 a resolution of 1° (latitude) × 1° (longitude) × 5 min (Rideout & Coster, 2006; Vier-
143 inen, Coster, Rideout, Erickson, & Norberg, 2016). Moreover, ionosonde measurements
144 from Sao Luis (2.6°S, 315.8°E) and Fortaleza (3.9°S, 321.6°E), as well as in situ plasma
145 density measurements onboard the Swarm A/C satellites are also used here to analyze
146 the characteristics of plasma irregularities.

147 Localized gravity waves that originated from the tropospheric convective zone could
148 be an essential factor in seeding EPBs, and the deep convection activity can be deduced
149 from cloud temperature data. These data are derived from global (60°S–60°N) 4-km pixel-
150 resolution infrared brightness temperature data, merged from selected geostationary satel-
151 lites measurements over the period of record (i.e., Geosynchronous Operational Environ-
152 mental Satellites [GOES]-8/9/10/11/12/13/14/15/16, United States; the Meteorolog-
153 ical Satellite [Meteosat]-5/7/8/9/10, European Community; Geosynchronous Meteoro-
154 logical Satellite[GMS]-5/Multi-functional Transport Satellite[MTSat]-1R/2/Himawari-
155 8, Japan) (Janowiak, Joyce, & Xie, 2017).

3 Results

157 EPBs are known to produce optical signatures observed as streaks of reduced emis-
158 sion in space-borne ultraviolet imaging spectrographs (Kelley et al., 2003; Kil et al., 2004).
159 Figure 1 shows continuous OI 135.6 nm radiance maps observed by GOLD in successive
160 disk scans during 21:10–22:55 UT on 24 October 2018. The bright zonal band in the low-
161 latitude region paralleling the magnetic equator (red line) is produced by enhanced oxy-
162 gen ion density in the equatorial ionization anomaly (EIA) region. The dark streaks that
163 cut through the EIA band represent reduced emissions caused by low density within plasma
164 bubbles. There are seven discernible dark streaks marked with #1–7 from east to west.
165 These streaks elongate from northwest to southeast direction, with a meridional length
166 of ∼1,500-2,000 km and inter-bubble distance of ∼500-800 km. Moreover, Figure 2 dis-
167 plays similar UV images for later time periods of 23:10–23:55 UT on October 24, 2018.
168 The white dotted curves show four different geomagnetic field lines (marked with I, II,
169 III, and IV) along which the EPBs were approximately extending. When comparing the

170 consecutive images, the EPBs depletion streaks were found to be drifting eastward and
171 developing westward-tilted (or backward C-shape) structure. The tilt angle ranges from
172 $10°$–$15°$ relative to the Earth's magnetic field line (Figure 2c and 2d). The airglow sig-
173 nature of EPBs and the tilted structure were also illustrated in simulations (e.g. Ret-
174 terer, 2010) and are consistent with the previous ground-based and space-borne obser-
175 vations (Jin et al., 2018; Kelley et al., 2003; Kil et al., 2009; Li et al., 2018; Tsunoda, Liv-
176 ingston, McClure, & Hanson, 1982), which will be further discussed in the next section.

177 Besides the UV images, the EPBs can also be observed in two-dimensional TEC
178 maps as a depletion structure perpendicular to the geomagnetic equator. Figure 3 shows
179 twelve successive TEC maps over the South American region with 15-min cadence dur-
180 ing 21:00–23:45 UT on 24 October 2018. The EIA crests can be seen as two regions with
181 enhanced TEC about 10 degrees north and south of the geomagnetic equator (black dot-
182 ted line). Two TEC depletion belts are parallel to the magnetic field lines, as highlighted
183 by the black dashed lines, which exist over the equatorial region around $45°W$ and $40°W$.
184 Comparing with the surrounding region, the amplitude of the TEC depletion within these
185 EPBs is approximately 10 TEC Unit (TECU, 10^{16} el/m^2). Taking the left-side branch
186 of the depletion as an example, we find an onset time of around 22 UT with a subsequent
187 gradual extension toward the EIA crest along the geomagnetic field line "I", which is the
188 same field line as that marked in Figure 2. The EPB along field line "II" also exhibited
189 similar but weaker evolution.

190 Moreover, there are two ionosondes, i.e., Sao Luis and Fortaleza, which are located
191 near these two depletion belts and are labeled as asterisk and diamond in Figure 3. Fig-
192 ure 4 shows the F-layer bottomside virtual height (h'F), vertical drift velocity, and zonal
193 drift velocity measured by these two ionosondes on 24 October 2018 (red), as compared
194 with the previous 5-day averaged values (black). It can be seen from the top panels that
195 the h'F over Sao Luis exhibited a significant pre-reversal enhancements (PREs, marked
196 with an arrow) from 250 km to 360 km at around 21 UT on 24 October, while the 5-day
197 averaged peak value of PREs is less than 300 km. A considerable h'F elevation around
198 the same time can be also observed for Fortaleza station, with the peak value of PREs
199 (310 km) on 24 October larger than 5-day average one (250 km). The corresponding peak
200 velocity of vertical drift shown in Figures 4c and 4d, which is 30 m/s over Sao Luis and
201 25 m/s over Fortaleza, also displayed considerable increase compared with the 5-day av-
202 eraged values ($\sim$10 m/s). These collectively demonstrate the presence of an enhanced
203 dusk sector zonal electric field, raising the F layer and amplifying the growth rate of the
204 R-T instability to generate the observed EPBs. The zonal drift exhibited eastward ve-
205 locity after the PREs.

206 The nighttime GOLD/UV OI 135.6 nm images were mainly fixed at the American-
207 Atlantic longitudes. The TEC maps have a broader coverage but with data gaps over
208 the ocean, especially near the Northern Hemisphere part of the EIA. These two data-
209 sets complement each other and thus were combined to generate a map shown in Fig-
210 ure 5, which provides a much broader spatial context for EPBs. The extension of EPBs
211 to the southern EIA crest and the backward C-shape streak spanning both hemispheres
212 are clearly indicated. Furthermore, three consecutive satellite passes of Swarm A/C and
213 the corresponding latitudinal profiles of the in situ electron density along these orbits
214 are also shown in Figure 5. Both Swarm A and Swarm C flew at the height of $\sim$450 km
215 and were located at nearby longitudes around 09 LT (dayside) and 21 LT (nightside).
216 Swarm B is not shown here since it did not pass through the American sector at local
217 dusk hours during this period. The signature of plasma irregularities can be clearly seen
218 in orbit #1 ($17.0°W$) of Swarm A during 22:00–22:30 UT and orbit #5 ($39.0°W$) of Swarm
219 C during 23:30–00:00 UT, where considerable plasma density bite outs with sawtooth-
220 like irregular fluctuations were measured near the magnetic equator (horizontal dotted
221 line). This revealed the presence of small-scale density fluctuations within the EPBs seen
222 in the GOLD/UV imaging and GNSS TEC results. Although Swarm A and C were very

²²³ close to each other and passed the EPBs nearly the same time, there are certain spatial
²²⁴ differences in the small-scale structures that are observed by them (e.g., compare pan-
²²⁵ els 1 and 4).

4 Discussion

²²⁷   First, the development of the westward tilt (or backward C-shape) of the EPBs de-
²²⁸ pletion has been clearly shown in GOLD/UV optical images in Figure 1 and Figure 2.
²²⁹ This shape has previously been suggested to be caused by latitudinal variation of zonal
²³⁰ plasma drift and/or the polarization electric field inside the EPBs. As described in the
²³¹ principle of F-region dynamo theory (Rishbeth, 1997): the neutral wind in the post-sunset
²³² sector is typically eastward at low latitudes, which generates a downward F-region dy-
²³³ namo electric field. This vertical electric field further drives an eastward $\mathbf{E} \times \mathbf{B}$ drift of
²³⁴ the F-region plasma with nearly similar velocities as the neutral wind. During this study
²³⁵ event, estimation of the eastward drift velocity of 80–120 m/s near the magnetic equa-
²³⁶ tor can be achieved through comparing the differences ($\sim 2°$–$3°$) of the central location
²³⁷ of the dark streaks #1 between Figure 2a and 2d, which is consistent with the zonal drift
²³⁸ velocities measured by ionosondes in Figures 4e and 4f and previous experimental/modeling
²³⁹ studies of EPBs zonal drift velocities (e.g. Chapagain et al., 2012; Gurav et al., 2018; Huba,
²⁴⁰ Ossakow, Joyce, Krall, & England, 2009; Sun et al., 2016). Furthermore, both numer-
²⁴¹ ical calculations and in situ observations have previously shown that this zonal plasma
²⁴² eastward drift often decreases with increasing altitude/latitude and thus forming a back-
²⁴³ ward C-shape (e.g., Kil, Kintner, de Paula, & Kantor, 2002; Martinis, Eccles, Baumgard-
²⁴⁴ ner, Manzano, & Mendillo, 2003; Pimenta, Fagundes, Sahai, Bittencourt, & Abalde, 2003).
²⁴⁵ On the other hand, Kil et al. (2009) and C.-S. Huang et al. (2010) suggested that a po-
²⁴⁶ larization electric field can develop inside the plasma depletion region due to conductiv-
²⁴⁷ ity gradients, which can also retard the eastward flow of the plasma depletion structures.

²⁴⁸   Second, in addition to generally favorable condition for the R-T instability created
²⁴⁹ by the usual Pre-reversal enhancement, various mechanisms have been proposed as pos-
²⁵⁰ sible seeding factors that can trigger initial plasma density perturbations on the bottom
²⁵¹ side F layer. These include: (1) Enhanced zonal eastward electric field due to solar wind-
²⁵² magnetosphere-ionosphere coupling processes. The prompt penetration electric field (PPEF)
²⁵³ from high latitude to low latitude can increase the F-layer vertical drift on the daytime
²⁵⁴ through dusk sectors and thus facilitate the development of EPBs (Abdu et al., 2003;
²⁵⁵ Basu et al., 2007; Ebihara & Tanaka, 2015; Tulasi Ram et al., 2008). (2) Gravity waves
²⁵⁶ (GWs) from the lower atmosphere. Gravity waves generated by upward propagating me-
²⁵⁷ teorological processes in the lower atmosphere may modulate the bottomside F-layer plasma,
²⁵⁸ producing large-scale wave structures (LSWS) with periodic spacing, which may accel-
²⁵⁹ erate the F-layer uplifting and trigger EPBs (Abdu et al., 2009; McClure, Singh, Bamg-
²⁶⁰ boye, Johnson, & Kil, 1998; Retterer & Roddy, 2014; Tsunoda, 2010; Tsunoda et al., 2011;
²⁶¹ Tulasi Ram et al., 2014). (3) Neutral wind shear. Some studies suggested that vertical
²⁶² shear in the zonal winds could cause wave-like vortex, which has a rapid growth rate that
²⁶³ can seed the R-T instability and initiate plasma irregularities (Hysell, Kudeki, & Chau,
²⁶⁴ 2005; Hysell, Larsen, Swenson, & Wheeler, 2006; Kudeki, Akgiray, Milla, Chau, & Hy-
²⁶⁵ sell, 2007). (4) Nighttime medium-scale travelling ionospheric disturbances (MSTIDs)
²⁶⁶ due to Perkins/Es instabilities (Perkins, 1973). The polarization electric field within MSTIDs
²⁶⁷ can map along the geomagnetic field lines to the equatorial bottomside F layer to ini-
²⁶⁸ tiate the EPBs (Krall et al., 2011; Miller, Makela, & Kelley, 2009; Taori et al., 2015; Val-
²⁶⁹ ladares & Sheehan, 2016).

²⁷⁰   For the current EPBs case, the geomagnetic activity condition was relatively quiet
²⁷¹ on 24 October 2018 with the interplanetary magnetic field (IMF) Bz close to zero and
²⁷² no geomagnetic storm or substorm onset within a few hours before the observed EPBs
²⁷³ (Figure 6a). The possibility of significant external driving forces (e.g., interplanetary elec-
²⁷⁴ tric fields) from the magnetosphere for EPBs in the postsunset sector is unlikely under

this circumstance. Figure 6b displays the rate of TEC index (ROTI) map to illustrate the ionospheric irregularities between 35°W and 55°W over the South American sector. Next, we discuss the possibility of forcing from below. Figure 6c shows the temporal variation of the electron density profile at Sao Luis between 12 and 24 UT on October 24, 2018. Of particular note, the ionosonde-retrieved topside profile above the F2 peak is obtained assuming a α-Chapman shape of plasma distribution (Reinisch & Huang, 2001), and thus only the bottomside profile should be examined. Three continuous quasi-periodic (~50 min) wave-like modulations of the bottomside F-layer height marked by white arrows can be clearly seen between 22–24 UT. Moreover, Figure 6d shows the F-layer true height as observed by the digisonde at specific plasma frequencies (3.0–6.5 MHz) over Sao Luis, plotted from 18 UT to 24 UT. There was a clear downward phase propagation (marked with a dashed line), which identifies the possible presence of atmospheric gravity waves (Abdu et al., 2009; Mandal et al., 2019). Furthermore, Figure 6e shows a keogram plot of detrended TEC as a function of latitude and time at 48°W longitude that around the EPBs region. Detrended TEC was calculated using the same method mentioned in Coster et al. (2017) and Zhang et al. (2017), where 1-hour TEC moving average was subtracted. Medium-scale travelling ionospheric disturbances (MSTIDs) that represent the ionospheric signature of atmospheric gravity waves are clearly observed in detrended TEC. Several possible TID wavefronts (marked with dashed lines) can also be clearly seen with an estimated propagation velocity of ~200–300 m/s and wavelength of ~500–800 km. The latter is close to the value of inter-bubble distance shown in GOLD/UV and TEC images. Many studies have demonstrated that such atmospheric gravity waves can be generated in the tropospheric convective region near the inter-tropical convergence zone (ITCZ) and can grow exponentially when propagating all the way upward into the thermosphere-ionosphere system before being entirely dissipated (Li et al., 2016; Vadas, 2007; Yiğit et al., 2012; Yizengaw & Groves, 2018). However, considering that troposphere excitation sources can be highly mobile and that wave propagation along the long path is strongly influenced by low atmosphere variability, the manifestation of TIDs in the keogram might not be so regular and well-organized. Thus, in order to further specify the potential source of the AGW/TIDs, Figure 6f shows an observation of deep clouds in brightness temperature at 22 UT on 24 October 2018. The purple to blue areas in South American and West African areas indicates that temperature was lower than 210 K, a signature suggesting that the tops of thunderstorms protrude well into the tropopause region (Hoffmann & Alexander, 2010). Such objects are referred to as deep convective clouds and can be an important source for the generation of upward propagating AGWs (e.g., Azeem et al., 2015; Jonah et al., 2018; Vadas & Liu, 2009). In particular, these studies indicated that concentric secondary gravity waves and TIDs with a wavelength of several hundred to thousand kilometers can be triggered by troposphere convection and detected at ionospheric heights. The deep convection activity shown here occurred in the local afternoon and continued for several hours, which was during the similar periods and in locations adjacent to where the MSTIDs were observed. Therefore, the combination of these mutually supportive pieces of evidence collectively suggests that convectively induced AGW/TIDs could have seeded the EPBs in this current case.

5 Conclusion

This paper presents coordinated ground-based and space-borne observational analysis of equatorial plasma bubbles over the South American area on 24 October 2018. The morphological structure and seeding mechanism of the bubbles were analyzed by using multi-instrument measurements, including the GOLD/UV imaging spectrograph, GNSS TEC maps, Swarm in situ electron density data, ionosonde measurements, and cloud temperature data. The new observations provided by GOLD/UV geosynchronous images provide a unique tool for studies of plasma irregularity evolution and equatorial ionospheric dynamics from a fixed longitude location. Furthermore, a combination of different measurements provides a powerful tool for the space weather community to achieve

328 a more integrated and detailed view on plasma irregularity structure. The main results
329 can be summarized as follows: (1) The plasma depletion developed westward-tilted struc-
330 ture of 10°–15° relative to the Earth's magnetic field line, with an eastward drift veloc-
331 ity of 80–120 m/s near the magnetic equator that gradually decreased with increasing
332 altitude/latitude. (2) Wave-like oscillations of travelling ionospheric disturbances were
333 observed both in ionosonde electron density profiles and detrended TEC keograms. Ob-
334 served wavelengths were consistent with inter-bubble distances of 500–800 km. (3) At-
335 mospheric gravity waves originating from the tropospheric convective zone are suggested
336 to be a possible seeding process for the development of this EPBs event.
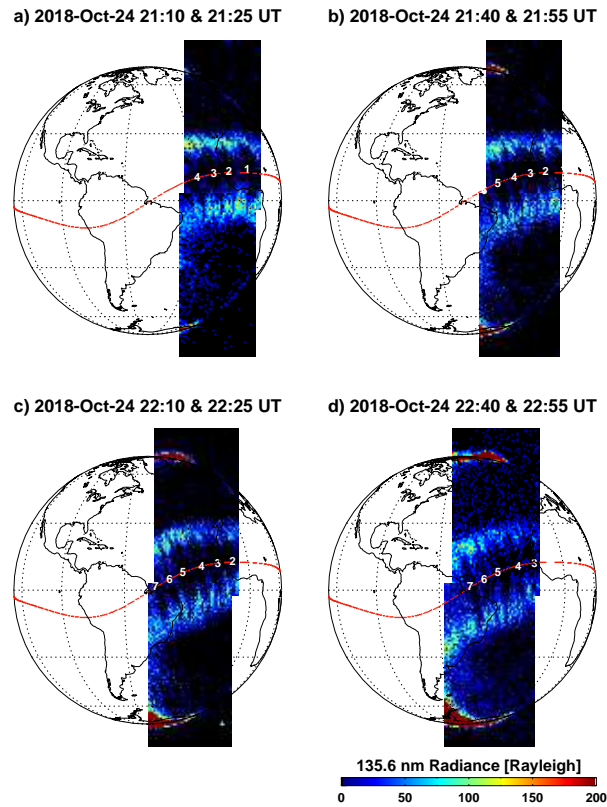
Figure 1. OI 135.6 nm radiance maps observed in successive disk scan of GOLD/UV nighttime imaging during 21:10–22:55 UT on 24 October 2018. The dark streaks marked by different numbers represent the optical signature of EPBs. The geomagnetic equator is also shown by red dashed lines. GOLD = Global-Scale Observations of the Limb and Disk; UV = ultraviolet; EPBs = equatorial plasma bubbles.

a) 2018-Oct-24 23:10 UT **b) 2018-Oct-24 23:25 UT**

c) 2018-Oct-24 23:40 UT **d) 2018-Oct-24 23:55 UT**

135.6 nm Radiance [Rayleigh]

0   50   100   150   200
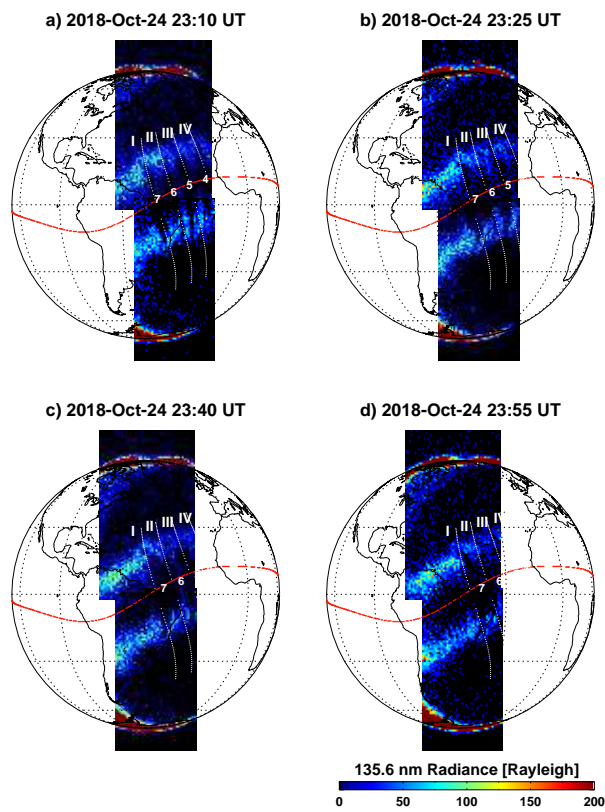
Figure 2.   The same as Figure 1, but during the time interval of 23:10–23:55 UT on 24 October 2018. The white dotted curves show 4 different geomagnetic field lines that go across the EPBs. EPBs = equatorial plasma bubbles.
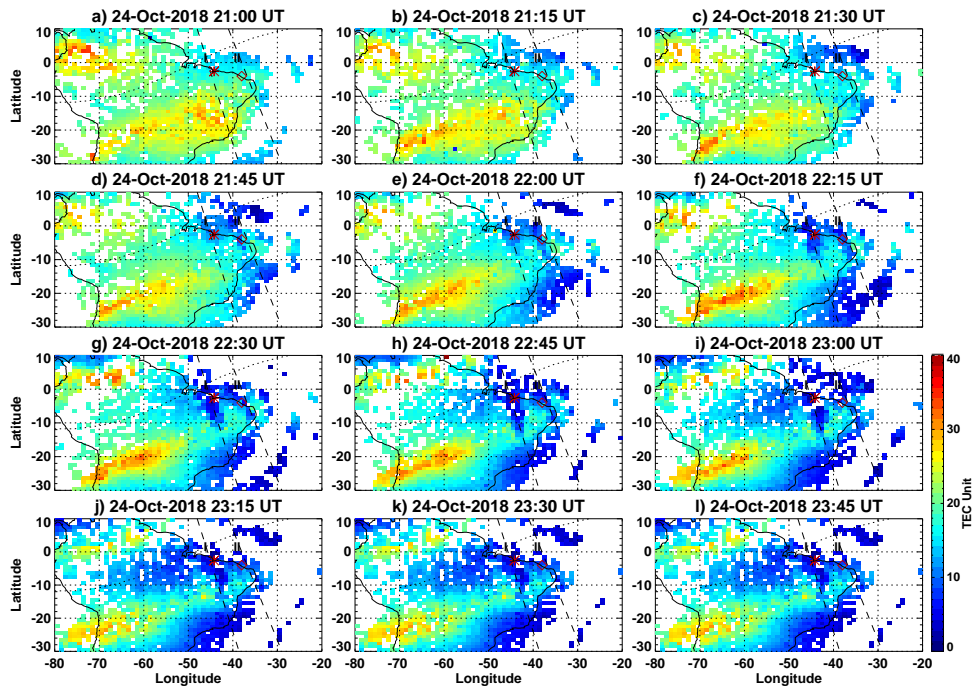
Figure 3. Gridded TEC maps over South American regions with 15-min interval during 21:00–23:45 UT on 24 October 2018. The ionosonde stations of Sao Luis and Fortaleza are marked with asterisk and diamond, respectively. Two geomagnetic field lines ("I" and "II") that go across the EPBs are marked in dashed lines, and the geomagnetic equator is shown in dotted line. EPBs = equatorial plasma bubbles.
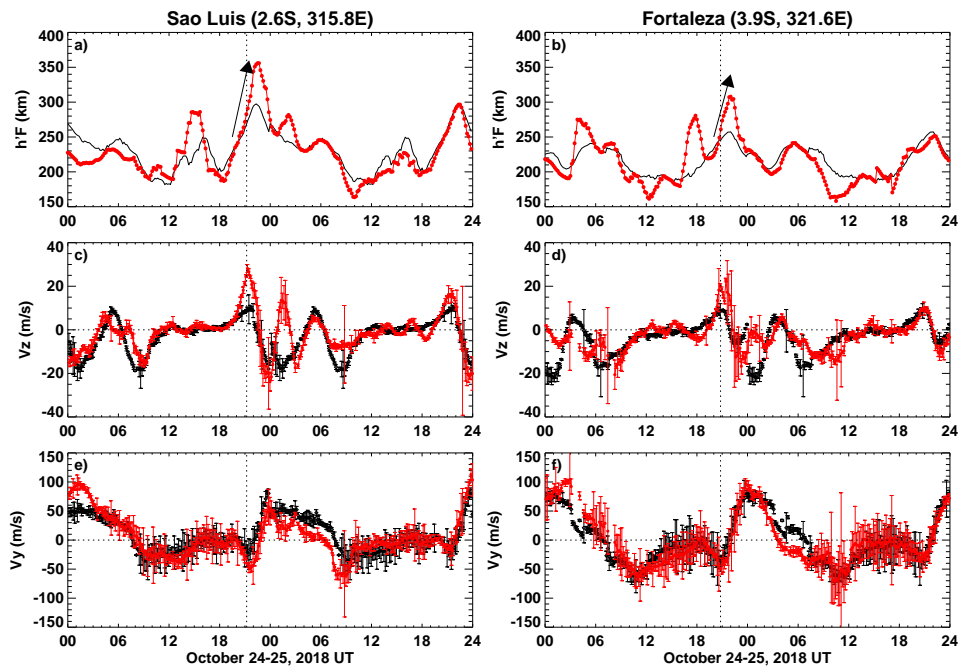
Figure 4. The temporal variation of ionospheric h'F, F layer vertical drift, and zonal drift velocity observed at Sao Luis (left panels) and Fortaleza (right panels) during the period of 24–25 October 2018. The black lines represent the values of previous 5-day average. The vertical dotted line represents the local sunset. The error bars represent the velocity spread.
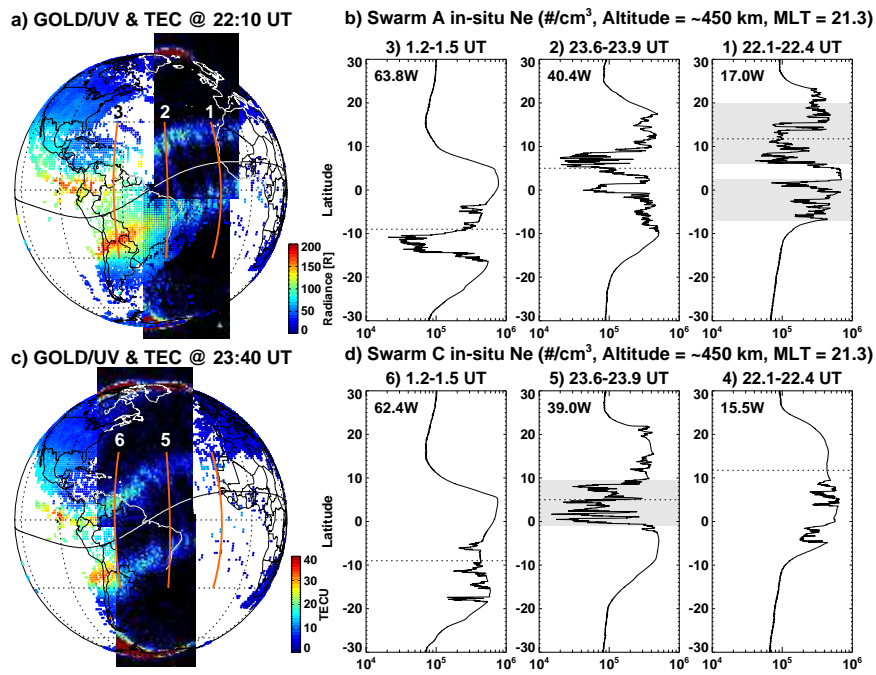
Figure 5. (a) Combined global map of GNSS TEC and OI 135.6 nm radiance of GOLD/UV imaging at 22:10 UT with three consecutive satellite paths of Swarm A. (b) Variation of in situ electron density as a function of latitudes along these paths. (c, d) The same as Figures 5a and 5b, respectively, but at 23:40 UT and for Swarm C satellite paths. The shaded areas represent certain plasma depletions. The magnetic equator is marked by solid line in left panels and dotted line in right panels. GNSS = global navigation satellite system; TEC = total electron content; GOLD = Global-Scale Observations of the Limb and Disk; UV = ultraviolet.
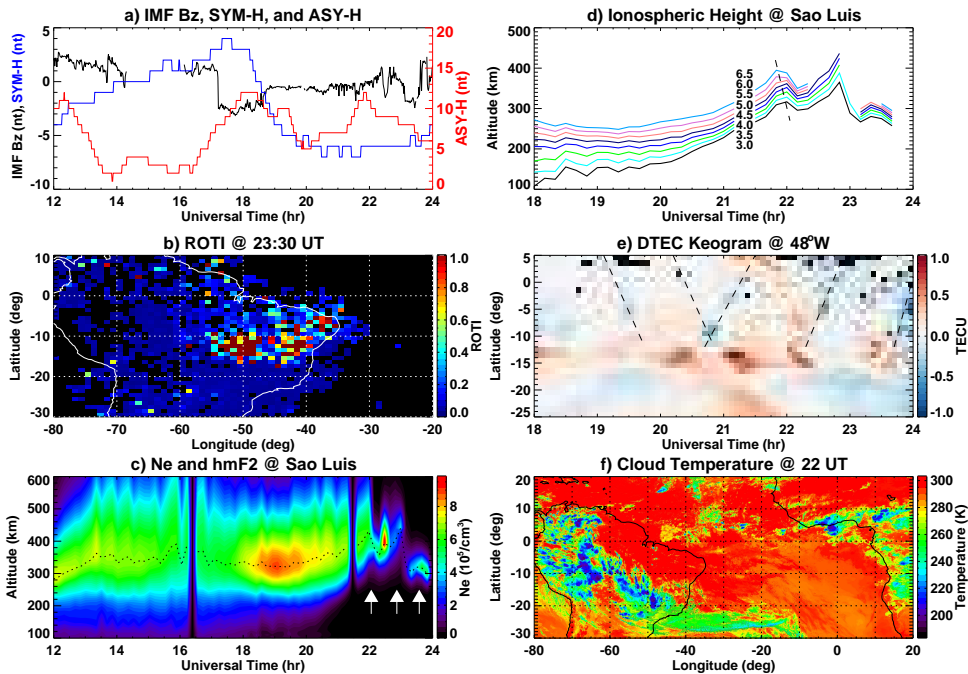
Figure 6. (a) Temporal variation of interplanetary magnetic field (IMF) Bz, the longitudinal asymmetric index (ASY-H), and the symmetric index (SYM-H) between 12 and 24 UT. (b) Rate of TEC Index plot at 23:30 UT. (c) Electron density profile and hmF2 at Sao Luis between 12 and 24 UT. Three quasi-periodic wave-like structures are marked by arrows. (d) Variation of F-layer true heights for different frequencies (3.0–6.5 MHz) at Sao Luis. (e) Keogram plot of detrended total electron content (TEC) as a function of latitude and time at 48°W longitude between 18 and 24 UT. The TID structures are marked by dashed lines. (f) Observation of deep clouds in brightness temperature at 22 UT. All six images are for 24 October 2018.

NIWeb service (https://cdaweb.gsfc.nasa.gov/). We acknowledge the University of Massachusetts Lowell for providing ionosonde data from the DIDB database of Global Ionospheric Radio Observatory (http://giro.uml.edu/). The Cloud brightness temperature (BT) data was provided by the National Aeronautics and Space Administration (NASA) Goddard Earth Sciences Data and Information Services Central (https://disc.gsfc.nasa.gov/).

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Figure 1.

a) 2018-Oct-24 21:10 & 21:25 UT
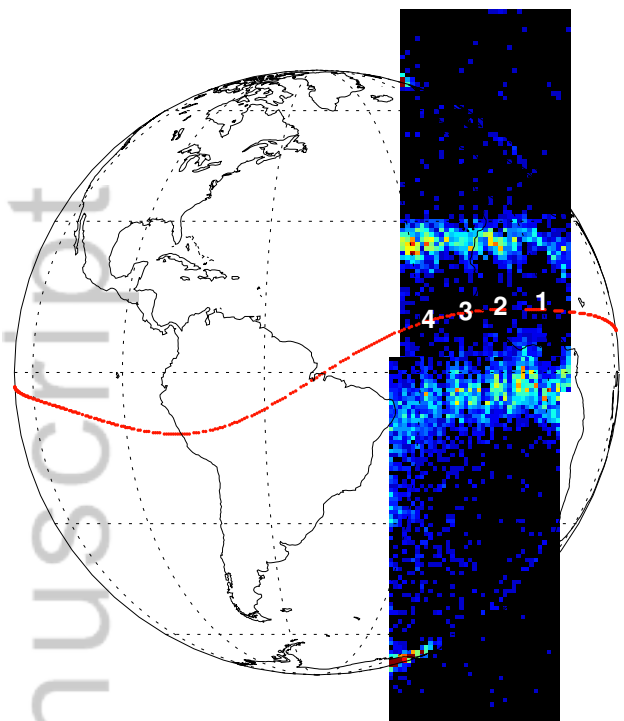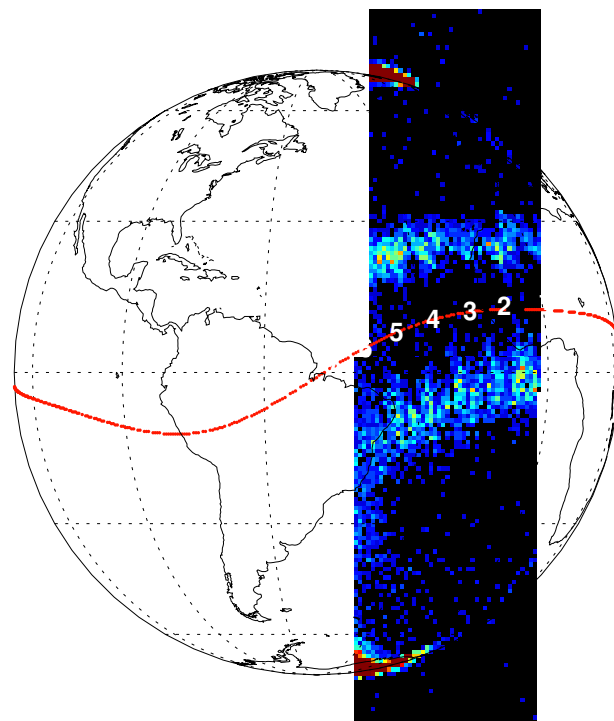
b) 2018-Oct-24 21:40 & 21:55 UT

c) 2018-Oct-24 22:10 & 22:25 UT

d) 2018-Oct-24 22:40 & 22:55 UT
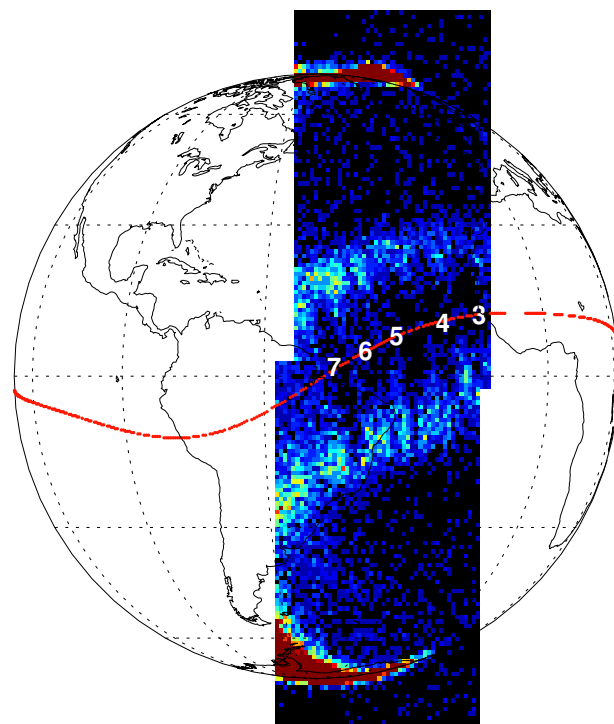
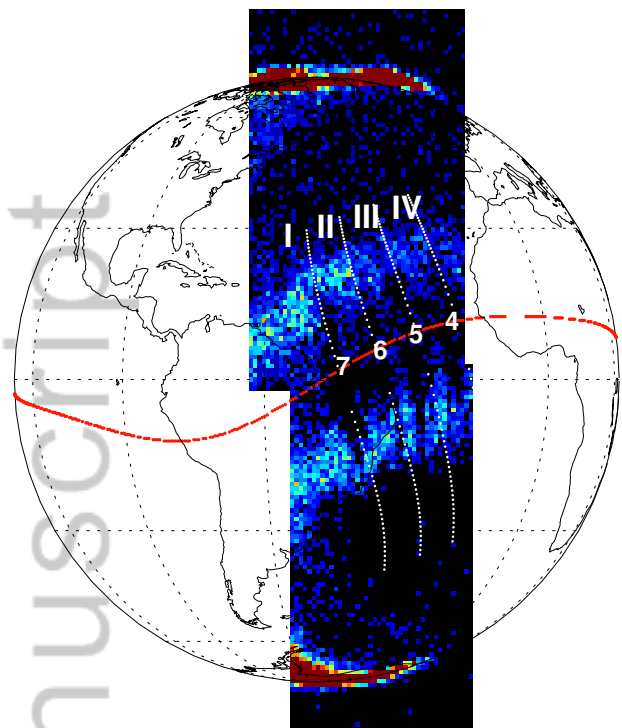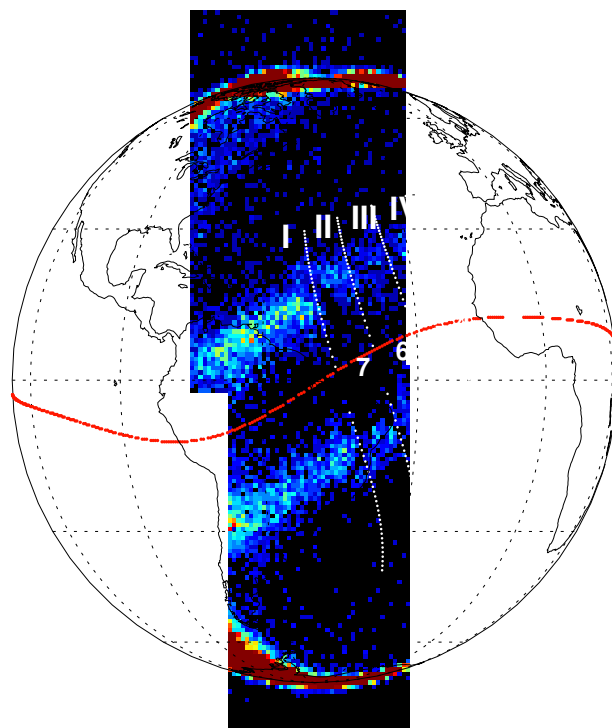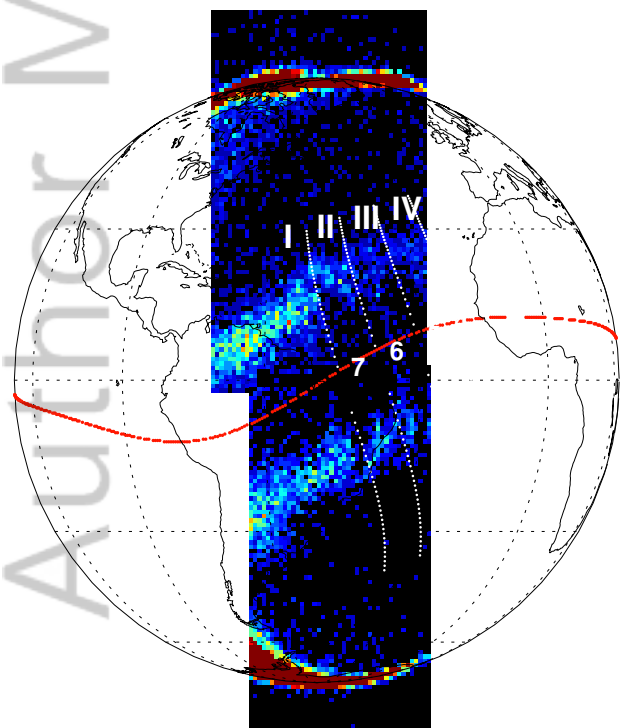**135.6 nm Radiance [Rayleigh]**

0   50   100   150   200

Figure 2.

a) 2018-Oct-24 23:10 UT

b) 2018-Oct-24 23:25 UT
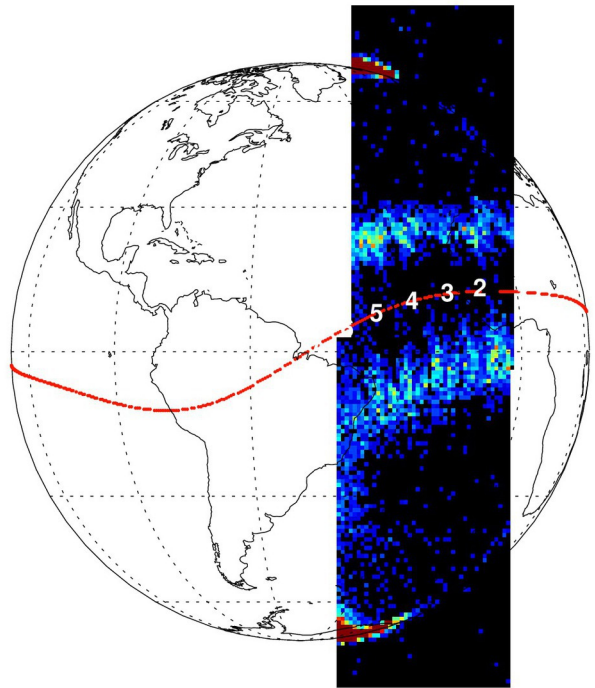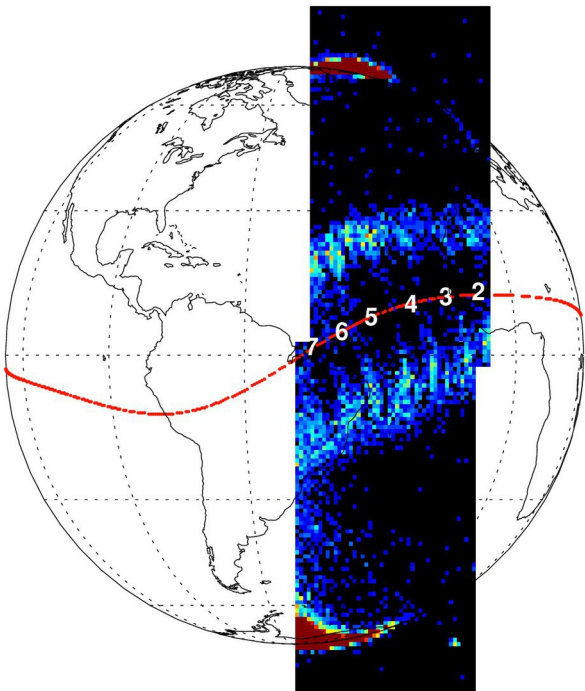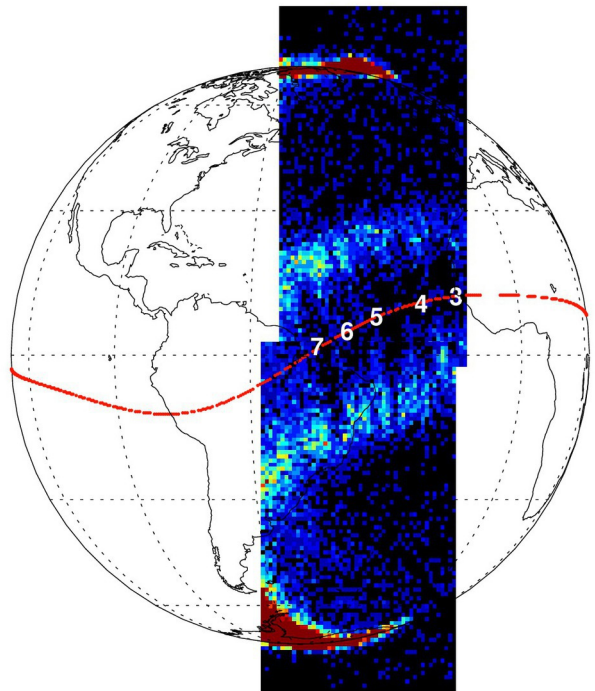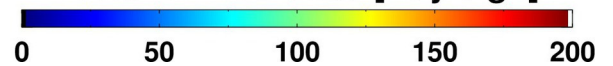
c) 2018-Oct-24 23:40 UT

d) 2018-Oct-24 23:55 UT

135.6 nm Radiance [Rayleigh]

0   50   100   150   200

Figure 3.

a) 24-Oct-2018 21:00 UT
b) 24-Oct-2018 21:15 UT
c) 24-Oct-2018 21:30 UT
d) 24-Oct-2018 21:45 UT
e) 24-Oct-2018 22:00 UT
f) 24-Oct-2018 22:15 UT
g) 24-Oct-2018 22:30 UT
h) 24-Oct-2018 22:45 UT
i) 24-Oct-2018 23:00 UT
j) 24-Oct-2018 23:15 UT
k) 24-Oct-2018 23:30 UT
l) 24-Oct-2018 23:45 UT

TEC Unit

Figure 4.

Figure 5.

c) GOLD/UV & TEC @ 23:40 UT

d) Swarm C in-situ Ne (#/cm³, Altitude = ~450 km, MLT = 21.3)

Figure 6.

a) IMF Bz, SYM-H, and ASY-H
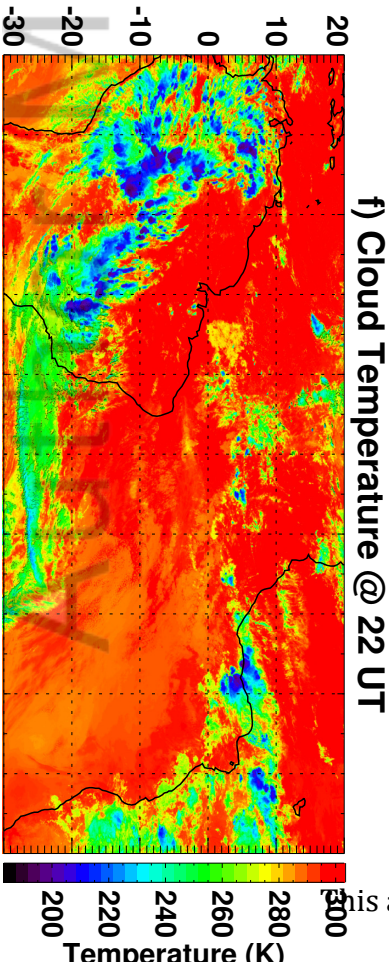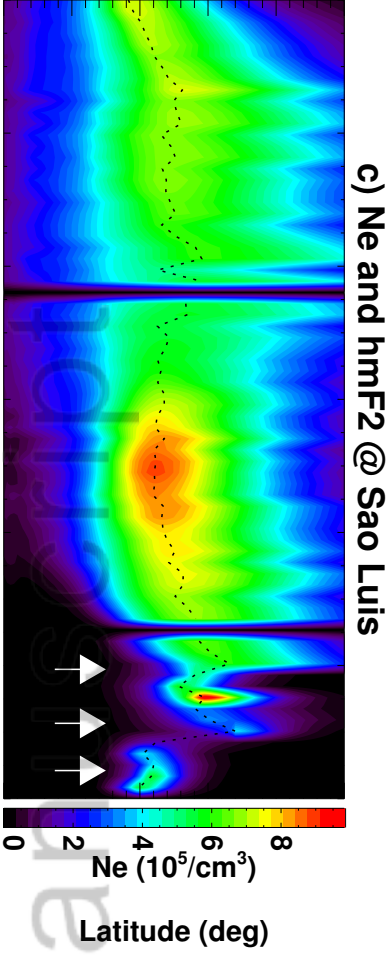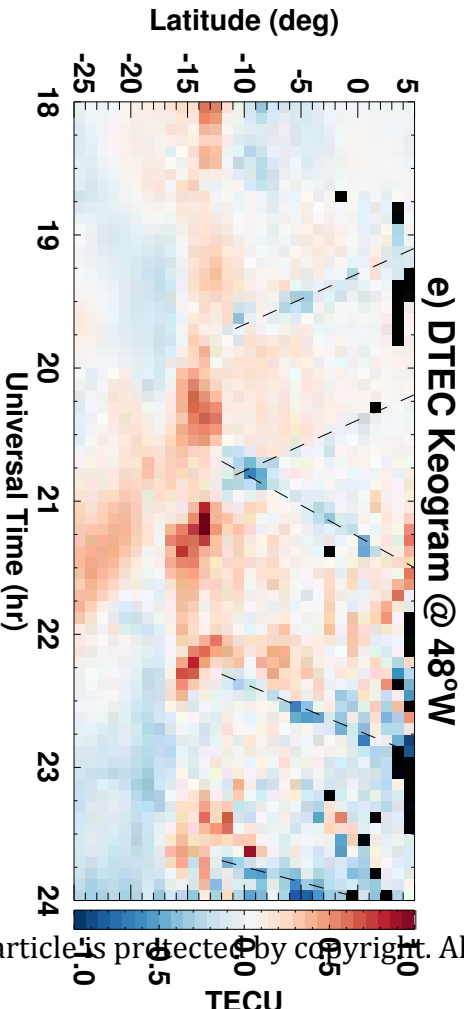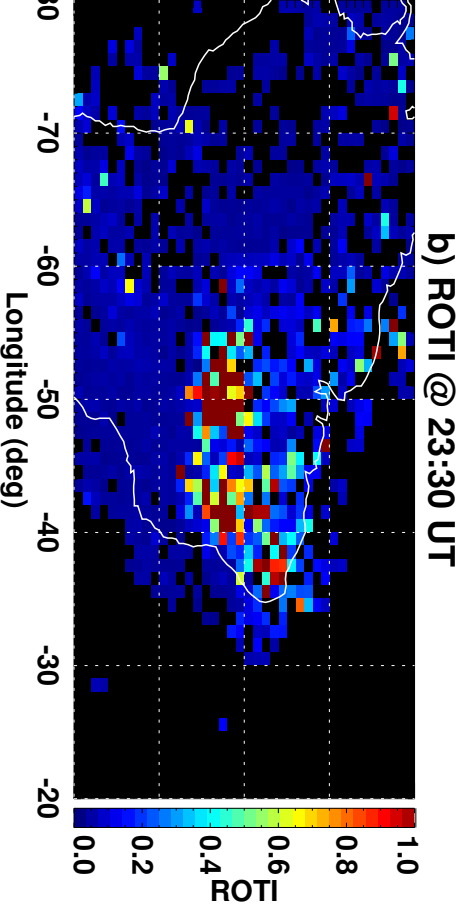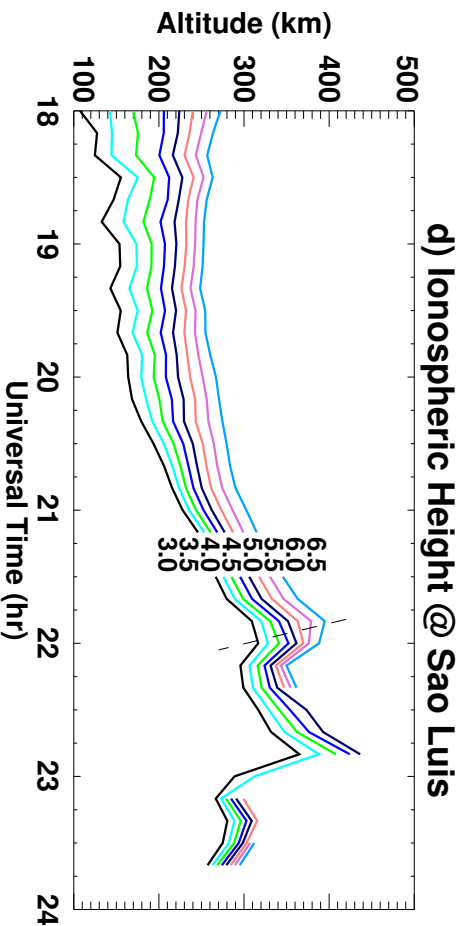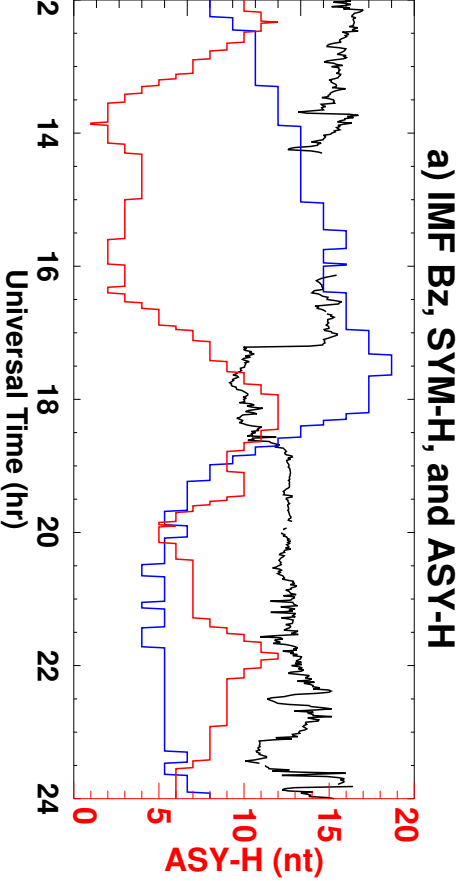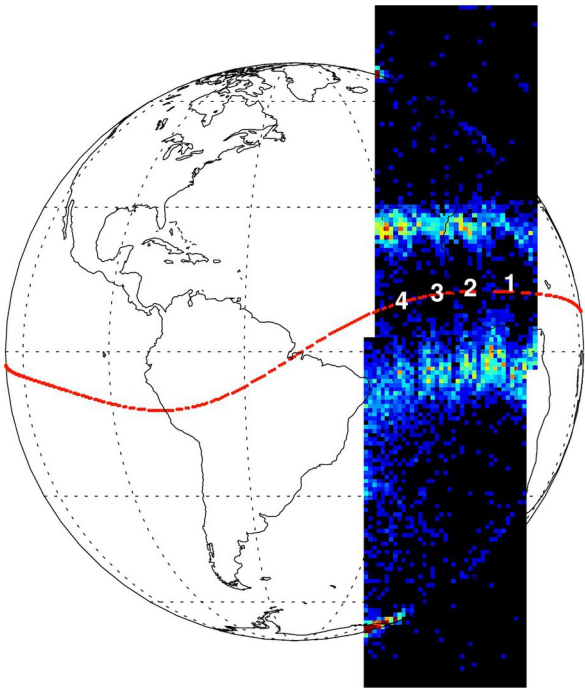
b) ROTI @ 23:30 UT

c) Ne and hmF2 @ Sao Luis

d) Ionospheric Height @ Sao Luis

e) DTEC Keogram @ 48°W

f) Cloud Temperature @ 22 UT

a) 2018-Oct-24 21:10 & 21:25 UT

b) 2018-Oct-24 21:40 & 21:55 UT

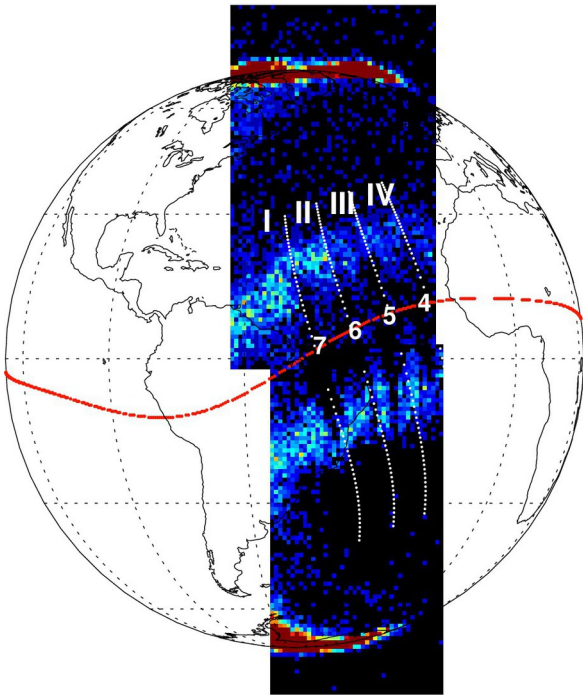## c) 2018-Oct-24 22:10 & 22:25 UT

d) 2018-Oct-24 22:40 & 22:55 UT

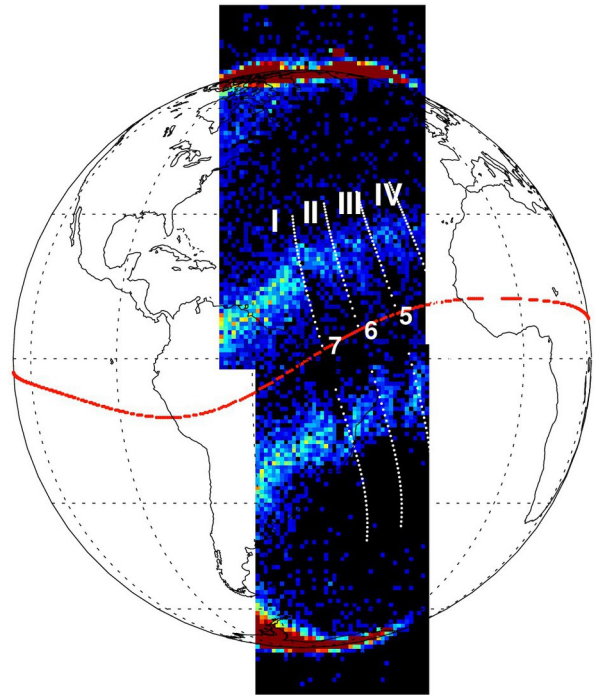**135.6 nm Radiance [Rayleigh]**

0   50   100   150   200
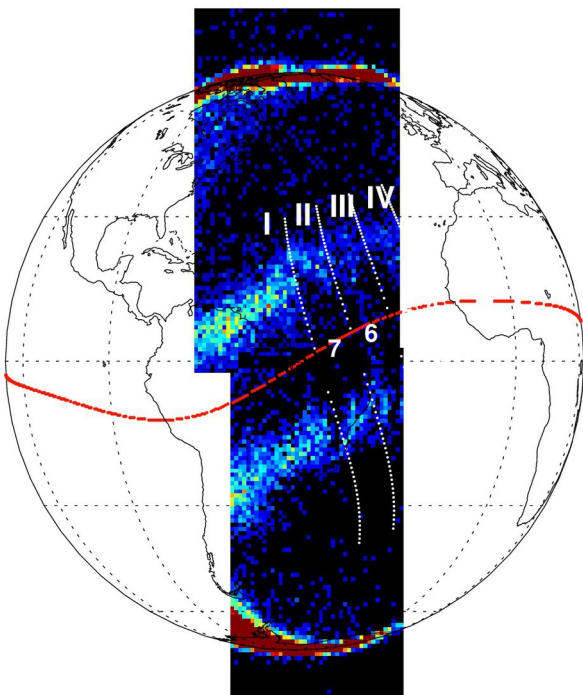
2019ja027569-f01-z-.eps
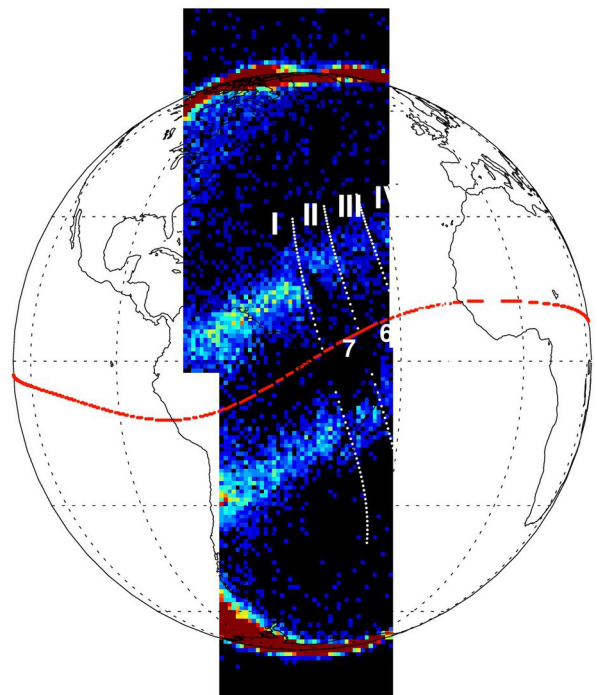
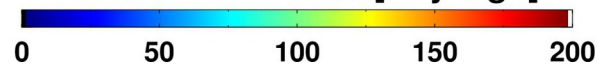**a) 2018-Oct-24 23:10 UT**

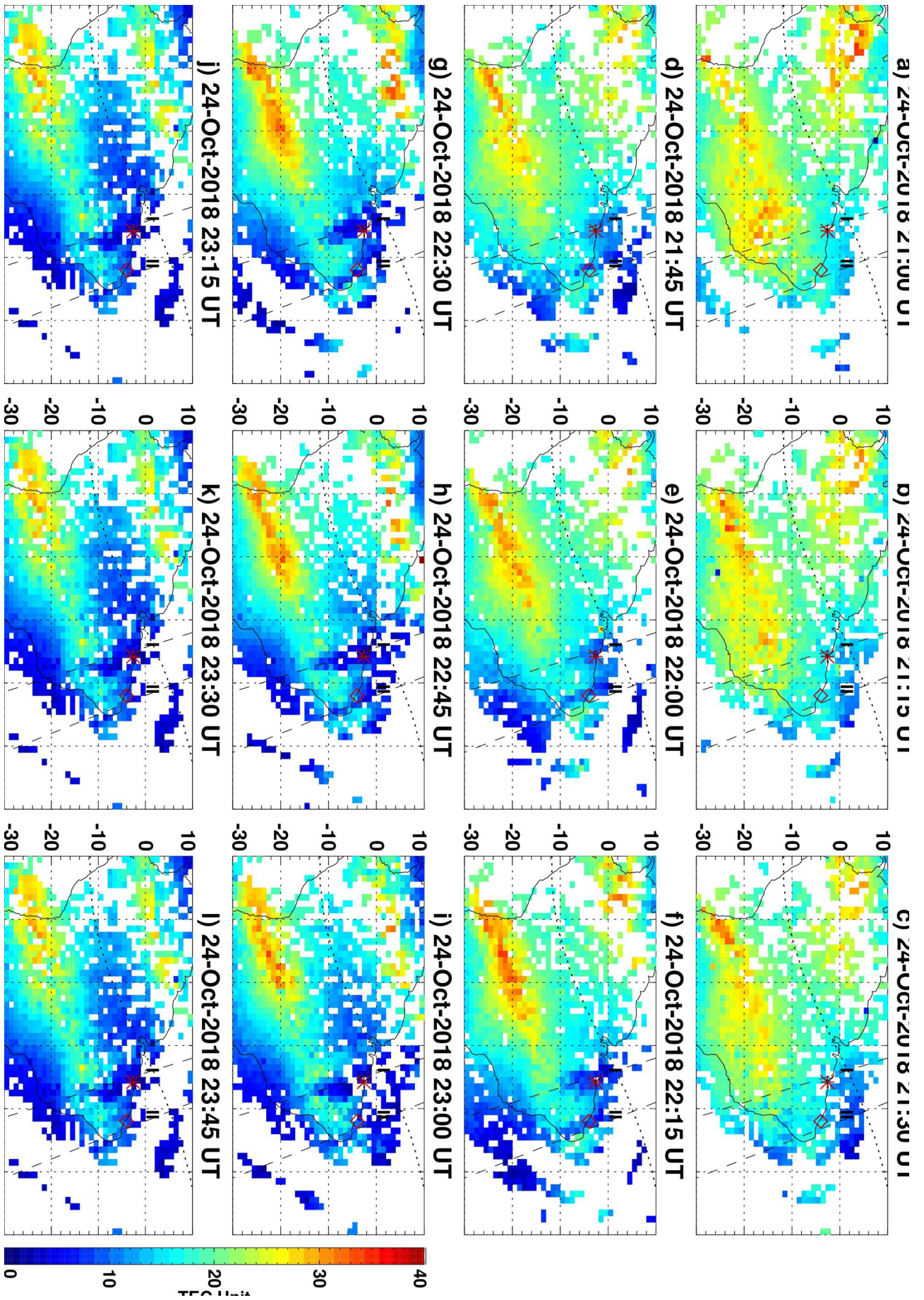**b) 2018-Oct-24 23:25 UT**

c) 2018-Oct-24 23:40 UT

d) 2018-Oct-24 23:55 UT

135.6 nm Radiance [Rayleigh]

0   50   100   150   200

2019ja027569-f02-z-.eps

a) 24-Oct-2018 21:00 UT
b) 24-Oct-2018 21:15 UT
c) 24-Oct-2018 21:30 UT
d) 24-Oct-2018 21:45 UT
e) 24-Oct-2018 22:00 UT
f) 24-Oct-2018 22:15 UT
g) 24-Oct-2018 22:30 UT
h) 24-Oct-2018 22:45 UT
i) 24-Oct-2018 23:00 UT
j) 24-Oct-2018 23:15 UT
k) 24-Oct-2018 23:30 UT
l) 24-Oct-2018 23:45 UT

TEC Unit

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São Luis (2.6S, 315.8E)

Fortaleza (3.9S, 321.6E)

h'F (km)

Vz (m/s)

Vy (m/s)

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c) GOLD/UV & TEC @ 23:40 UT

d) Swarm C in-situ Ne (#/cm³, Altitude = ~450 km, MLT = 21.3)

TECU
0 10 20 30 40

Radiance [R]
0 50 100 150 200

Latitude

3) 1.2-1.5 UT
63.8W

2) 23.6-23.9 UT
40.4W

1) 22.1-22.4 UT
17.0W

6) 1.2-1.5 UT
62.4W

5) 23.6-23.9 UT
39.0W

4) 22.1-22.4 UT
15.5W

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a) IMF Bz, SYM-H, and ASY-H

b) ROTI @ 23:30 UT

c) Ne and hmF2 @ Sao Luis

d) Ionospheric Height @ Sao Luis

e) DTEC Keogram @ 48°W

f) Cloud Temperature @ 22 UT

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