A mesoscale wave-like structure in the nighttime equatorial ionization anomaly

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Key Points:

- Characteristics of a mesoscale wave-like structure in the nighttime equatorial ionization anomaly are reported using GOLD far-ultraviolet observations.
- The structure is symmetric about the dip equator, appears stationary with time over the night, and is highly variable on a day-to-day basis.
- A cluster or quasi-periodic wave train of equatorial plasma depletions is often detected within the mesoscale structure.

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Abstract

Both ground- and satellite-based airglow imaging have significantly contributed to our understanding of the low-latitude ionosphere, especially of the morphology and dynamics of the equatorial ionization anomaly (EIA). The NASA Global-scale Observations of the Limb and Disk (GOLD) mission focuses on far-ultraviolet airglow images from a geostationary orbit at 47.5°W. This region is of particular interest at low magnetic latitudes because of the high magnetic declination (i.e., about -20°) and proximity of the South Atlantic magnetic anomaly. Nighttime airglow images from GOLD reveal an exciting feature of the EIA. Using observations from 5 October 2018 to 30 June 2020, we characterize a wave-like structure of few thousands of kilometers seen as poleward and equatorward displacements of the nighttime EIA-crests. Initial analyses show that the mesoscale structure is symmetric about the dip equator and appears nearly stationary with time over the night. In quasi-dipole coordinates, maxima poleward displacements of the EIA-crests are seen at about ±12° latitude and around 20° and 60° longitude (i.e., in geographic longitude at the dip equator, about 53°W and 14°W). The wave-like structure presents typical zonal wavelengths of about 6.7×10^3 km and 3.3×10^3 km. The structure's occurrence and wavelength are highly variable on a day-to-day basis with no apparent dependence on geomagnetic activity. In addition, a cluster or quasi-periodic wave train of equatorial plasma depletions (EPDs) is often detected within the mesoscale structure. We further outline the difference in observing these EPDs from FUV images and in situ measurements during a GOLD and Swarm mission conjunction.

1 Introduction

The Earth's ionosphere corresponds to the region of transit between the atmosphere and outer space. It is created by ionization via extreme ultraviolet solar radiation and particle precipitation. At mid and low magnetic latitudes, the former mechanism is the primary source of plasma. The region with the highest plasma density is typically found at about 300-400 km altitude, consisting mainly of atomic oxygen ions (O^+). It is referred to as F-region and is generally treated as a collisionless environment. However, collisions with neutrals are essential when referring to coupling with the lower thermosphere (e.g., H. Liu et al., 2009). In the E-region, between 100-150 km, collisions are much more often, resulting in faster recombination and a significant reduction of the plasma density right after sunset (Heelis, 2004).

At low magnetic latitudes, the ionosphere presents a bimodal meridional distribution of the plasma centered at the dip equator. This regular structure is commonly referred to as the equatorial ionization anomaly (EIA) (Appleton, 1946). The EIA is formed due to the uplift of plasma at the dip equator by eastward dynamo electric fields in the E-region and its subsequent downward diffusion along magnetic field lines (Duncan, 1960). Variations in any of these processes, especially in the dynamo-electric field, can cause substantial changes in the EIA morphology. By using far-ultraviolet (FUV) emissions measured by the IMAGE satellite mission, Immel et al. (2006) reported a repeated separation and rapprochement of the EIA-crests seen as a wavenumber 4 structure. The authors analyzed the correspondence between the tidal temperatures in the E-region and both the latitude and brightness of the EIA-crests. With an excellent match among these parameters, the authors showed the effect of atmospheric tides on the EIA morphology. Recently, using FUV images from the Special Sensor Ultraviolet Spectrographic Imager (SSUSI) instrument onboard the Defense Meteorological Satellite Program (DMSP) F18, Guo et al. (2020) have identified evidence of wavenumbers 1 to 4 in the EIA and reported significant annual and semiannual periods of these wave structures.

An interesting phenomenon of the nighttime EIA is the existence of plasma instabilities. After sunset at the dip equator, the sharp vertically upward gradient of the plasma density, the magnetic field, and currents driven by the background electric field and grav-

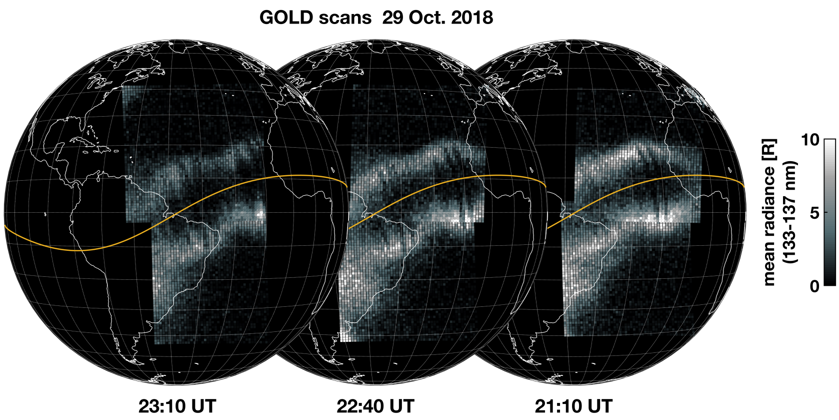

Figure 1. Three consecutive images of GOLD on 29 October 2018. It depicts a wave-like structure of the EIA and equatorial plasma depletions (EPDs) within. Each image displays two scans. The time on top of each image corresponds to the starting time of the northern scan. Each scan takes about 15 min.

ity are mutually perpendicular. This configuration allows interchange instabilities to operate and generate plasma irregularities; commonly term equatorial spread F (Hysell, 2000). The large-scale structures (10s to 100s of kilometers) of the spread F, generally known as equatorial plasma depletions (EPDs), can reach altitudes of up to 2000 km. Since they are mapped along the magnetic field lines, they can disrupt the post-sunset EIA's ionospheric density profile. This phenomenon is observed as wedge-like density depleted channels in global observations (e.g., Kil et al., 2009; Eastes et al., 2019).

A well-established feature of the low latitude ionosphere is a brief and intense lifting of the F-region produced by an increase of the dayside eastward electric field, just before its nighttime reversal (e.g., Kelley et al., 2009; Richmond et al., 2015). This phenomenon, named pre-reversal enhancement (PRE), causes an intensified vertical uplift of the ionosphere, favoring the generation of EPDs (e.g., Basu et al., 1996). The agreement between the longitudinal and seasonal variability of both the PRE and EPDs occurrence has been already shown (e.g., Stolle et al., 2008; Huang & Hairston, 2015). Even though this is evident in the climatological sense, the day-to-day variability of the vertical drift does not seem to agree with that of the occurrence of EPDs (e.g., Hysell & Burcham, 2002). Since EPDs tend to occur in clusters or quasi-periodic wave trains (e.g., Makela et al., 2010; Eastes et al., 2019), it has been suggested they might result from the electrodynamical process within an upwelling, generally amplified by the post-sunset rise of the F-region due to the PRE (Tsunoda et al., 2018). Different phenomena such as gravity waves (Singh et al., 1997) and shear flow (Hysell & Kudeki, 2004) seem capable of forming localized upwellings that can explain these observations.

In this study, we use FUV images of the nighttime ionosphere by the Globalscale Observations of the Limb and Disk (GOLD) mission to investigate a mesoscale wave-like structure in the EIA-crests observed between about 80°W and 10°E longitude. This phenomenon is seen as poleward and equatorward displacements of the EIA-crests in a short longitude distance. It is symmetric about the dip equator and nearly stationary with time over the night. Within these structures, there are clusters of EPDs shaped in latitude by the EIA-crests. This work aims to report characteristics of this phenomenon,

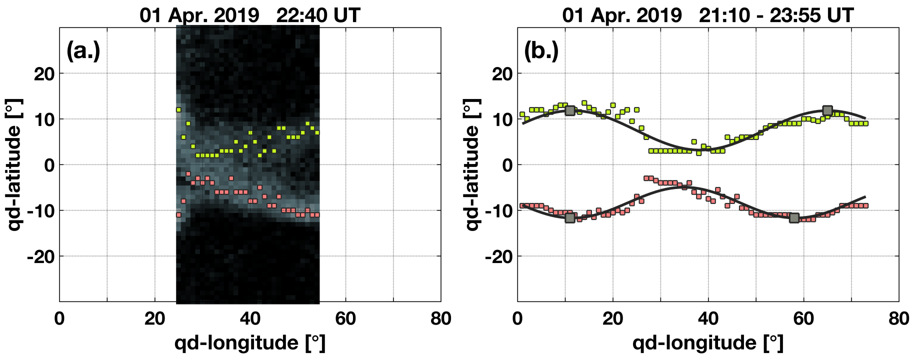

Figure 2. (a.) Single FUV image of both hemispheres (sFUVI). Green and pink dots indicate the detection of the EIA-crests. The time on the title indicates the start of the scans. (b.) Position of the EIA-crests from all the sFUVI on 1 April 2019. The time of the beginning of the first and last scan is indicated. Thick black lines are nonlinear regressions fitting the green and pink dots. Gray dots indicate the maxima latitudinal values.

such as location, zonal wavelength, amplitude, day-to-day variability and potential relation to the occurrence of EPDs.

2 GOLD far-ultraviolet nightglow observations

At night, emissions from the ionosphere come from radiative processes in the F-region either by recombination of atomic oxygen ions with electrons ($O^+ + e$) or ion-ion mutual neutralization ($O^+ + O^-$). Both processes generate an excited state of atomic oxygen (O I). Since the recombination rates are sufficiently slow in the F-region, areas of enhanced ion density such as the EIA's crests may persist through the night. The most significant emission of the EIA observed at night is O I 135.6 nm. GOLD is a NASA mission launched on 25 January 2018. It observes the far-ultraviolet (FUV) spectrum of Earth's atmosphere (ca. 134-162 nm). The instrument is a dual-channel (A and B), spectral imager hosted in geostationary orbit on SES-14, a satellite located at 47.5°W longitude (Eastes et al., 2020). Nighttime scans cover about 45° of longitude, maintaining a cadence of 15 minutes per scan. From 20:10 to 23:10 UT, channel-B scans alternating between both hemispheres. From 23:10 to 00:40 UT, channel-A scans the northern hemisphere while channel-B scans the southern hemisphere. Figure 1 displays a sequence of GOLD FUV images showing both the nighttime EIA-crests and EPDs, seen as black stripes perpendicular to the dip equator (solid yellow line). An exciting observation is a substantial change of the EIA morphology over a short longitude distance - far less than the well-known wavenumber 4. It consists of displacements of the EIA-crests away from and toward the dip equator, seen as a mesoscale wave-like structure. For this particular night, the EIA-structure presents two nearly symmetric poleward displacements, both with EPDs whose latitudinal extension follows the EIA-crests.

3 Mesoscale wave-like structure in the EIA

To describe EIA's morphology, we use GOLD nighttime scans (NI1) from 5 October 2018 to 30 June 2020. Because of the high magnetic declination in the region covered by the GOLD scans (c.a., -20°), and the conjugate character between magnetic hemispheres of both the wave-like structures and EPDs, we use quasi-dipole coordinates throughout the study. The processing starts by converting each FUV image (single scan) from geographic to quasi-dipole coordinates. To obtain a single FUV image of both hemispheres

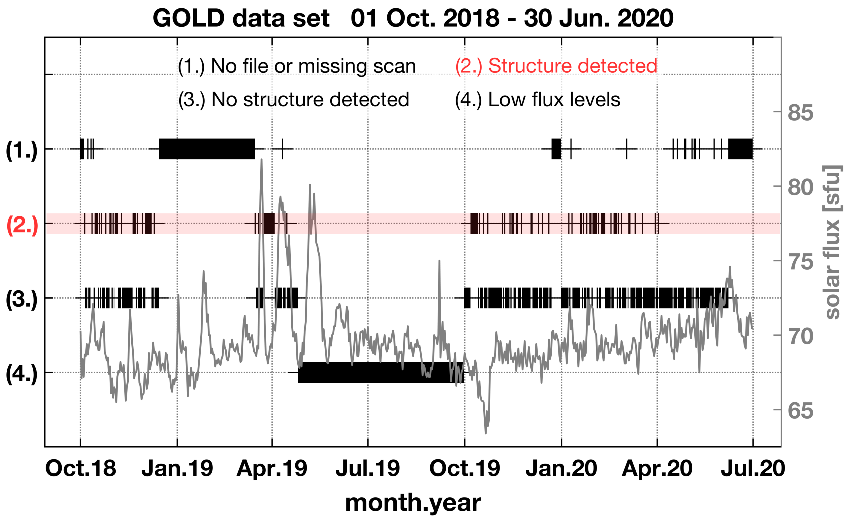

Figure 3. GOLD data set description and solar flux for the period between 1 October 2018 and 30 June 2020. Highlighted in red are the data used in this study. As a reference in the study, the solar radio flux at 10.7 cm (F10.7 index) is provided.

(sFUVI), like the one in Figure 2a, consecutive or simultaneous scans of the two hemispheres are merged within the same grid (1°×1° of quasi-dipole longitude and latitude). As mentioned earlier, channel-B scans alternating between both hemispheres from 20:10 to 23:10 UT. In this interval, an sFUVI comprises two scans shifted by 15 min. From 23:10 to 00:40 UT, sFUVIs are based on simultaneous scans of the northern and southern hemispheres by channel-A and channel-B, respectively.

A single day generally comprises 13 sFUVI. As a requisite, we only consider days with complete and successive sFUVIs at least between 21:10 and 23:55 UT. Since the structure appears nearly stationary with time, we can use successive sFUVIs without a jump at the boundaries between sFUVIs. To characterize the mesoscale structure, we detect the EIA-crests (green and pink squares in Figure 2a). This procedure is done for each sFUVI individually. After that, we merge the output from all the daily sFUVIs, remove outliers using a 5° window in longitude, and get a median value per degree of longitude (green and pink squares in Figure 2b). Finally, we use nonlinear regression to find the sinusoidal function that best fits each EIA-crest morphology, independently (solid black line in Figure 2b). The zonal wavelengths and amplitudes we use in this study correspond to those of the sinusoidal fitting curve.

Finally, 95 wave-like structures are selected (one per day). The selection corresponds to structures with zonal wavelengths between 20° and 100°, and amplitudes at both EIA-crests greater than or equal to 1°. Wavelengths greater than 100° did not present a well-defined wave-like structure in the FUV images. Wavelengths of less than 20° were mostly related to issues in the EIA-crests' detection associated with noisy FUV images or cases with no clear EIA structure. Furthermore, there are gaps in the data set either due to missing scans or images with very low flux levels (blank images). Figure 3 displays a description of the data set. It indicates when: (1.) there were no files, or missing scans, (2.) a wave-like structure was detected and used in this study, (3.) the structure recog-

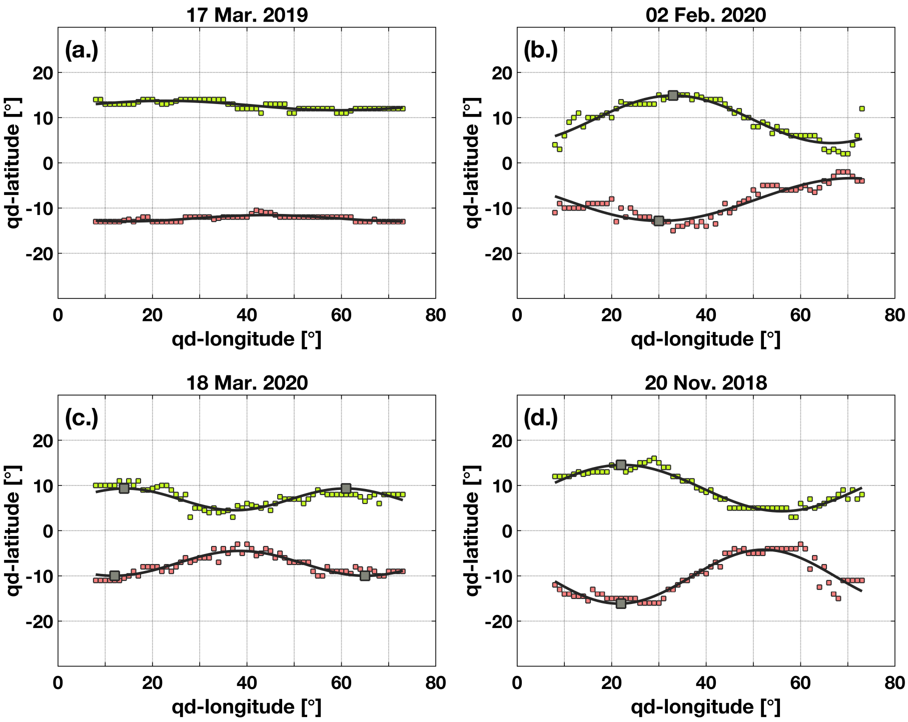

Figure 4. Typical observations of the EIA in GOLD FUV images. (a.) No wave-like structure. (b.) Single structure. (c.) Double structure. (d.) Apparent double structure with one part out of the range (more than half). Gray squares indicate the maxima latitudinal displacements.

nized did not comply with the requirements above, and (4.) the FUV image was blank due to low flux levels.

Interestingly, the mesoscale wave-like structure is not local time-dependent, which means it is observed as steady-structures centered at specific longitudes throughout the night. This feature is already evident in the example shown in Figure 2b, which, as explained above, it is the result of combining consecutive daily sFUVIs. It is also observed that their morphology varies from day to day. Figure 4 displays four typical structures found in the GOLD FUV images. The plots describe, (a.) a no wave-like structure, (b.) a single structure, (c.) a double structure, and (d.) an apparent double structure with one part out of the range (more than half). The latter case is considered as a single structure. From all the structures found in this study (95 cases), 60.87% are single, and 39.13% are double. It is important to note that these four examples do not constitute any classification of the phenomenon. They merely show how the EIA-structure lines up with GOLD's FUV.

To assess the location of the mesoscale structure, we detect the position of the maximum latitudinal displacement of the EIA-crests (i.e., gray squares in Figure 2b and Figure 4). They are generally located at about 20° and 60° of quasi-dipole longitude (i.e., in geographic longitude about 53°W and 14°W at the dip equator), and ±12° of quasi-dipole latitude, as seen in Figure 5a. Regarding their associated zonal wavelength, Figure 5b shows a general preference for values around 35° and 65° (i.e., ca. 3.3×10^3 km and 6.7×10^3 km, respectively). However, values around the maximum at 65° suggest a higher variability, with a range of wavelengths expanding from about 45° to 80°. Another observation is the apparent correlation between the amplitudes and zonal wavelengths of the EIA-structure. Figure 5c depicts the relation between these two param-

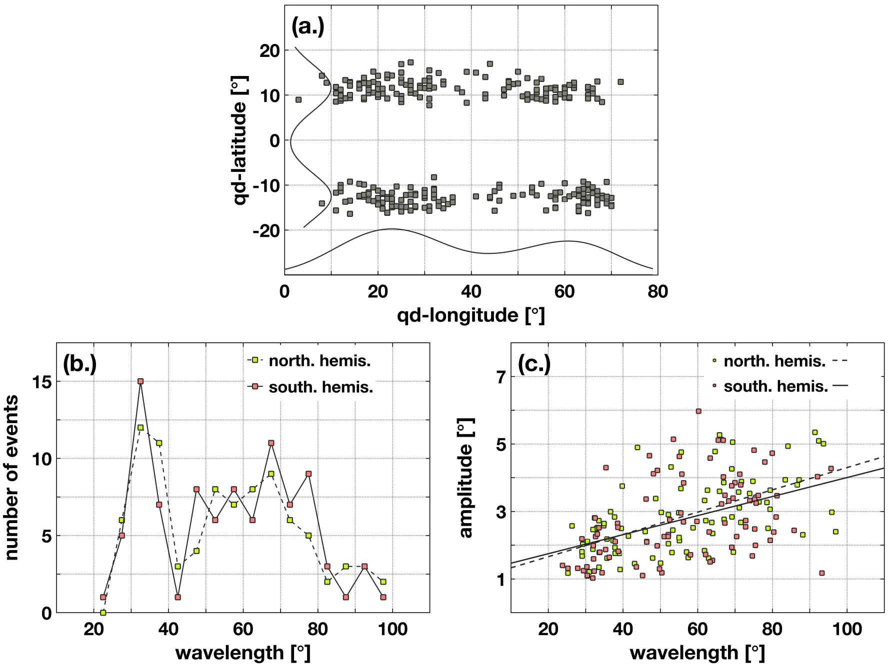

Figure 5. (a.) Spatial distribution of the maximum latitudinal displacement of each wave-like structure event. Solid black lines represents their density distribution. (b.) The number of events as a function of zonal wavelength for the northern and southern magnetic hemispheres. (c.) Variation of the amplitude as a function of zonal wavelength for the northern and southern EIA-crests separately. Correlation coefficients of 0.58 and 0.45, respectively.

eters separately for the northern and southern EIA-crests. The correlation coefficients are 0.58 and 0.45, respectively. Even though they do not represent a high correlation, there seems to be an interesting tendency for the EIA-structure to simultaneously expand in both latitude and longitude.

It is important to mention that variations from one day to another of the structures' wavelength do not show any apparent periodicity or dependence on geomagnetic activity. Figure 6a shows for a sample period, variations of the zonal wavelength of the northern EIA-crest on a day-to-day basis. Even though the events are not equally spaced in time, it is easy to note the high variability of the zonal wavelength from one day to another. Figure 6b depicts variations of the northern EIA-crest wavelengths for the 95 cases as a function of geomagnetic activity (3-hour Kp index). Since a single event is composed of complete and consecutive sFUVIs at least between 21:10 and 23:55 UT, we have selected the Kp index for the last three hours of the corresponding day (i.e., 21-24 UT). With a correlation coefficient of -0.02, we conclude that this phenomenon does not depend on geomagnetic activity.

4 Discussion

Based on the results above, we can highlight three main characteristics of the nighttime EIA's mesoscale structure. It is symmetric about the dip equator, remains nearly stationary with time over the night, and presents a high variability on a day-to-day basis with no dependence on geomagnetic activity. The symmetric poleward and equator-

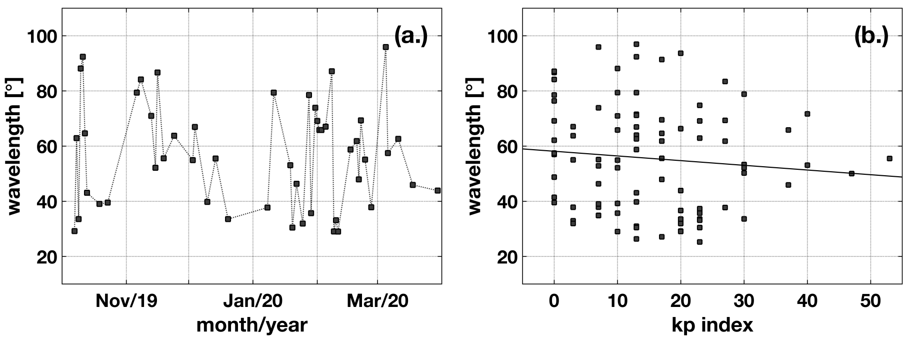

Figure 6. (a.) Day-to-day variations of the northern EIA-crest wavelength for a sample period. (b.) Variations of the northern EIA-crest wavelength as a function of geomagnetic activity, as denoted by the Kp index (R=-0.02).

ward displacements of the EIA-crests suggest that the underlying mechanisms perturb the vertical plasma drift (i.e., the EIA's fountain effect). Regarding the EIA morphology, studies have shown how atmospheric tides can modify the daytime eastward dynamo electric field at low magnetic latitudes; therefore, the vertical plasma drift. England et al. (2006) used a set of observations from IMAGE FUV, TIMED GUVI, and OGO D 12 to show that the well-known EIA wavenumber four structure is the results of nonmigrating diurnal tides at E region altitudes. They demonstrated that the good correlation between the tidally modulated winds and temperatures in the lower thermosphere could explain the EIA's fountain effect's modulation. Further studies have also shown climatological analysis of wave-like structures in the EIA. A recent study by Guo et al. (2020) shows global nighttime airglow images from the SSUSI instrument onboard the DMSP F18. The authors reported evidence of wavenumbers 1 to 4 with different annual and semiannual periods among them. The reason why some earlier studies have not detected mesoscale structures is because of their substantial phase variability. As demonstrated in this paper, the wave-like structure phase presents large changes on a day-to-day basis (see Figure 6a). In climatological studies, the data that contain wave-like structures with different phases are analyzed together. Climatological averaging would remove a large part of wave structures even if they existed in the data. It is interesting, however, to find in the results of England et al. (2006), two mesoscale structures at about 50°W and 30°W longitude between two peaks of the global wavenumber four feature. Even though we cannot prove they are the structures we address in this study, they should be considered in further analysis.

Figure 5b shows typical zonal wavelengths of about 35° and 65°, with the latter value having a more significant spread. These two values are associated with single structures of half of their wavelengths, like the ones in Figure 4c and Figure 4b, respectively. By taking into account that the PRE's typical duration is two hours (Fejer et al., 1991), its associated uplift generally extends over 30° in longitude. Commonly, models and observations have presented large-scale and smooth longitudinal variations of the PRE. If so, this mechanism could not explain structures like the ones reported in this study due to its continuous and long-lasting effect across much longer zonal distances. Nevertheless, using the Whole Atmosphere Community Climate Model with thermosphere and ionosphere extension (WACCM-X), H.-L. Liu et al. (2018) showed that the PRE presents a substantial day-to-day variability. In Figure 11 of their work, the authors present daily values of PRE under high and low solar flux conditions. Interesting is the longitudinal variation of a few tens of degrees observed between days. Significant sharp longitudinal gradients of this kind have also been observed in the daytime zonal electric field and to-

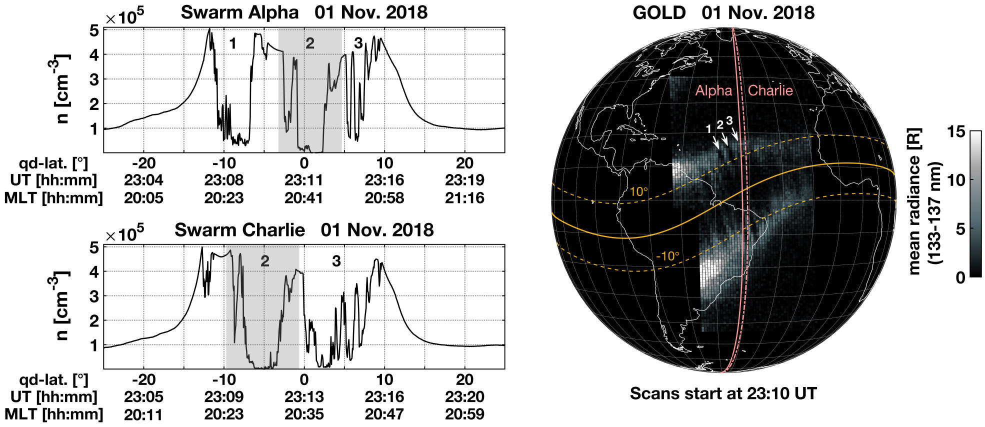

Figure 7. Simultaneous observations of GOLD and Swarm Alpha and Charlie on 1 November 2018. On the right, the GOLD FUV scan starting at 23:10 UT. It displays the dip equator as a thick yellow line and $\pm 10^{\circ}$ of quasi-dipole latitude as dashed yellow lines. Pink lines show Swarm Alpha and Charlie's orbits that intercept the depletions noted with white numbers and arrows. On the left, two panels present in situ measurements of the plasma density as a function of quasi-dipole latitude, universal time, and magnetic local time. They correspond to the orbits shown on the right plot. The depletions are numbered to match those in the FUV image.

tal electron content (e.g., Alken et al., 2015; Anderson et al., 2009). Although these results cannot be directly compared with ours because of the different methodologies, these gradients represent a scale of dynamics whose characterization and identification of sources are essential in studying mesoscale structures.

The strong day-to-day variability of both the occurrence of the EIA-structure and its associated zonal wavelength and the non-dependence on geomagnetic activity (see Figure 6) suggest the driving mechanism being of a highly variable nature. To unveil the phenomenon responsable for the local modulation of the nighttime EIA, we need further studies. Two possible candidates might be the superposition of two or more tides or large-scale gravity waves. In the first case, the change of amplitudes/phases of tides could result in smaller wave-like structures with high day-to-day variability. Different studies have addressed tidal variability in the ionosphere (e.g., Forbes et al., 2008). They usually do not focus on tides with zonal wave numbers larger than six, as those tidal components are less significant in global climatology. In this regard, we need dedicated studies to evaluate how powerful tides with large wavenumbers could be on a daily basis. Concerning gravity ways (GWs), it is known that small- and medium-scale GWs dissipate momentum in the thermosphere. This localized momentum deposition can create horizontal thermospheric body forces with large sizes and amplitudes and generate largescale secondary GWs with horizontal wavelengths of about 2100-2200 km (Vadas & Liu, 2009). The GOLD observations are locally near the Andes mountain range, known to be a source of GWs (e.g., Spiga et al., 2008). Other nearby regions believed to be sources of GWs are the Amazon rainforest and the Antarctic Peninsula.

Independent of the mechanisms responsible for the modulation of the nighttime EIA, the variation of the plasma uplift in the nighttime EIA directly affects the occurrence of EPDs. As shown in Figure 1, the latitudinal extension of the EPDs follows the EIA-crests. At the center of the structures (i.e., where the EIA-crests reach their maximum latitude), EPDs exhibit the most significant latitudinal extension, suggesting a larger growth rate than their neighboring EPDs, therefore, a larger vertical drift. It is also noticed in the FUV images that EPDs generally appear in the EIA regions, but no structure is seen near the dip equator. However, in situ satellite observations show that EPDs do present a clear structure at the dip equator. Figure 7 presents simultaneous observations of a set of EPDs by the Swarm and GOLD missions. Swarm is an ESA constellation satellite mission widely used in studying ionospheric phenomena (e.g., Xiong et al., 2016; Chartier et al., 2018; Rodríguez-Zuluaga et al., 2019; Park et al., 2020). In the right panel, a train of EPDs is seen in the FUV image, of which three (numbered and indicated by white arrows) are intercepted by both Swarm Alpha and Charlie satellites (pink lines). From the FUV images, the separation between the three EPDs is not evident at the dip equator; however, in situ plasma density measurements displayed on the left side clearly show strong depletions near and at the dip equator. Among the 95 wave-like events considered, 83 cases (87.4%) present well-defined EPDs. Nevertheless, based on the previous observations by Swarm and GOLD, small EPDs confined to latitudes closed to the dip equator are likely not to be detected by FUV images.

Climatologically, the occurrence of EPDs has been associated with the sudden postsunset rise of the ionosphere due to the PRE (e.g., Fejer et al., 1999; Gentile et al., 2006; Stolle et al., 2008; Su et al., 2008). Nevertheless, the presence of EPDs as clusters or quasiperiodic wave train (e.g., Makela et al., 2010; Eastes et al., 2019) cannot be explained by the local time (longitudinal) variability of the PRE. On the other side, different phenomena such as gravity waves (Singh et al., 1997) and shear flow (Hysell & Kudeki, 2004) seem capable of forming localized upwellings to explain these observations. The characterization of the mesoscale structure in this study brings up the need for further studies to understand EIA modulations' nature at small and medium-scales, especially in the nighttime ionosphere where phenomena such as EPDs might be affected.

5 Summary and conclusions

We report the characterization of a mesoscale wave-like structure observed in the nighttime equatorial ionization anomaly, EIA. The structure is seen as poleward and equatorward displacements of the EIA-crests over a short longitude distance. We use GOLD FUV images from 5 October 2018 to 30 June 2020 to assess spatial and temporal characteristics. A few events are currently available such that only a limited statistical analysis can be performed. The main findings are as follows:

1. The mesoscale structure is symmetric about the dip equator. This suggests the underlying mechanisms is perturbing the vertical plasma drift (i.e., EIA's fountain effect).
2. It appears stationary with time over the night. In quasi-dipole coordinates, the maxima poleward displacements of the EIA-crests are located at about ±12° latitude and 20° and 60° longitude (i.e., in geographic longitude about 53°W and 14°W at the dip equator).
3. The typical zonal wavelengths are about 35° and 65° (i.e., about 3.3×10^3 km and 6.7×10^3 km, respectively).
4. There is a strong day-to-day variability of their occurrence and zonal wavelength, with no dependence on geomagnetic activity.
5. EPDs are seen to be modulated by the mesoscale structure. Among the 95 cases considered in this study, 83 (87.4%) present well-defined EPDs. Within the wave-like structure, the latitudinal extension of the EPDs coincides with the EIA-crests.
6. A conjunction event between GOLD FUV images and Swarm orbits could show that EPDs detected with GOLD are also significantly structured equatorward of the EIA-crests, although the low flux levels of FUV images cannot resolve it.

Due to the high day-to-day variability of the mesoscale structure (i.e., occurrence and zonal wavelength), we suspect that variable wave forcing from the lower part of the atmosphere might be the source of the modulation of the fountain effect. The observed short zonal wavelength could result from large-scale gravity waves or the superposition of two or more tidal waves. In addition, the agreement between the latitudinal displacement of EPDs and the EIA-crests suggests an effect of the mesoscale structure on the occurrence of EPDs by providing the ionospheric uplift favorable for perturbations at the bottom side F-region to develop into EPDs.

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