Observation of scintillation enhancements and large-scale structures within the equatorial ionization anomaly during a Sudden Stratospheric Warming event

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Abstract

Total Electron Content (TEC) and L-band scintillations measured by several networks of GPS and GNSS receivers that operate in South and Central America and the Caribbean region are used to observe the morphology of the equatorial ionization anomaly (EIA), examine the evolution of plasma bubbles, and investigate the enhancement of L-band scintillations that occurred on February 12 and 13, 2016. A few weak and short magnetic storms developed these days, and a minor Sudden Stratosphere Warming (SSW) event was initiated a few days before. During these unusual conditions, TEC maps reported a split of the otherwise continuous crests of the EIA and the formation of a large-scale (thousands of kilometers) almost-circular structure. The western part of the southern crest faded, and a north-south aligned segment developed near the center of the South American continent, joining the north and south crests of the EIA, forming an anomaly that resembled a closed loop on the eastern side of the continent. Concurrently with the anomaly events, several GPS stations reported increases in the L-band scintillation index from 0.4 to values greater than one. We analyzed TEC values from receivers between ±6° from the magnetic equator to identify and follow TEC depletions associated with plasma bubbles when they reach different stations. Although the magnetic activity was moderate ($k_p=3^0$), we believe that the anomaly redistribution and the scintillation enhancements are not related to a prompt penetration electric field but to enhancing the semidiurnal lunar tide propitiated by the onset of the minor SSW event.

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Observation of scintillation enhancements and large-scale structures within the equatorial ionization anomaly during a Sudden Stratospheric Warming event

Short Title: Scintillation enhancements during an SSW event

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Key Points:

Sudden increases in L-band scintillations coincide with changes in the geometry of the equatorial ionization anomaly.

These events occurred on 12 and 13 February 2016, a few days after a minor sudden stratospheric warming event.

The analysis suggests that a meridional neutral wind associated with an increased lunar tide is responsible for anomaly variability.

5 September 2022

Abstract

Total Electron Content (TEC) and L-band scintillations measured by several networks of GPS and GNSS receivers that operate in South and Central America and the Caribbean region are used to observe the morphology of the equatorial ionization anomaly (EIA), examine the evolution of plasma bubbles, and investigate the enhancement of L-band scintillations that occurred on February 12 and 13, 2016. A few weak and short magnetic storms developed these days, and a minor Sudden Stratosphere Warming (SSW) event was initiated a few days before. During these unusual conditions, TEC maps reported a split of the otherwise continuous crests of the EIA and the formation of a large-scale (thousands of kilometers) almost-circular structure. The western part of the southern crest faded, and a north-south aligned segment developed near the center of the South American continent, joining the north and south crests of the EIA, forming an anomaly that resembled a closed loop on the eastern side of the continent. Concurrently with the anomaly events, several GPS stations reported increases in the L-band scintillation index from 0.4 to values greater than one. We analyzed TEC values from receivers between ±6° from the magnetic equator to identify and follow TEC depletions associated with plasma bubbles when they reach different stations. Although the magnetic activity was moderate ($k_p=3^0$), we believe that the anomaly redistribution and the scintillation enhancements are not related to a prompt penetration electric field but to enhancing the semidiurnal lunar tide propitiated by the onset of the minor SSW event. We found that depending on the lunar tide phase cycle, the neutral wind's meridional component can augment sub-km scale irregularities and enhance L-band scintillations through the wind gradient instability when $U \cdot \nabla n < 0$ or the action of wind gradients (∇U) within the bubbles. Our observations imply that the SSW event enables prominent changes in the thermosphere wind system at F-region altitudes.

1.Introduction

Meridional neutral winds, E×B drifts, and plasma diffusion along the field lines control the amplitude, the latitudinal separation, and the asymmetry of the equatorial ionization anomaly (EIA). These physical drivers also inhibit or, in other instances, depending on their sign, favor the formation of plasma bubbles. In addition, thermosphere winds can boost irregularity formation by modifying density gradients and enhancing secondary plasma instabilities that enable scintillation intensifications in the frequency domain between HF and L-band.

The EIA is a daytime and early evening persistent feature of the low-latitude ionosphere that enhances the ionospheric density on both sides of the magnetic equator. During the daytime, an upward plasma drift prevails near the magnetic equator [*Woodman* 1970, *Fejer et al.,* 1999], transporting plasma density to higher altitudes followed by diffusion along the field lines, forming two regions of high density equidistant from the magnetic equator [*Appleton,* 1946; *Hanson and Moffett,* 1966]. Several publications have described the morphology of the EIA, its seasonal variability, and numerical simulations of the anomaly [*Walker et al.,* 1994; *Balan and Bailey,* 1995; *Valladares et al.,* 2001, 2004; *Whalen,* 2001, 2003].

Scintillations in the frequency range between HF and L-band occur when a radio wave transverse a disturbed ionosphere contaminated with km- and sub-km-scale irregularities. The scintillation technique is typically used to identify and diagnose the spread-F phenomena [*Aarons,* 1977; *Basu et al.*, 1996, 2010] and investigate the morphology and velocity of plasma irregularities [*Rino et al.,* 2019; *Sheehan and Valladares*, 2004]. Ionospheric scintillation is a ubiquitous phenomenon that occurs almost daily at low latitudes. In the American sector, scintillations are observed practically every day during the spread F season (September through March) [*Aarons*, 1977; *Basu and Basu*, 1985].

In addition to the quiet time variability, the low latitude F-region ionosphere is modified by electric fields, thermospheric winds, and energy from magnetospheric and high latitude processes during magnetic storms. During moderate and large magnetic storms, the low latitude ionosphere experiences significant electrodynamic changes due to an expansion of prompt penetration and dynamo disturbance electric fields [*Fejer et al.,* 1983; *Fejer and Scherliess*, 1995; *Heelis and Mohapatra*, 2009; *Huang et al.,* 2018, 2019; *Blanc and Richmond,* 1980]. Prompt penetration electric fields produce upward drifts with a maximum value at 19 LT, increasing the pre-reversal enhancement (PRE) and downward drifts with a peak at 05 LT. The lifetime of these penetration electric fields is mainly controlled by the southward component of the IMF [*Huang et al.,* 2019] and can continuously exist if B_z remains south. In contrast, the disturbance dynamo electric field generates downward drifts, decreasing the PRE [*Fejer et al.,* 2008; *Huang et al.,* 2016]. Recently, *Huang et al.* [2018] reported that the disturbance dynamo diminishes the PRE drift for Dst $<$ -60 nT but remains stable for Dst values larger than -60 nT. These authors concluded that only moderate and large magnetic storms generate Joule heating intense enough to reach the low latitude ionosphere.

Sudden stratospheric warming (SSW) events consist of rapid temperature increases in the winter polar stratosphere (10-50 km altitude). During SSW events, the polar vortex weakens due to the breaking of planetary-scale waves propagating upward from the troposphere [*Matsuno,* 1971]. SSW events are divided into major warmings when a break of the polar vortex and a reversal of the zonal flow from eastward to westward occurs at 60° N latitude, and minor when the polar vortex is merely displaced from its typical polar latitude. In addition to SSW controlling tropospheric weather patterns, wind changes during SSW can trigger anomalies in the mesosphere and thermosphere wind systems. These wind variabilities lead to changes in atmospheric tides, precisely the lunar tide, that can exceed the solar atmospheric tide [*Pedatella et al.,* 2014]. SSW effects have also been observed to reach the equatorial and low latitude ionosphere [*Goncharenko et al.,* 2010; *Chau et al.,* 2012]. *Chau et al.* [2009] and *Fejer et al.* [2010] found a clear signature of a semidiurnal lunar tide in the drift velocities measured at Jicamarca. *Fejer et al.* [2010] used differential magnetic fields recorded at low latitude stations to imply a correlation between SSW events and equatorial vertical drifts. *Goncharenko et al.* [2018] studied the nighttime effects of the SSW event of January 2013. They reported a profound decrease in TEC that reached a factor of 5 and was observed between local midnight and sunrise at latitudes between 55° S to 45° N. Despite these investigations, it is unclear if these changes in the thermosphere wind system and the concurrent electric fields can increase or decrease the formation of plasma irregularities and ESF [*Patra et al.,* 2014; *de Paula et al.*, 2015].

This investigation utilizes the Low-latitude Ionospheric Sensor Network (LISN) data. The LISN project has deployed a network of receivers to monitor and study the low latitude and equatorial ionospheres. It performs as a distributed array of small instruments (DASI) in the South American Continent. One of the network's goals is to assess the variability of the L-band scintillation index when plasma bubbles transit across the continent. This network provides real-time measurements (nowcast) of scintillations and total electron content (TEC) to the space weather community.

This paper presents an uncommon event that has not been reported. The EIA was abruptly modified during the evening hours, and scintillations increased two hours after plasma bubbles were formed. Several GPS and GNSS receiver networks in the American sector measured the TEC and scintillation values to investigate the causes of this unusual EIA variability and the concurrent appearance of intense scintillations. Our observations correspond to 12 and 13 February 2016, two days in which L-band scintillations become enhanced threefold and two hours after the plasma depletions were formed. We also employ ion drift values measured by the Defense Meteorological Satellite Program (DMSP) to estimate magnetospheric inputs during this observing period. Finally, magnetic field variations measured at Huancayo and Piura are used to investigate the phase changes of the lunar tide. MERRA data of polar temperatures are used to calculate the onset time of the SSW event. February 12 and 13, 2016, are days of moderate magnetic activity ($K_P = 3^o$), in which several weak storms developed during the SSW event. In addition, the scintillation events reported here occurred a few days after a moderate storm impinged the Earth and were followed by another moderate storm (SYM-H $<$ -50 nT) four days later.

Section two of this report introduces the TEC values and L-band scintillations measured in South and Central America and the Caribbean on February 12 and 13, 2016. Section three shows the solar wind conditions and the high-latitude ion drifts that preceded and prevailed during the observing days. The northern hemisphere polar stratospheric temperature that existed before and during the events of February 2016 is presented in section four, along with an analysis of TEC and magnetic field data to elucidate the phase of the enhanced lunar tide. Section five elaborates on the causes of the EIA redistribution, scintillation intensifications, and the variability of the low latitude electrodynamics during this event. In section six, we list our conclusions.

2. TEC and Scintillation observations

Regional networks of GNSS receivers can provide a suite of ionospheric measurements, including regional TEC map, scintillation S4 index, and TEC perturbation (TECP) variations. This section presents these three types of parameters measured in South America to illustrate the evolution of the low-latitude ionosphere on 12–13 February 2016. During these two days, TEC maps of the EIA display a striking variability that coincided with a sudden enhancement of L-band scintillations. S4 indices as high as 1.0 were observed near the center of South America.

Figure 1 displays the locations of 25 selected GPS receivers (see blue and red circles) that operated in 2016 at distances $\pm 6°$ from the magnetic equator. The red circles point out the position of six Low-latitude Ionospheric Sensor Network

(LISN) GPS receivers. In addition to providing the pseudo-range and phase values for TEC computation, these receivers perform real-time calculations of the scintillation S4 index. We also estimate TEC values from all 700+ receivers that operated in South and Central America and the Caribbean region in 2016. TEC values from these receivers readily provide identification of TEC depletions, mark their physical boundaries, and quantify other morphological parameters such as the depletion width, depth, and bubble multiplicity.

2.1 TEC perturbations and scintillations observed on 12 and 13 February 2016

Figure 2 shows a sequence of TECP values originating from the transit of several equatorial plasma bubbles (EPB). The effect of EPBs is to produce negative excursions of the TECP values. The TECP values corresponding to each station are plotted according to their magnetic longitude to visualize the bubble's eastward motion. In this subset of 25 receivers, the station located further west in central Peru, named Cuzco (Latitude = 13.52° S, Longitude = 71.96° W, label = lcuz), is plotted at the top. The TECP curve corresponding to Altamira situated in eastern Brazil (3.18° S, 52.18° W, paat) is displayed at the bottom of Figure 2a. This station arrangement, called "the bubble transit mode," provides a longitude vs. time display and a quick view of the bubble journey through the South American continent. The display format was initially developed to identify bubble changes and conduct velocity calculations during the bubble lifetime. Different bubble parameters can be easily extracted for further analysis and investigations. This display mode also enables a reliable location of the bubble initiation and, more importantly, diagnosing scintillation variability during plasma bubbles' transit across several countries in South America. Depletion and scintillation information from receivers situated more than 6° from the magnetic equator are omitted to avoid a "display contamination" produced by the westward tilt of the plasma bubbles at altitudes above 450 km [*Woodman and LaHoz,* 1976; *kil et al.*, 2009]. As GPS satellites transit with a 55° inclination angle, the sub-ionospheric intersection point of the line-of-sight between satellite and receiver moves toward northeast or southeast with a velocity <100 m/s for elevation angles larger than 30°. Instead, bubbles typically move eastward with speeds >100 m/s; consequently, it is expected that most GPS receivers will first detect the eastern wall of the EPB.

Each curve of Figure 2a was derived by performing a two-step fitting process. In the first step, we fit a fifth-order polynomial function to every 3-hour segment. This procedure filters out TEC variations with a periodicity larger than three hours. The second step involves a calculation of $TECP = TEC - TEC_{fit}$ followed by a second polynomial fit without considering any point that has a TECP below a threshold value (commonly set to -0.75 TEC units). This simple scheme provides the bubble envelope or the TEC background value if no bubble has developed. A new TECP curve is derived using the original TEC and the results of the second fit. These new TECP values are displayed in the left frame of Figures 2 and 3, corresponding to 12 and 13 February 2016, respectively. We also use the TECP curves to derive the boundaries of the westward and eastward walls of the TEC depletions. Negative TECP values equal to -0.75 TEC units and slopes above 0.6 TEC units/min are employed to define the western and eastern edges of the TEC depletions. The yellow shading in Figures 2a and 3a highlights all the depletion detections. Further processing provides the depletion geographic location.

Figure 2a also displays three large red numbers inside circles near local sunset at 75° W (00 UT) to point out the first time a new depletion or a series of depletions is detected. Red number 1 at the top signals a series of four closely spaced depletions. However, these EPBs originated earlier and further west of Cuzco. The following TECP traces display the time evolution of these four depletions that seem to merge and form an extended TEC perturbation. This viewing effect is due to the low elevation angle of the observations ($< 35°$) as some stations are located more distant from the equator, and their lower line of sight may intersect several depletions at once. The circled number 2 marks the initiation of a single EPB detected initially at Oruro in Bolivia (17.95° S, 67.11° W, urus). We follow the trajectory of this single EPB and record the S4 scintillation index as it passes through different LISN scintillation-gathering stations (Figures 2b-2g). The TEC depletion on the left frame and the corresponding scintillations on the right are indicated with an arrow pointing to the EPB observation time. The "single" EPB/TEC depletion was first detected at 00:20 UT and stayed within the field of view of several GPS receivers for 220 min. Later, the EPB passes through the Rio Branco station (9.96° S, 67.87° W, lrbr). Here, the minimum TECP value, or bubble depletion depth, is only about -1.5 TEC units. The depletion reaches maturity (TEC depletion = -15 TEC units) ~25 min later when it goes through Porto Velho (8.84° S, 63.94° W, lpvh). About 90 min later, the single EPB reaches the Alta Floresta site (9.87° S, 56.10° W, lafl), where it has developed a much broader structure and a bifurcation. It is important to note that the separation between adjacent stations can be quite variable, especially between Juina (mtji) and Alta Floresta (lafl), installed 250 km distant. This fact contributes to the long delay between the EPB observations of Alta Floresta and Juina. The TEC depletion is last seen at Santarem (2.43° S, 54.73° W, lstm), where the single bubble has split into two TEC depletions. The EPB finally decays before entering the field of view of the Altamira GPS station (paat). The TEC depletion has decayed before reaching this station as its depth is less than 0.75 TEC units. This observing scheme has demonstrated its practicality in displaying the temporal evolution of plasma bubbles using the GPS resources presently operating in South America. We used cross-correlation analysis and assessed the bubble's lifetime to be ~220 min and the average velocity near 165 m/s.

Figures 2b-2g introduce the L-band scintillation measured by six Novatel GPS receivers. The orange curves show the elevation angle of the line of sight to the GPS satellite. On February 12, 2016, we found an unusual scintillation increase at 02:10 UT, almost two hours after the TEC depletions formed and when TEC depletions/EPBs were transiting near central Brazil. Rio Branco (lrbr) is the first station to observe a significant scintillation level associated with the TEC depletion labeled 2 (S4 > 0.2). Thirty minutes later, when the EPB crosses Porto Velho (lpvh), the scintillation peak becomes 0.3. However, 90 min later, when the EPB passes through Alta Floresta, the S4 index increases to > 0.6. The most significant scintillation value is observed at Santarem (lstm), where the S4 index is close to 1.0. This scintillation index occurs only minutes before the EPB decays and when the depletion depth is not the largest. We also note that the scintillation enhancement discussed here does not correspond to a geometrical scintillation effect as the elevation angle was near 30°.

Figure 3a shows the passage of several EPBs through the western and central parts of South America that developed on February 13, 2016. The circled red number 1 indicates the first sight of a series of EPBs formed west of Piura (5.17° S, 80.64° W, lpiu) in the Pacific Ocean. The red number 2 reveals the initiation of a series of narrow TEC depletions that likely originated between Piura and Huancayo (12.04° S, 75.32° W, lhyo) as they are detected in the latter station but not in Piura. A total of 13 depletions propagating eastward are observed at the Huancayo station; some of these TEC depletions originated before reaching the Piura station, but others were created close to and west of the Huancayo site. This plot provides an overview of the appearance and behavior of the TEC depletions and indicates that these bubbles decay three hours later at 04 UT. This display mode can be used to derive several different morphological parameters related to the beginning and decay of plasma bubbles. However, this is not the purpose of this paper, and bubble lifetime will be dealt with in another publication. It is important to note that these large series of EPBs will likely fill the sky and present a natural radio wave propagation hazard. The number three (in red) signals the beginning of a single but wider EPB that develops near the Rio Branco station. No scintillations are seen in the corresponding S4 values of Figure 3e. About 40 min later, the EPB crosses through Porto Velho, where the depletion depth is about 12 TEC units, and the scintillation S4 reaches 0.25. Two hours later, the EPB is spotted at the Alta Floresta site, where the depletion depth has decayed to 5 TEC units, but the S4 index is equal to 1.0. Less than one hour later, the EPB finally wears out, and no depletion is observed at Santarem. It is important to note that on February 12, the enhanced scintillations (S4 > 0.4) occurred after 02 UT; on February 13, the S4 increase occurred after 03 UT.

2.2 TEC maps corresponding to 12 and 13 February 2016

Figures 4 and 5 show TEC maps measured by all 700+ GPS receivers that operated in South and Central America and the Caribbean region on February 12 and 13, 2016. These maps were obtained following the nonlinear regression analysis described by *Valladares and Chau* [2012]. Each panel of these Figures displays TEC maps using a linear scale to emphasize subtle TEC variations in response to the temporal changes in the electric field, neutral wind, and the normal nighttime decay of the low latitude ionosphere.

The crests of the EIA of Figure 4a are nearly symmetric; however, across the continent, the distance between the crests of the anomaly and the magnetic equator is not equal. The crests are displaced ~10° away from the magnetic equator (small eastward E field) on the west coast of South America, but a much larger separation (~20°) is evident on the east coast (a larger E field). This longitude-dependent separation persists in each frame of Figure 4 and continues until 04:30 UT. The variable width of the EIA is produced by an eastward E field that is smaller on the west coast and much larger at the eastern longitudes.

Figure 4b exhibits the initiation of a dramatic morphological change, in which a north-south aligned segment develops near the center of the South American continent, joining the north and south crests of the EIA. On the western side of South America, the southern crest of the anomaly fades, and its amplitude falls below 20 TEC units. This plasma behavior can be explained by the existence of a trans-equatorial meridional wind that moves the plasma along the field lines transporting plasma from the northern crests toward the magnetic equator and into the southern hemisphere. Here, the southern wind transports the plasma down the field line toward lower altitudes, where recombination proceeds more promptly. We also indicate that the southern wind may decrease near the center of South America, slowing the plasma motion and giving time for forming a north-south aligned plasma density segment. Further east, the meridional wind may be near zero or even northward directed, leaving the anomaly's crests almost unchanged. The ensuing TEC distribution consists of a large-scale structure extending between the center of South America and the eastern coast and resembling a semi-circle or a horseshoe pattern (see Figures 4c and d). This large-scale structure is about 3000 km longitude and at least 2000 km latitude. The large-scale structure fades after 05 UT. The large red arrow in Figure 4c points out the location of a subtle, nevertheless significant effect seen near 60° W and 25° S latitude. Figures 4b and 4c show a change in TEC values or a retraction of the southern end of the anomaly. This motion can be better visualized in movie S1, which is part of the additional information described later in this section. It is suggested that this plasma motion may be associated with a northward wind system that is part of a reverse fountain effect [*Balan and Bailey,* 1995] that can produce near midnight TEC enhancements [*Valladares and Chau,* 2012].

Although Figures 5a-d show an evolution similar to the TEC maps in Figure 4, the circular structure presents some timing and morphological differences. On 13 February 2016, the circular anomaly formed one hour later, is smaller in size, and is located at longitudes further east. Despite these differences, their electrodynamics and driving sources may be equal. Figures 5c-d depict a fully formed circle extending 2000 km in longitude, compared to over 3000 km on 12 February 2016. In summary, the TEC data corresponding to February 12 and 13, 2016, reveals that the EIA is highly variable, and changes in the order of ten minutes are typical. A similar TEC pattern of a circular anomaly configuration was presented by *Villalobos and Valladares* [2020] (Figure 4b), in which an almost complete vortex developed on the western side of South America. However, these authors did not discuss the possible drivers of this anomalous low-latitude

TEC configuration. In addition, this pattern occurred in the afternoon sector, and their electrodynamics could not influence any irregularity formation or S4 index enhancement.

Additional information is available in the supporting material that accompanies this publication. Movie S1 displays a series of TEC images produced every 5 min, using the same format as Figures 4 and 5, spanning between 23:00 UT on 11 February 2016 and 05:00 UT on 12 February 2016. S1 movie presents the TEC maps' high temporal and spatial variability and reveals how the north-south aligned branch of the vortex develops and moves eastward between 01 and 02:30 UT. The almost complete vortex seems to originate in the center part of South America and drifts rapidly eastward. The vortex stops at 05:00 UT when there is a total decrease of the background TEC due to a rapid descent of the F layer. A second movie, called S2, shows the dynamics of TEC images on 13 February 2016 between 00 and 05 UT. This movie repeats several features of movie S1, but the appearance and development of the vortex are delayed by ~1 hour.

3. Magnetic storm conditions during the 12 and 13 February 2016 event

Figure 6 shows the SYM-H, the B_z component of the interplanetary magnetic field (IMF), and the zonal averaged polar temperature corresponding to days between 31 January and 16 February 2016. This Figure presents the solar wind conditions and the northern pole's stratospheric temperature during the minor SSW event in February 2016. On February 1, 2016, a moderate magnetic storm reached the magnetosphere, producing an SYM-H decrease equal to -50 nT. Two days later, the second magnetic storm of almost similar magnitude struck the Earth generating SYM-H values near -60 nT. It is essential to mention that during the events presented in Figures 2-5 for 12 and 13 February 2016, a low level of magnetic activity ($K_p = 3^+$ and 2^0), associated with two weak magnetic storms created, as we will see later in this section, some minor disturbances at high latitudes. The red lines in Figures 6a and 6c point out when scintillations were enhanced and the S4 index reached values >1.0 (i. e. Figures 2 and 3). These two periods coincide with large values of B_z and B_y. B_z is close to -10 nT during the first scintillation period and +15 nT during the event on 13 February 2016. Periods of negative B_z are highlighted using yellow shading. The black curve of Figure 6c shows the zonal mean polar temperature measured between 80° and 85° geographic latitude and ten hPa, the green curve displays the temperature at 90°, and the zonal mean temperature between 70° and 80° is in red. The maximum temperature variability peaked at 00 UT on 09 February 2016, when the temperature reached 257° K. This is about 36° above the average polar temperature level for years spanning 1979 and 2020.

The lower panels of Figure 7 illustrate the variability of the high and mid-latitude zonal ion drifts measured between days 41 (10 February 2016) and day 45 (14 February 2016) by the Defense Meteorological Satellite Program (DMSP) F18. The two top panels display the Dst, IMF B_y, and B_z components. It is essential to mention that B_z (red curve) is mainly northward on 12 and 13 February 2016. Accordingly, during these days, the DMSP F18 zonal velocities within both polar caps consist of a blend of sunward and anti-sunward ion velocities. During periods of Northward IMF, the polar cap and auroral oval retreat to latitudes above 70° magnetic [*Cumnock et al.,* 1995]. It is evident in the lower panel that the drift velocities at latitudes near 50° are smaller than 200 m/s in both dawn and dusk sectors and on both hemispheres. Based on this drift distribution, we conclude that no large velocities penetrated to latitudes below 60°. The black dots near 60°-70° magnetic latitude at both hemispheres and on both dawn and dusk sides mark the regions where the gradient in zonal flows falls below 25 m/s/degree. This boundary distinguishes quiet time drifts at low latitudes, driven by thermosphere winds, from drifts at higher latitudes produced by magnetospheric processes [*Heelis and Mahapatra*, 2009; *Chen et al., 2015*]. We indicated above that February 12 and 13, 2016, were days when we observed the scintillation enhancements and the prominent TEC disturbances in the EIA region. A close inspection of the time of the enhanced scintillations of 12 February 2016 reveals that this event occurred during the recovery phase of the first weak storm (see vertical red line in Figure 6). The event of 13 February developed during a time of positive SYM-H values or sudden commencement. No appreciable difference in the zonal drifts at mid latitudes is seen at both times. In summary, Figure 7 illustrates the lack of penetration of the zonal ion drifts into sub-auroral latitudes.

4. SSW effects during February 2016

During Arctic SSW events, equatorial electrojet currents suffer significant changes produced by variations in the thermosphere wind on a global scale. The cause of this variability is attributed to an enhancement of the semidiurnal lunar tide [*Fejer et al.,* 2010, 2011; *Chau et al.,* 2010; *Goncharenko et al.,* 2010] produced by the propagation of planetary waves. Despite the vast support for the role of the semidiurnal lunar tide on SSW events, the chain of events leading to an enhancement of the lunar tide has not been determined yet [*Pedatella et al.*, 2014]. An essential characteristic of the lunar tide is the phase shift that appears on consecutive days [*Fejer et al.,* 2010], producing an afternoon counter-electrojet during new and full moons and a morning counter-electrojet that occurs 9 or 21 days after the full moon [*Fejer et al.,* 2011]. To investigate the development of an enhanced lunar tide in February 2016, we examine the daily changes of the differential magnetic field variations measured by ground magnetometers operating at Jicamarca (11.9° S, 76.8° W) and Piura. Figure 8 shows that between February 09 and 16, 2016, there was a linear delay of positive values on later days. A three-day modulation of the lunar tide is evident, containing higher magnetic values between 11 and 13 February 2016 and smaller values afterward. Similar to the values presented by *Fejer et al.* [2010], Figure 8 shows early afternoon counter-electrojet values (negative) between 09 and 11 February 2016. This behavior is followed by morning counter electrojet effects on 14 and 15 February 2016. It is also pointed out that a new moon occurred at 14 UT on 08 February 2016, near the western coast of South

America. Although our primary emphasis is to describe the behavior of the low-latitude ionosphere during the SSW event, it is essential to mention that a recurrent and moderate magnetic storm developed ~22 UT on 16 February 2016, terminating the lunar tide-dominated plasma electrodynamics pattern that prevailed during the SSW event. Note that the delta(H) values preceding the SSW event on 09 February and the one following the storm of 16 February 2016 have similar magnetic field characteristics containing positive during daytime hours and no phase delays.

The phase progression of the lunar tide is also evident in the sequence of TEC latitudinal profiles presented in Figure 9. The TEC monthly average corresponding to February 2016 is shown in Figure 9a. This frame was generated by selecting the TEC values measured along the field line intersecting the magnetic equator at 75° W geographic longitude. The average TEC latitudinal profiles show an almost symmetric anomaly in the afternoon and an asymmetry in the early evening hours (LT = UT − 5 hours at 75° W). The differential TEC images of Figures 9b-9h were obtained by subtracting the monthly average of Figure 9a from the TEC values observed between February 9 and 15, 2016. These frames illustrate TEC differences associated with the SSW event; for example, the symmetric differential "anomaly" seen in Figure 9c-9h suggests an additional vertical velocity associated with the SSW event that drives the fountain effect. This delta or difference anomaly shows two crests equidistant from the magnetic equator by 10° to 17°. The difference "anomaly" develops ~1 hour later every day between 09 and 15 February 2016. This delay agrees with the phase shift of the magnetic field measurements in Figure 8. Although not shown here, the differential TEC did not exhibit any organized phase progression during the days before and after the SSW event and displayed a combination of positive and negative difference anomaly crests.

SSW events also influence the thermosphere dynamics producing changes in the meridional wind. As the asymmetry of the EIA depends on the direction of the north-south meridional wind, we have used TEC latitudinal profiles between ±40° magnetic latitude to investigate the direction and the variability of the meridional component of the neutral wind. Figure 10 shows hourly latitudinal profiles of TEC measured near 75° W longitude between 09 and 16 February 2016, covering a time interval between 12 and 05 UT (07 - 24 LT at 75° W). The yellow shaded squares indicate when enhanced L1-band scintillations (S4 ~ 1.0) were detected in Figures 2 and 3. The red and blue diagonal lines divide regions with different EIA amplitudes and asymmetries. The TEC profiles on the left of the red diagonal line are centered near the magnetic equator and lack the double crest that characterizes the development of the fountain effect. The TEC profiles between the red and blue lines present symmetric crests of the EIA. The crest separation is sometimes near ±20°, and their amplitudes exceed 100 TEC units, as observed between 19 and 23 UT on 13 February 2016. These TEC profiles are typical during times of significantly high upward vertical drifts. The TEC profiles on the right side of the blue line exhibit highly asymmetric crests of the EIA, where the northern crest is always more prominent. The southern crest is sometimes absent, as seen near local midnight (04 UT) on 12 February. This pronounced asymmetry can be created by a trans-equatorial southward-directed meridional wind that moves the plasma up in the northern magnetic hemisphere and down in the southern hemisphere. The altitude changes cause slower (faster) recombination at the north (south) latitudes and consequently higher (lower) TEC values.

Information on the longitudinal variability of the electric field and the meridional neutral wind during the SSW event of February 2016 is provided in Figure 11. We indicate herein that the latitudinal separation, the amplitude, and the asymmetry of the equatorial anomaly crests vary as a function of longitude during the nighttime hours. Consequently, the vertical plasma drift increases on the east side of South America, and the meridional neutral wind reverses from southward on the west side to northward on the east side of SA. Each row of Figure 11 displays the anomaly distribution at different longitudes extending between 80° W and 50° W. The location of the anomaly's peak is displayed using a vertical black line. Note that some TEC profiles at longitudes equal to 80° and 50° show some gaps due to the limited extension of the South American continent. The top row, corresponding to 80° W, displays a highly asymmetric anomaly in which the southern crest is non-existent. The northern crest is well developed and 9° away from the magnetic equator. This distribution prevails between 01 and 04 UT. The second row of TEC latitudinal profiles, measured at 70° W, show an asymmetric anomaly in which the amplitude of the southern crest is approximately half the amplitude of the northern crest. However, after 03 UT, the southern crest diminishes and fades out. Near 60° W, the anomaly shows a more significant latitudinal displacement with a separation of ~15°. Near 00 UT, the anomaly is symmetric, with the southern crest decreasing and vanishing at 05 UT. The bottom row of TEC profiles shows a different anomaly behavior in which the southern crest predominates, and the northern crest diminishes and disappears at 05 UT. Figure 11 demonstrates the usefulness of the latitudinal TEC profiles at low latitudes in diagnosing the role of E fields and meridional winds. Based on the anomaly characteristics between 80° and 50° W longitude, we conclude that the meridional wind reverses between 60° and 50° West, and the eastward E field increases in the eastern part of South America.

Figures 2-11 have demonstrated how the polar stratosphere can control the low latitude ionosphere's behavior and the scintillations' intensity during the minor SSW event of February 2016. We expect that any significant SSW event will likely produce similar effects. However, the amplitude of the wind variability may differ and make some events more prominent than others. Regarding scintillation increases, and similarly to bubble production, the positive correlation with SSW events may occur only for a few days during a lunar tide's specific period or phase. Further analysis of other SSW events is required to fully characterize the effect of SSW on the onset of equatorial plasma bubbles and the variability of the S4 scintillation index.

5. Discussion

We have used TEC values provided by hundreds of stations that operate at equatorial and low latitudes in the American sector to build TEC maps and record changes in the EIA on 12 and 13 February 2016. During the early evening hours, the EIA experienced a dramatic reconfiguration developing a north-south aligned segment at the center of South America, forming an almost circular structure centered near the magnetic equator and displaced to the eastern side of South America. This newly reconfigured anomaly lasted for a few hours and consisted of a loop of enhanced densities around the magnetic equator. On both days, the northern crest of the anomaly survived the drastic changes, suggesting that a southward-directed meridional wind had driven the plasma toward the opposite hemisphere and was responsible for the formation of the north-south aligned branch. This impressive anomaly display was accompanied by prominent intensifications of L-band scintillations that reached saturation values ($S4 > 1.0$) within the TEC depletions. However, the depletions themselves were generated before the anomaly reconfiguration. We observed some bubbles split; nevertheless, the origin of all the TEC depletions can be traced back to local times near sunset. The circled red numbers in Figures 2a and 3a point out the times when the depletions were formed, occurring first at eastern longitudes in agreement with the motion of the sunset terminator.

Our observations demonstrate that the EIA does not always consist of two parallel density enhancements aligned on both sides of the magnetic equator. Instead, the anomaly can assume various shapes, asymmetries, and widths as it is constantly modified by an E field that can vary with respect to longitude and by significant meridional winds able to transport enhanced densities from one crest of the EIA to the opposite hemisphere. A longitude-dependent eastward E field (an upward vertical drift) across South America will produce a crest displacement different on the west and east coasts. This effect was observed on 12 February 2016 before the formation of the circular structure, persisted for several hours, and continued after the circular anomaly formed. Figures 4 and 11 show a short anomaly separation of 9° on the West Coast (80° W) and 16° on the East Coast (50° W) of South America. On 13 February 2016, the anomaly crest separation showed a minimum near the continent's center and a more significant crest distance on South America's western and eastern coasts.

The source of the unusual pattern of electric field and meridional wind that formed the large-scale circular structure was investigated using solar wind and polar stratospheric temperature data to assess the role of the magnetosphere and atmospheric processes. We also realized that two weak magnetic storms developed near the enhanced scintillations, and a minor SSW event occurred a few days before, on 08 February 2016. The question is if a prompt penetration electric field or a disturbance dynamo wind associated with these storms could reconfigure the EIA and form the observed circular anomaly that persisted for a few hours on February 12 and 13, 2016. Figure 7 distinctly illustrates that the storm effect is neglectable on 12 and 13 February 2016. The zonal ion drift at sub-auroral latitudes (~50° magnetic latitude) corresponds to and is equal to the quiet time ion drift (~200 m/s). Auroral and polar cap velocities were slightly enhanced on 12 February 2016. The following day, the IMF B_z was positive, yielding a smaller auroral oval and again quiet time drifts at 50° latitude. The DMSP observations corroborated that those weak magnetic storms containing SYM-H minimum values between -30 and -50 nT do not alter the F region dynamics at mid and low latitudes. It is concluded that the E-field and wind patterns that created the EIA loop are related to the dynamics of the SSW event.

During SSW events, the low and mid-latitude ionospheres undergo significant changes [*Chau et al.,* 2012; *Fejer et al.,* 2010; and *Goncharenko et al.,* 2010; 2013]. One of the prominent characteristics of SSW events is the intensification of the semi-diurnal lunar tide and the consequent daily phase shift in the appearance of daytime E-region currents. The magnetic field signatures produced by this current can be measured using a pair of ground-based magnetometers [*Anderson et al.,* 2002]. These instruments must be placed one near the magnetic equator and a second at ±6° from the equator. We have used the Jicamarca–Piura pair to demonstrate the presence of an enhanced semidiurnal lunar tide near 75° W that shows a daily phase shift in accord with previous SSW-related measurements [*Fejer et al.,* 2010; 2011]. The diurnal phase advance of the lunar tide was also observed in the daily TEC latitudinal profiles implying that the electrodynamic effects of the E region map to the F region. The TEC maps of Figures 4 and 5 and the TEC latitudinal profiles of Figures 10 and 11 suggest that minor, and likely any major, SSW events could generate nighttime effects that reach F-region altitudes and produce significant changes in the ionosphere such as meridional winds and vertical drifts able to modify the low and equatorial TEC values and even increase L-band scintillations. All these phenomena demonstrate a physical connection between the polar stratosphere and the low latitude F region during SSW events.

TEC latitudinal profiles observed on 12-13 February 2016 displayed the appearance of a highly asymmetric anomaly. Several authors have reported the existence of asymmetric EIAs and elaborated on the role of a trans-equatorial wind in transporting the plasma along the field lines [*Valladares et al.,* 2004; *Tulasi Ram et al.,* 2009; *Khadka et al.,* 2018]. A meridional wind directed southward will produce an enhanced northern crest by moving the plasma to higher altitudes of slow recombination in the northern hemisphere and a depleted southern crest at lower altitudes and faster recombination. *Tulasi Ram et al.* [2009] found the EIA to present asymmetric characteristics during the northern hemisphere's summer and afternoon local time hours. *Datta-Barua*, [2009] and *Khadka et al.* [2018] used anomaly profiles to reverse model and derive meridional winds. *Khadka et al.* found meridional wind values close to 80 m/s that reasonably agreed with meridional wind measurements conducted by the SOFDI Fabry-Perot interferometer in Huancayo.

The fact that TEC was enhanced along a north-south segment near 60° W suggests the presence of a convergent meridional wind system, similar to the wind arrangement that exists during a reverse fountain effect [*Valladares and Chau*, 2012] when plasma is transported from both crests of the EIA toward the magnetic equator. It is also indicated that the meridional wind modified all altitudes of the F region, was large enough, and persisted for a necessary time to transport plasma along the field lines.

Figure 12 illustrates a 3D schematic representation of the vertical drifts (red arrows along the magnetic equator) and the meridional winds (blue arrows at 30 TEC units) during the formation of the circular TEC loop and the S4 index intensification. Figure 12 also includes the TEC latitudinal profile measured at 80° W on 12 February 2016 in blue colors and the TEC profile corresponding to 50° W using reddish tones. To better visualize the extension of the latitudinal profile, the TEC peaks are projected to one side of the graph at -30° geographic longitude. Here it is seen that the EIA crests are near 16°. This value is larger than the 9° displacement of the northern crest at 80° W, indicating that the vertical velocity, and the E field, on the east side at 50° W are greater than at 80° W. The significant asymmetry observed at 80° W (blue lines) suggests that the southward meridional wind is large and covers tens of degrees in latitude. The TEC profile at 50° W shows the opposite behavior; the southern crest is much larger than the northern one, implying that the meridional wind has reversed signs across the Continent.

The blue arrows in Figure 12 portray our conceptual model of the meridional winds that prevailed during the formation of the TEC loop and the sudden increase in scintillations. We believe that at 80° W, the meridional wind was mainly large and directed south. It presents a shear and a smaller amplitude near the location of the southern crest. At 70° W, the meridional wind is smaller and shows a reversal in the southern magnetic hemisphere. We also indicate that at 60° W, the meridional wind diminishes but is still directed south at the northern end of the EIA. The wind reverses near the magnetic equator producing a reverse fountain effect that generates the north-south aligned side of the anomaly circle. At 50° W, the meridional wind is primarily directed northward, creating a prominent southern crest. In summary, our conceptual model of the meridional wind over South America suggests the importance of a wind reversal as a function of longitude and latitude. Movies S1 and S2 have also indicated that the circular TEC structure moves eastward, likely carried by the nighttime eastward plasma drift.

Scintillation enhancements during the lifetime of an existent or fully formed depletion/bubble are rare. In some cases, when the line of sight between receiver and satellite coincides with the bubble tilt angle, the S4 index increases producing a geometrical enhancement. Unfortunately, this mechanism does not seem to explain the scintillation enhancements of February 2016, as the looking direction angle was between 30° and 45°. We suggest that the meridional wind shear and its reversal produce the scintillation enhancements. *LaBelle et al.* [1986] indicated that wind could generate irregularities when blowing across a steep wall, as it is typically observed within the bubble sides when $(U \cdot \nabla n < 0)$. Bubble walls possess horizontal scale lengths of order km or less [*Rodrigues et al.* 2009]. Then, a wind component in the antiparallel to the density gradients will enhance the irregularities. Notice that at longitudes east of 60° W, the field line declination is negative, making the eastern wall unstable to the wind gradient instability. In addition, a reversal of the neutral wind also contains different scale sizes that can be transferred to the density and amplify km-scale and sub-km-scale irregularities, consequently enhancing the scintillation level.

Circular EIA patterns have been presented by *Villalobos and Valladares* [2020] (Figure 4b). However, those vortical patterns occurred at different local times (13 LT) and were not accompanied by enhanced scintillations. These authors did not explain the origin of circular anomalies but implied that the meridional wind was likely responsible for the unusual anomaly configuration. Here, we have introduced a conceptual model that involves a zonal E field and a meridional wind system that can explain our TEC observations and is conducive to interpreting scintillation enhancements.

6. Conclusions

Regional maps of TEC values over South America, together with records of the transit of depletions across the Continent, DMSP-F18 horizontal plasma drifts, and horizontal E-region currents, have inferred the response of the low-latitude ionosphere during the minor SSW event of February 2016. Space weather resources presently operating in South America allowed us to follow the temporal evolution of plasma bubbles and continuously examine the scintillation S4 index. We also used TEC latitudinal profiles to investigate the ionospheric drivers of the unusual variability of the EIA and S4 index. Specifically, the symmetry/asymmetry of the EIA and its latitudinal extension can reasonably estimate the electric field and the meridional neutral wind that drives the ionospheric variability.

This study has led to the following:

1. TEC measurements collected in the American sector have shown that the EIA can be drastically disturbed and how its typical configuration of two-parallel crests equidistant from the magnetic equator develop asymmetries and build up segments that are aligned in the North-South (N-S) direction. Simultaneous, records of L-band scintillations corresponding to depletions initiated more than one hour before indicated an enhancement of the S4 index by a factor of 3-4 that occurred on two consecutive days.

2. Polar stratospheric temperatures and zonal mean zonal velocities indicated the northern hemisphere polar vortex displacement that started on 8 February 2016. This stratospheric phenomenon originated from a minor SSW event that propitiated an increase in the amplitude of the lunar tide.

3. Magnetic field values derived using a pair of ground-based magnetometers and differential TEC confirmed the presence of an enhanced semi-diurnal lunar

tide that produced significant changes in the vertical drift and meridional wind across South America. This fact endorsed our hypothesis that the SSW event was responsible for the low-latitude ionosphere development that originated an EIA circular structure and scintillation increases.

4. We have proposed that changes in the meridional wind associated with an SSW event can enhance L-band scintillations at low latitudes by increasing the intensity of intermediate scale irregularities in the ~1 km regimen. This investigation surmises that wind shears and reversals near 60° W help increase scintillations. We also emphasize that SSW events' role must be included in any empirical and numerical model of scintillations and spread F. However, it is necessary to assess the impact of the amplitude and phase of the lunar tide on the corresponding amount of scintillation enhancement for different SSW events. This effort will be the topic of future investigations.

5. DMSP-F18 measurements of horizontal velocities indicated that the weak magnetic storms of 12 February 2016 do not modify the electrodynamics of the EIA nor induce scintillation enhancements as observed on 12 and 13 February 2016.

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References

Aarons, J., (1977) Equatorial scintillations: A review, IEEE Trans. Antennas Propagation, AP-25, 729, 1977.

Anderson, D., Anghel, A., Yumoto, K., Ishitsuka, M., and Kudeki, E., (2002) Estimating daytime vertical ExB drift velocities in the equatorial F-region using ground-based magnetometer observations, *Geophys. Res. Lett.*, 29(12), doi:10.1029/2001GL014562.

Anderson, D., Anghel, A., Chau, J., and Veliz, O. (2004). Daytime vertical **E** × **B** drift velocities inferred from ground-based magnetometer observations at low latitudes. *Space Weather*, *2*(11), https://doi.org/10.1029/2004SW000095.

Appleton, E. V. (1946). Two Anomalies in the Ionosphere. *Nature*. Nature Publishing Group. https://doi.org/10.1038/157691a0.

Balan, N., and Bailey, G. J. (1995). Equatorial plasma fountain and its effects: Possibility of an additional layer. *Journal of Geophysical Research*, *100*(A11), 21421. https://doi.org/10.1029/95JA01555.

Basu, Su., and S. Basu (1985), Equatorial scintillations: Advances since ISEA-6, J. Atmos. Terr. Phys., 47, 753 – 768, doi:10.1016/0021-9169(85)90052-2.

Basu, S., et al. (1996), Scintillations, plasma drifts, and neutral winds in the equatorial ionosphere after sunset, *J. Geophys. Res.*, 101(A12), 26795– 26809, doi:10.1029/96JA00760.

Basu, S., Basu, Su., MacKenzie, E., Bridgwood, C., Valladares, C. E., Groves, K. M., and Carrano, C. (2010), Specification of the occurrence of equatorial ionospheric scintillations during the main phase of large magnetic storms within solar cycle 23, *Radio Sci.*, 45, RS5009, doi:10.1029/2009RS004343.

Blanc, M., and Richmond, A. (1980), The ionospheric disturbance dynamo, *J. Geophys. Res.*, 85(A4), 1669 –1686, doi:10.1029/JA085iA04p01669.

Chau, J. L., Fejer, B. G., and Goncharenko, L. P. (2009), Quiet variability of equatorial **E** × **B** drifts during a sudden stratospheric warming event, *Geophys. Res. Lett.*, 36, L05101, doi:10.1029/2008GL036785.

Chau, J. L., Aponte, N. A., Cabassa, E., Sulzer, M. P., Goncharenko, L. P., and González, S. A. (2010), Quiet time ionospheric variability over Arecibo during sudden stratospheric warming events, *J. Geophys. Res.*, 115, A00G06, doi:10.1029/2010JA015378.

Chau, J. L., Goncharenko, L. P., Fejer, B. G. *et al.* (2012) Equatorial and Low Latitude Ionospheric Effects During Sudden Stratospheric Warming Events. *Space Sci. Rev.* 168, 385–417. https://doi.org/10.1007/s11214-011-9797-5.

Chen, Y.-J., Heelis, R. A., and Cumnock, J. A. (2015), Response of the ionospheric convection reversal boundary at high latitudes to changes in the interplanetary magnetic field. *J. Geophys. Res. Space Physics*, 120, 5022– 5034. doi: 10.1002/2015JA021024.

Cumnock, J. A., Heelis, R. A., Hairston, M. R., and Newell, P. T. (1995), High-latitude ionospheric convection pattern during steady northward interplanetary magnetic field, *J. Geophys. Res.*, 100(A8), 14537–14555, doi:10.1029/94JA03318.

Datta-Barua, S., Bust, G. S., Crowley, G., and Curtis, N. (2009), Neutral wind estimation from 4-D ionospheric electron density images, *J. Geophys. Res.*, 114, A06317, doi:10.1029/2008JA014004.

de Paula, E. R., Jonah, O. F., Moraes, A. O., Kherani, E. A., Fejer, B. G., Abdu, M. A., Muella, M. T. A. H., Batista, I. S., Dutra, S. L. G., and Paes, R. R. (2015), Low-latitude scintillation weakening during sudden stratospheric warming events. *J. Geophys. Res. Space Physics*, 120, 2212 – 2221. doi: 10.1002/2014JA020731.

Fejer, B.G. and L. Scherliess, (1995), Time dependent response of equatorial ionospheric electric fields to magnetospheric disturbances, *Geophys. Res. Lett.*, 22, 7 https://doi.org/10.1029/95GL00390.

Fejer, B.G., Larsen, M.F. and Farley, D.T. (1983), Equatorial disturbance dynamo electric fields. Geophys. Res. Lett., 10: 537-540. https://doi.org/10.1029/GL010i007p00537.

Fejer, B. G., L. Scherliess, and E. R. de Paula (1999), Effects of the vertical plasma drift velocity on the generation and evolution of equatorial spread *F*, *J. Geophys. Res.*, 104(A9), 19859–19869, doi:10.1029/1999JA900271.

Fejer, B. G., Jensen, J. W., and Su, S.-Y. (2008), Seasonal and longitudinal dependence of equatorial disturbance vertical plasma drifts, *Geophys. Res. Lett.*, 35, L20106, doi:10.1029/2008GL035584.

Fejer, B. G., Olson, M. E., Chau, J. L., Stolle, C., Lühr, H., Goncharenko, L. P., Yumoto, K., and Nagatsuma, T. (2010), Lunar-dependent equatorial ionospheric electrodynamic effects during sudden stratospheric warmings, *J. Geophys. Res.*, 115, A00G03, doi:10.1029/2010JA015273.

Fejer, B. G., Tracy, B. D., Olson, M. E., and Chau, J. L. (2011), Enhanced lunar semidiurnal equatorial vertical plasma drifts during sudden stratospheric warmings, *Geophys. Res. Lett.*, 38, L21104, doi:10.1029/2011GL049788.

Goncharenko, L. P., Coster, A. J., Chau, J. L., and Valladares, C. E. (2010), Impact of sudden stratospheric warmings on equatorial ionization anomaly, *J. Geophys. Res.*, 115, A00G07, doi:10.1029/2010JA015400.

Goncharenko, L., Chau, J. L., Condor, P., Coster, A., and Benkevitch, L. (2013), Ionospheric effects of sudden stratospheric warming during moderate-to-high solar activity: Case study of January 2013, *Geophys. Res. Lett.*, 40, 4982– 4986, doi:10.1002/grl.50980

Goncharenko, L. P., Coster, A. J., Zhang, S.-R., Erickson, P. J., Benkevitch, L., Aponte, N., et al. (2018). Deep ionospheric hole created by sudden stratospheric warming in the nighttime ionosphere. *Journal of Geophysical Research: Space Physics*, 123, 7621 – 7633. https://doi.org/10.1029/2018JA025541.

Hanson, W. B., and Moffett, R. J. (1966). Ionization transport effects in the equatorial F region. *Journal of Geophysical Research*, *71*(23), 5559–5572. https://doi.org/10.1029/JZ071i023p05559.

Heelis, R. A., and Mohapatra, S. (2009), Storm time signatures of the ionospheric zonal ion drift at middle latitudes, *J. Geophys. Res.*, 114, A02305, doi:10.1029/2008JA013620.

Huang, C.-S. (2016), Plasma drifts and polarization electric fields associated with TID-like disturbances in the low-latitude ionosphere: C/NOFS observations, *J. Geophys. Res. Space Physics*, 121, 1802–1812, doi:10.1002/2015JA022201.

Huang, C.-S. (2018). Effects of geomagnetic storms on the postsunset vertical plasma drift in the equatorial ionosphere. *Journal of Geophysical Research: Space Physics*, 123, 4181 – 4191. https://doi.org/10.1029/2018JA025360.

Huang, C.-S. (2019). Long-lasting penetration electric fields during geomagnetic storms: Observations and mechanisms. *Journal of Geophysical Research: Space Physics*, 124, 9640 – 9664. https://doi.org/10.1029/2019JA026793.

Khadka, S. M., Valladares, C. E., Sheehan, R., & Gerrard, A. J. (2018). Effects of the electric field and neutral wind on the asymmetry of equatorial ionization anomaly. *Radio Science*, 53, 683–697. https://doi.org/10.1029/2017RS006428.

Kil, H., Heelis, R. A., Paxton, L. J., and Oh, S.-J. (2009), Formation of a plasma depletion shell in the equatorial ionosphere, *J. Geophys. Res.*, 114, A11302, doi:10.1029/2009JA014369.

LaBelle, J., Kelley, M. C., and Seyler, C. E. (1986), An analysis of the role of drift waves in equatorial spread *F*, *J. Geophys. Res.*, 91(A5), 5513– 5525, doi:10.1029/JA091iA05p05513.

Matsuno, T. (1971), A dynamical model of the stratospheric sudden warming, *J. Atmos. Sci.,* 28, 1479–1494. https://doi.org/10.1175/1520-0469(1970)027%3C0871:VPOSPW%3E2.0.CO;2

Patra, A. K., Pavan Chaitanya, P., Sripathi, S., and Alex, S. (2014), Ionospheric variability over Indian low latitude linked with the 2009 sudden stratospheric warming, *J. Geophys. Res. Space Physics*, 119, 4044 –4061, doi:10.1002/2014JA019847.

Pedatella, N. M., Liu, H.-L., Sassi, F., Lei, J., Chau, J. L., and Zhang, X. (2014), Ionosphere variability during the 2009 SSW: Influence of the lunar semidiurnal tide and mechanisms producing electron density variability, *J. Geophys. Res. Space Physics*, 119, 3828 – 3843, doi:10.1002/2014JA019849.

Rino, C., Carrano, C. S., & Groves, K. M. (2019). Wave field propagation in extended highly anisotropic media. *Radio Science*, 54, 646– 659. https://doi.org/10.1029/2019RS006793.

Rodrigues, F. S., Kelley, M. C., Roddy, P. A., Hunton, D. E., Pfaff, R. F., de La Beaujardière, O., and Bust, G. S. (2009), C/NOFS observations of intermediate and transitional scale-size equatorial spread *F* irregularities, *Geophys. Res. Lett.*, 36, L00C05, doi:10.1029/2009GL038905.

Sheehan, R. E. and Valladares, C. E. (2004) Equatorial ionospheric zonal drift model and vertical drift statistics from UHF scintillation measurements in South America, Ann. Geophys., 22, 3177–3193, https://doi.org/10.5194/angeo-22-3177-2004.

Tulasi Ram, S., Su, S.-Y., and Liu, C. H. (2009), FORMOSAT-3/COSMIC observations of seasonal and longitudinal variations of equatorial ionization anomaly and its interhemispheric asymmetry during the solar minimum period, *J. Geophys. Res.*, 114, A06311, doi:10.1029/2008JA013880.

Valladares, C. E., and Chau, J. L. (2012). The Low-Latitude Ionosphere Sensor Network: Initial results. *Radio Science*, *47*(3). https://doi.org/10.1029/2011RS004978

Valladares, C. E., S. Basu, K. Groves, M. P. Hagan, D. Hysell, A. J. Mazzella Jr., and R. E. Sheehan (2001), Measurement of the latitudinal distributions of total electron content during equatorial spread *F* events, *J. Geophys. Res.*, 106(A12), 29133–29152, doi: 10.1029/2000JA000426.

Valladares, C. E., Villalobos, J., Sheehan, R., and Hagan, M. P. (2004) Latitudinal extension of low-latitude scintillations measured with a network of GPS receivers, Ann. Geophys., 22, 3155–3175, https://doi.org/10.5194/angeo-22-3155-2004.

Villalobos, J., and Valladares, C. E. (2020). Statistical analysis of TEC distributions observed over South and Central America. *Radio Science*, 55, e2018RS006725. doi.org/10.1029/2018RS006725.

Walker, G. O., Ma, J. H. K., Golton, E. (1994). The equatorial ionospheric anomaly in electron content from solar minimum to solar maximum for South East Asia. *Annales Geophysicae*, *12*(2–3), 195–209. https://doi.org/10.1007/s00585-994-0195-0.

Whalen, J. A. (2001), The equatorial anomaly: Its quantitative relation to equatorial bubbles, bottomside spread *F*, and E×B drift velocity during a month at solar maximum, *J. Geophys. Res.*, 106(A12), 29125 –29132, doi:10.1029/2001JA000089.

Whalen, J. A. (2003), Dependence of the equatorial anomaly and of equatorial spread F on the maximum prereversal E × B drift velocity measured at solar maximum, *J. Geophys. Res.*, 108, 1193, doi:10.1029/2002JA009755.

Woodman, R. F. (1970), Vertical drift velocities and east-west electric fields at the magnetic equator, *J. Geophys. Res.*, 75(31), 6249– 6259, doi:10.1029/JA075i031p06249.

Woodman, R. F., and C. La Hoz (1976), Radar observations of *F* region equatorial irregularities, *J. Geophys. Res.,* 81(31), 5447–5466, doi:10.1029/JA081i031p05447.

Figure Captions

Figure 1. Geographic locations of the GPS receivers (blue open and red circles) are used in Figure 2. GPS receivers in red belong to the low-latitude Ionospheric Sensor Network (LISN) and perform scintillation calculations. Receivers in blue belong to other networks in South America and do not perform real-time calculations of S4 index values.

Figure 2. TEC perturbation (TECP) and scintillation information measured by the receivers are shown in Figure 1. (a) Bubble/depletion information is portrayed using yellow shading to indicate the transit of the depletions across South America. TECP traces are displayed according to the longitude of the receivers; TECP values corresponding to the receiver located further west are at the top, and for the most eastward receiver at the bottom. (b-g) Scintillation S4 index from the LISN receivers and for PRN=23. See text for additional description.

Figure 3. Similar to Figure 2 but corresponding to 13 February 2016. Note that the S4 index enhancement occurs at 03:20 UT instead of 02:30 in Figure 2.

Figure 4. TEC values over South and Central America were measured every half hour between 30° N and 60° S on 12 February 2016. Integration time for each plot corresponds to 10-min periods between 01 and 03 UT. Note the evolution of an initial symmetric EIA into a non-symmetric anomaly and the development a semi-circle structure in the eastern part of South America.

Figure 5. TEC values over South America were measured every half hour on 13 February 2016. Note the formation of a similar loop structure, although smaller in size, occurring almost 1 hour later than the one on 12 February 2016 (Figure 4).

Figure 6. (top) SYM-H values measured between 31 January 2016 and 18 February 2016 (day 49). (center) shows the IMF B_z values corresponding to the day interval. (lower) Northern hemisphere, polar stratospheric temperature for 10 hPa was measured at three different latitudes (70°, 80°, and 90°). Red vertical lines indicate the times of loop, or circle, observations in Figures 4 and 5. Notice the start of the temperature increase on day 37 (6 February 2016).

Figure 7. The top two panels show the Dst and the IMF B_y and B_z traces corresponding to days 41 (10 February 2016) and 45 (14 February 2016). DMSP-F18 zonal drift velocities measured during these five days in February. The black dots between 70 and 50 latitude point out locations where the gradient of the zonal drift falls below 25 m/s/degree.

Figure 8. Differential magnetic field values of the H component were measured at Jicamarca and Piura as a function of day and local time. The amplitude is proportional to the electric field in the E region. Notice that at 75° W longitude LT = UT − 5.

Figure 9. Daily TEC and differential TEC plots for February 2016. The top frame shows the average or seasonal TEC values for February. TWC values vary between 0 and 50 TEC units. The following panels display differential TEC plots, one per day, between 09 and 15 February 2016. Note the phase progression that starts on 09 February 2016. The full moon occurred on 08 February 2016.

Figure 10. Latitudinal TEC profiles observed at 75° W during the SSW event between ±40° magnetic latitude. The times indicated in the upper left corner of each frame show the UT for each plot. The diagonal red and blue lines divide the profiles into three different categories. On the left side are profiles without a double crest EIA. In the middle panels are symmetric TEC profiles. On the right side of the blue line are highly asymmetric TEC profiles. See text for more details. Yellow shaded squares correspond to times when scintillation enhancements were observed.

Figure 11. Hourly latitudinal (±40° magnetic) TEC profiles are a function of longitude between 00 and 05 UT. Note the significant change in asymmetry as a function of longitude. At 80° W, the northern crest dominates, and at 50° W, the southern crest contains a higher amplitude.

Figure 12. 3-dimensional schematic representation of the TEC profiles, vertical plasma drifts (red arrows), and the meridional wind (blue arrows) on 12 February 2016 and during the SSW event discussed in this publication. Two TEC profiles are displayed in this figure. Both profiles were observed between 01 and 03 UT. The blue traces present the TEC profile observed at 80° W, and the red lines measured at 50° W. Notice the change in the magnitude and direction of the blue arrows indicating a shear and reversal of the neutral wind.