When Plasma Streams Tie up Equatorial Plasma Irregularities with Auroral Ones

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Abstract We present a new pattern of storm-induced ionospheric irregularities behavior at midlatitudes—poleward-streaming plasma density depletions. Under disturbed conditions, they appear at North America low latitudes as a part of extended postsunset equatorial plasma bubbles, and further, they are streaming from low latitudes in a northwestward, poleward direction toward the main ionospheric trough and auroral irregularities zone. The poleward-streaming plasma depletions represent a new phenomenon with the similar northwestward transportation path across the continental United States as storm-enhanced density (SED) plumes. The channels of poleward-streaming plasma depletions were stretched from low-latitude base toward higher latitudes—they are found to occur for geomagnetic storms under specific combination of steady southward interplanetary magnetic field, subauroral polarization streams (SAPS) electric fields, and enhanced westward drifts at midlatitudes, resulting in northwestward plasma transportation equatorward of the SAPS region. The poleward-streaming plasma depletions form an illusion of traveling ionospheric disturbances (TIDs) moving in a poleward, northwestward direction—this propagation direction is opposite to typical equatorward propagation of storm-induced large-scale TIDs generated in the auroral zone and propagated toward the equator. This phenomenon is accompanied by strong ionospheric irregularities that occurred over both edges of plasma depletion channel at midlatitudes. For two comparable geomagnetic storms, these poleward-streaming plasma depletions persisted for several hours, posing a localized threat for GPS-based positioning applications. Even moderate-to-intense storms (Dst minimum−145 nT) can promote such effects at midlatitudes.

1. Introduction

The midlatitude ionosphere (30–60° magnetic latitude [MLAT]) is typically considered being relatively free from the strong ionospheric irregularities and plasma density gradients. But under geomagnetic disturbances, the midlatitude ionosphere becomes more complicated than it was previously thought as different scale structures can appear here when a zone of intense auroral irregularities expands equatorward and can reach ~45–55° MLAT (Aaron, 1997; Aaron & Lin, 1999; Cherniak et al., 2015; Hajkowicz, 1982; Prikryl et al., 2016). From another side, the storm-induced penetrating electric fields can lead to plasma bite-outs near the magnetic equator and promote development of very intense equatorial plasma bubbles (EPBs). Sometimes, such super bubbles extend substantially toward low latitudes and midlatitudes occasionally reaching 25–35° MLAT (Basu et al., 2005, 2007; Cherniak & Zakharenkova, 2016; Foster & Rich, 1998; Huang et al., 2007; Ma & Maruyama, 2006). Usually, these expanded zones of storm-induced auroral and equatorial irregularities are naturally separated by ~15–25° zone of midlatitudes (e.g., Cherniak et al., 2019).

The known exceptional phenomenon at midlatitudes—storm-enhanced density (SED)—is a spatially continuous two-dimensional plume of enhanced density transported from lower latitudes toward higher latitudes in the noon sector (Foster, 1993). As a source/root of SED at low latitudes, a large plasma density increase can be formed by enhanced eastward electric fields at low and middle latitudes and poleward expansion of the equatorial ionization anomaly. Most often, SED is observed in the American sector, but it was also detected at other longitudes (e.g., Coster et al., 2007; Yizengaw et al., 2006, 2008). The subauroral polarization stream (SAPS) electric fields are considered as a major driver of SED (Foster & Burke, 2002). Sharp plasma density gradients (>10×) can be found at the edges of the stretched SED plume (Foster & Vo, 2002; Coster et al., 2007; Coster & Scone, 2009); they can lead to intense scintillations of the received GPS signals and to performance degradation of GPS-based systems even at midlatitudes (Doherty et al., 2004; Ledvina et al., 2002).
Here, we report an observational evidence of a more curious phenomenon when—instead of SED-like enhanced plasma density structures—the poleward-streaming plasma density depletions were stretched from low latitudes through the continental United States toward subauroral/auroral latitudes.

2. Database and Methods

We utilize measurements from 6,000+ ground-based Global Navigation Satellite Systems (GNSS) stations that receive signals from GPS (all stations) and GLONASS (3,000+ stations from data set) satellite systems. For each link receiver satellite with an elevation cutoff of 20°, we calculate values of (1) vertical total electron content (TEC), (2) Rate of TEC Index (ROTI), and (3) detrended TEC with a removed 60-min running mean. Details on TEC processing from raw GPS/GLONASS measurements can be found in Zakharenkova et al. (2016). Further, the obtained values are binned into 0.5° geographic latitude/longitude grid to create the high-resolution global maps with a temporal cadence of 5 min. The high-resolution vertical TEC maps show storm-induced dynamics of ionospheric density in space and time. The global ROTI maps are used to detect strong TEC gradients and plasma density irregularities (Cherniak et al., 2018). The maps of detrended ΔTEC can be used to study signatures of the medium-scale and large-scale traveling ionospheric disturbances (MSTIDs/LSTIDs) propagation (Otsuka et al., 2013; Tsugawa et al., 2007; Zakharenkova et al., 2016). Additionally, we utilize data provided by the Swarm satellites operating at ~465 to 515-km orbit altitude: (1) in situ electron density (Ne) from Langmuir probe instrument, (2) GPS ROT (rate of TEC) from the onboard Swarm GPS receiver measurements (Zakharenkova & Cherniak, 2018), (3) field-aligned currents (FACs) estimated from the Swarm magnetometer data (Lühr et al., 2015), as well as in situ ion density (Ni) and horizontal ion drifts measured onboard DMSP (Defense Meteorological Satellite Program) satellites at ~845-km altitude.

3. Results and Discussion

3.1. Midlatitude Plasma Density Depletions as Detected in Ground-Based ROTI Observations

We analyze a new repeatable pattern of storm-induced ionospheric irregularities at midlatitudes that developed during two geomagnetic storms of 27–28 May 2017 and 7–8 September 2017. These storms occurred during a low solar activity period of the 24th solar cycle. Both storms can be classified to a moderate-to-severe level with a Dst minimum reaching −145 nT (Figures 1a–1b). Both events were characterized by the steady southward interplanetary magnetic field (IMF) and by a strong increase of the auroral electrojet (AE) index to ~1,500 nT (Figures 1a–1b). Both events were characterized by the steady southward interplanetary magnetic field (IMF) and by a strong increase of the auroral electrojet (AE) index to ~1,500 nT (Figures 1a–1b). Figures 1c–1d show an example of global ROTI maps with a focus on the American sector that illustrates development of strong ionospheric irregularities in several hours after the storm commencement. Full sets of such ROTI maps with a 5-min temporal resolution are presented as supporting information, Movies S1–S2. The ROTI maps show an absence or very low intensity of ionospheric irregularities (dark-blue color) and highlight very intense ionospheric irregularities (ROTI > 0.8–1.0 TECU/min, yellow–red color) that can be recognized through their impact on received GNSS signals (here, phase scintillations). On Figures 1c–1d, we note an extension of the auroral irregularities zone forming an oval-like structure at high latitudes of the Northern Hemisphere. We also note some intensification of the equatorial ionospheric irregularities in the post-sunset sector over South America. But what kind of ionospheric irregularities were developed over North America middle latitudes? On first sight, it looks like a classical signature of a SED plume elongated from low-to-middle latitudes toward subauroral latitudes, and SED is typically accompanied by strong plasma density gradients and irregularities well reflected in ROTI. Was it the case?

Let’s check the equatorial region. The eastward prompt penetration electric fields (PPEFs), usually attributed to the sudden southward turning of the IMF, can appear at the equator practically instantly and result in a rapid plasma uplift near the magnetic equator. Such storm-induced ionospheric uplift can be greater in the American longitudinal sector in the vicinity of the South Atlantic magnetic anomaly (Foster & Erickson, 2013). In the dusk sector, the eastward PPEFs superimpose to the post-sunset E fields that led to a stronger plasma uplift and even plasma bite-outs near the equator and favorable conditions to form more intense plasma bubbles (Busu et al., 2007). For both considered geomagnetic storms in 2017, an IMF southward turning occurred near 21–22 UT when the dusk sector was over Western South America and the Atlantic sector. Further, the IMF Bz was steady negative −14 hr for the May 2017 storm and −6 hr for the September 2017 storm (Figures 1a–1b). Huang et al. (2005) reported that PPEFs can be long lasting (several hours) under the steady negative IMF Bz. Thus, both storms set off very favorable conditions for development of storm-
induced plasma bubbles over the equatorial region in the American sector. The enhanced upward $E \times B$ drift of the equatorial ionosphere supports the transportation of plasma bubbles to much higher altitudes; the depleted flux tube at higher apex heights extends to higher latitudes, resulting in a much larger latitudinal extent (in a poleward direction) of storm-induced plasma bubbles. The 5-min ROTI maps can track development of equatorial irregularities in dynamics for both events (Movies S1–S2).

For the 27–28 May geomagnetic storm, Movie S1 shows (1) the absence of ionospheric irregularities at equatorial and middle latitudes of the American sector for 20–23 UT; (2) that after 23 UT, equatorial irregularities occur over South America; (3) that after 01 UT, auroral irregularities zone expanded toward midlatitudes and an odd plume started to stretch out from the equatorial region through Caribbean/Florida toward the auroral zone; and (4) signatures of multiple plumes streamed north-westward were most pronounced during 01–04 UT and persisted till ~07 UT. For the 7–8 September 2017 storm, the IMF southward turning occurred

**Figure 1.** Variations of interplanetary magnetic field Bz, auroral electrojet (AE), and SYM-H indices for two events: (a) 27–28 May 2017 and (b) 7–8 September 2017 geomagnetic storms. Bottom panel shows rate of total electron content index (ROTI) maps with an occurrence of strong ionospheric irregularities (red color) at high, middle, and low latitudes for both events. Gray shading shows nighttime and solar terminator at 100-km altitude. Grid lines mark 30° separation. Full sets of ROTI maps with a 5-min resolution are presented as Movies S1–S2.
~1 hr earlier (20:30–20:40 UT), but first postsunset equatorial irregularities were also registered over South America after 23 UT (Movie S2). At 23:11–23:30 UT, the IMF Bz rapidly changed from ~9 to ~31 nT—the dusk sector was exactly over South America. We observe a rapid intensification of equatorial irregularities over the whole region. From ~23:45 UT, again over the Caribbean/Florida area, part of equatorial irregularities started to extend toward higher latitudes. The most pronounced signatures of intense irregularities streamed through midlatitudes were registered at 00–02 UT, and they persisted till ~06 UT with a smaller intensity.

3.2. Midlatitude Plasma Density Depletions as Seen in Absolute TEC and Satellite Observations

Figures 2a–3a present absolute TEC maps for both geomagnetic storms when Swarm satellites appeared for a first time over the American sector. The following similar features are found: (1) TEC depletion corresponding to the main ionospheric trough (MIT) well developed at the evening sector at 40–50° N (50–60° MLAT) over North America; (2) TEC enhancement (~30–40 TECU) at low latitudes of Central/Northern America in the early postsunset time; (3) pronounced plasma density depletions at equatorial South America; and (4) distinct plasma density depletions stretched from US Florida through U.S. midlatitudes in the north-westward direction toward the MIT.

For both storms, we consider the Swarm observations of in situ electron density (Ne), GPS ROT for links above satellite orbit, and FACs, when satellites overpassed the American longitudinal sector. The equatorial crossing time was ~0.5 LT for Swarm B on 28 May 2017 and ~22.3 LT for Swarm C on 8 September 2017—several hours afterwards the storm-induced EPBs occurred in the region. Each panel presents from left to right: (1) TEC map, Swarm observations of (2) in situ electron density (Ne), (3) uplooking GPS ROT, and (4) FAC measurements along Swarm orbit, as well as DMSP observations of (5) total ion density (Ni) and (6) horizontal ion drift (Vy) at ~845 km altitude. Figures 2, 3 show a sequence of four ground-based TEC maps with corresponded plasma density changes along consecutive Swarm and DMSP overpasses for two events. In both cases (Figures 2, 3), Swarm in situ plasma density (Ne) observations reveal an occurrence of severe plasma density depletions and irregularities at equatorial latitudes as compared with the prestorm conditions (blue curves). GPS ROT observations indicate presence of the intense ionospheric irregularities even above the Swarm orbit. Since the downward R2 FAC closes through the low ionospheric conductivity MIT region (e.g., Anderson et al., 1993), the Swarm FAC observations can be effectively used to identify the MIT location. High values of Swarm FACs along orbit coincide with the Swarm Ne decrease corresponding to the MIT position (grey-shaded area).

For the May 2017 event, we have a wide plasma bite-out (~30° in latitude) over Western South America (Figure 2a). Next Swarm overpass (Figure 2b) encountered the highly structured ionosphere with large-scale plasma density depletions covered 40°–40°N MLAT; ionospheric irregularities above ~500 km were detected by high ROT values from GPS onboard Swarm. A DMSP F15 satellite that overpassed the region later revealed the presence of intense ionospheric structuring at ~845-km altitude. In North America, the most poleward plasma depletions were intersected at ~30–35°N (~40° MLAT) and were well separated from the MIT (Figures 2b–2c), whose position is clearly seen in Swarm Ne and FACs variations. At 07 UT on 28 May (Figure 2c), the Swarm overpassed at ~96°W over North America and Pacific Ocean—here, Swarm Ne observations showed less intense structuring at ~500-km altitude comparing with the previous overpass at ~72°W (Figure 2b), but at the same time, Swarm GPS ROT indicated presence of strong ionospheric irregularities at altitudes above the satellite. The DMSP F15 overpass was ~20–30° eastward from Swarm one, and it encountered very strong plasma density structuring in the topside ionosphere at ~845-km altitude over the American sector. In ~1.5 hr later (Figure 2d), the next DMSP F15 overpass appeared over the same region as Swarm B was before (Figure 2c) and confirmed persistence of these topside ionospheric irregularities at ~845-km altitude. For the May 2017 storm, DMSP F15 has an equatorial crossing time at ~2.7 LT; it is ~7 hr later that first storm-induced EPBs occurred in the American region. At 08:30 UT (Figure 2d), the DMSP F15 showed that signatures of the most poleward depletion were still detected over the continental United States at ~28°N, 90°W (40° MLAT); it was well separated by ~8° from the MIT and corresponded to location of the plasma density depletion seen ~5 hr ago, in TEC map for ~03:45 UT (Figure 2a). Thus, signatures of midlatitude plasma density depletion were detected independently over the same area by ground- and space-based instruments indicating their persistence over long time and different altitudes.
**Figure 2.** Vertical total electron content maps showing occurrence of plasma density depletions at middle latitudes of North America for 28 May 2017. Magenta lines show projections of consecutive overpasses by Swarm and DMSP satellites. Gray shading shows nighttime and solar terminator at 100-km altitude. Each panel presents Swarm observations of in situ electron density (Ne) variation as a function of geographical longitude for storm day (black) and previous day (blue); uplooking GPS ROT and field-aligned current measurements along Swarm orbit; DMSP observations of total ion density (Ni) and horizontal ion drift (Vy). Green shading shows large-scale depletions, and grey shading shows the main ionospheric trough (MIT) location. Grey line marks the magnetic equator.
Figure 3. Same as Figure 2 but for 8 September 2017.
For the September 2017 event, we observe a deep plasma density depletion over the magnetic equator and plasma structuring mainly southward from the equator in Swarm Ne observations (Figure 3a). We emphasize that satellites with polar orbits intersecting an inclined narrow plasma bubble may provide asymmetrical results with respect to the equator (e.g., Kil et al., 2016). The next overpass (Figure 3b) encountered plasma density depletions mainly northward from the equator, over Central America. In North America, Swarm C encountered the most poleward depletions at ~25–32°N (~35–40° MLAT) that were again well separated from the MIT location as indicated by Swarm Ne and FACs observations (Figures 3b–3c). At that time and with corresponding midlatitude depletions, Swarm GPS ROT indicated presence of strong ionospheric irregularities at altitudes above the satellite. For this storm, the equatorial crossing time was ~22.3 LT for Swarm C, ~18.8 LT for DMSP F17, and ~2.6 LT for DMSP F15 satellites.

The evening overpass of DMSP F17 (Figure 3a) crossed North America at ~01:20 UT on 8 September 2017 and registered the following (1) westward ion drift of ~1,600 m/s near 40°N; (2) MIT at 40°–45°N; and (3) plasma density depletion at 34–37°N, 109°W (45°MLAT) just equatorward from the MIT position. The plasma density depletion detected by DMSP at ~845 km corresponded to the location of the northernmost part of stream plasma density depletion recognized in the ground-based TEC map (Figure 3a, map). The postmidnight (~2.6 LT) overpasses of DMSP F15 satellite over South America show that equatorial plasma density depletion appeared at ~845-km altitudes (Figures 3c–3d). We should highlight that intensity of storm-induced ionospheric irregularities as detected by DMSP satellites in ~2.6 LT sector was greater for the May 2017 storm.

The appearance and further transportation of plasma depletions are shown in a series of 5-min TEC maps for both events (supporting information, Movies S3–S4). After sunset, we note a clear signature of plasma depletions stretched from the evening side at low latitudes toward dayside midlatitudes to the MIT location. The important difference is that for the first storm, U.S. midlatitudes were crossed by several narrow depletion plumes, whereas for the second storm, it was a much wider single channel of depleted TEC.

### 3.3. Midlatitude Plasma Density Depletion Channel and LSTIDs Propagation

In Figure 4, we show comparison of poleward-streaming plasma depletion signatures as detected in absolute TEC, ROTI, and detrended ΔTEC values for the May and September 2017 events. In Figures 4a–4b, we plot pseudo-3-D surfaces of absolute TEC values that clearly illustrate shape of a narrow plasma depletion channel and its magnitude with respect of surrounding background plasma density. For both cases, we observe narrow plasma depletions in TEC stretched from ~10°N at low latitudes toward the MIT located at ~40°N (Figures 4a–4d). These narrow channels serve as a source of strong ionospheric irregularities and plasma gradients—high ROTI values at midlatitudes coincide well with location of these channels and their edges (Figures 4e–4f). Typically used for TIDs detection, the detrended ΔTEC maps (Figures 4g–4h) show a complex picture where one can suggest signatures of TIDs wave fronts exactly over the same locations as narrow depleted channels. Recently, Aa et al. (2019) analyzed the ionospheric features observed on 8 September 2017 and plausible mechanisms of their formation; finally, the authors favor a version with interpretation of these ionospheric effects in terms of merging EPBs with TIDs. However, we consider that TIDs/LSTIDs do not merge with plasma bubbles but should propagate through these structures without merging. First, there is a technique shortcoming. Like an ionosonde’s ionogram that may contain multiple vertical reflections, oblique reflections, TIDs, spread-F, and radio noise recorded simultaneously, any detrended TEC map is also a snapshot of various signatures and structures, and not all of them are TIDs. Particularly, if TEC measurements along a receiver satellite link were affected by rapid TEC gradients and irregularities, a low-pass filter like a 60-min running mean of TEC cannot remove such rapid TEC gradients. Thus, a detrended ΔTEC map may also contain signatures of strong ionospheric irregularities and quasi-stationary structures. It is well seen as rapidly variable ΔTEC values at high and low latitudes (Figures 4g–4h) where auroral and equatorial irregularities were detected in ROTI (Figures 4e–4f). At midlatitudes, the stretched narrow wedge depletion resulted in a series of positive-negative-positive fronts relative its edges at ΔTEC maps. Second, to define TIDs from TEC perturbation component, there should be applied additional criteria on amplitude, horizontal wavelength, propagation direction, and number of propagating phase fronts (e.g., Otsuka et al., 2013). We examine an appearance and propagation of TIDs signatures in dynamics with a series of detrended ΔTEC maps constructed with a 5-min temporal resolution for both events (supporting information, Movies S5–S6). After ~23 UT with a rapid AE intensification, a series of LSTIDs with a wide,
Figure 4. Signatures of storm-induced plasma depletion channel over North America as detected in absolute total electron content (TEC) in (a–b) pseudo 3D and (c–d) 2D TEC map, (e–f) ROTI, and (g–h) detrended ΔTEC values for 28 May and 8 September 2017 events.
continent-size wave front and amplitude above 1 TECU appeared at high latitudes of North America and propagated equatorward. When the streams of depleted plasma appeared at midlatitudes, these plasma streams were seen in the deterended TEC maps as TIDs signatures moving in opposite direction (poleward from the equator). It is clearly seen that LSTIDs propagated through plasma stream signatures further southward to the equatorial region while plasma stream signatures were still keeping their own northwestward direction across the continent. Therefore, we could not consider these phenomena as TIDs merging plasma bubbles but as signatures of the poleward-moving plasma streams also detectable in ∆TEC maps.

To illustrate a spatio-temporal dynamics of the ionospheric plasma density disturbances more clearly, Figure 5 presents keograms of the ROTI and TEC perturbation constructed along five longitudes over North America (70°, 80°, 90°, 100°, and 110°W) for 27–28 May 2017. The keograms, plotted as a function of geographic latitude and time (UT), represent an averaged value within the band of ±3.5° around a selected longitude. Figure 5 (left column) shows keograms of the ROTI observations. For higher latitudes (poleward of ~55–60°N), the ROTI keograms have a rather similar pattern—the intense ionospheric irregularities occurred after ~22 UT; this zone rapidly expanded toward midlatitudes and remained well expanded during the whole period of an enhanced auroral activity with the AE index above ~1,000–1,500 nT (Figure 1a). For low latitudes to midlatitudes, the situation was more complex. For longitude of 70°W (Figure 5a), an inclined pattern shows that the first irregularities of equatorial origin occur after 00:30 UT near 0°–5°N, and with time, they expand poleward reaching ~25–35°N at ~02–03 UT. For longitude of 80°W (Figure 5b), there is no such direct connection with lower latitudes, a localized area with intense irregularities seems to appear directly at ~25–35°N after ~01:30 UT, and further, it intensifies with time for ~2 hr. For longitude of 90°W (Figure 5c), we also note an absence of connection with irregularities at lower latitude, and such a localized area with high ROTI intense irregularities appears later after ~02 UT and even more poleward at ~35–40°N than those for more eastern longitudes. This longitudinal difference can be explained by the fact that these atypical ionospheric irregularities were registered first over the east coast, near Florida, and then, they moved in the northwestward direction across the continental United States (see Figure 4e, Movie S1); thus, at every more westward longitude, the irregularities signatures would appear later and more poleward, while a direct connection with equatorial and low latitude irregularities would be seen only for eastern longitudes. We should also mention that these localized areas with intense irregularities were well separated from the zone of auroral irregularities at higher latitudes. And only for longitudes of 100°W and 110°W (Figures 5d and 5e), these localized areas at ~40–45°N appear to be closer to and connected with high-latitude irregularities.

Figure 5 (right column) shows keograms of the TEC perturbation (∆TEC) component constructed for this set of longitudes to illustrate the LSTIDs propagation summary. The storm-induced LSTIDs are generated within the auroral irregularities zone and near the MIT (e.g., Borries et al., 2017; Cherniak & Zakharenkova, 2018) and then propagate equatorward. After 23–00 UT with a rapidly increased AE index, a series of LSTIDs was registered. These waves with an amplitude larger than 1 TECU propagated equatorward from high to low latitudes of North America with an estimated horizontal velocity of ~700–750 m/s. Comparison of ROTI and ∆TEC keograms reveals an evident difference between location of the intense ionospheric irregularities and propagation of LSTIDs. Despite the presence of ionospheric irregularities at midlatitudes, LSTIDs easily propagate further equatorward reaching at least 0–10°N latitudes. However, as it was discussed above, signatures of irregularities (like rapid TEC fluctuations) cannot be removed by a low-pass filtering (here, a 60-min running mean), so they remain quite visible in the detrended ∆TEC maps and in the resulted keograms too. All keograms also reveal a clear signature of the quasi-stationary structure of plasma depletion channel that forms a long-lasting, near-horizontal depletion at ~45°N. We note that LSTIDs propagated much more southward from the location of this quasi-stationary structure.

Figure 6 illustrates keograms of the ROTI and ∆TEC perturbation constructed in the same way for 7–8 September 2017. Here, auroral irregularities occurred after ~21 UT on 7 September 2017 following the AE index increase to ~1,000–1,500 nT (Figure 1b). This zone was extended toward midlatitudes from ~70°N to ~50°N at ~23 UT. The principal difference of the September 2017 storm case is the presence of much stronger plasma irregularities recognized in the ROTI keograms at equatorial and low latitudes for 70°, 80°, and 90°W longitudes and related with the storm-induced plasma bubbles development. These irregularities occurred rapidly in a burst-like mode around 00 UT, fast extended toward higher latitudes, and were alive until 05 UT. The LSTIDs signatures seen from the ∆TEC keograms have a similar pattern as for the May storm. The LSTIDs were generated after ~23 UT, and signatures of their equatorward propagation were
Figure 5. Keograms representing spatio-temporal signatures of storm-induced plasma disturbances for different longitudes of North America as detected in (a–e) rate of total electron content index (ROTI) and (f–j) detrended ΔTEC values for 27–28 May 2017. White/empty cells are due to the data absence.
Figure 6. Same as Figure 5 but for 7–8 September 2017.
observed till ~07–08 UT. The LSTIDs are more clearly seen for longitudes of 100°W and 110°W, which were not affected directly by a huge poleward expansion of equatorial irregularities. There is an obvious and strong impact of auroral and equatorial irregularities in the distortion of the ΔTEC results as observed at other longitudes. For ~01–02 UT, a specific localized signature started to merge from the south with the extended zone of auroral irregularities at ~35–40°N (Figures 6c–6e)—which represent irregularities associated with extended plasma depletions moving through midlatitudes. The front of this quasi-stationary structure of plasma depletion channel is also seen at the same location in the ΔTEC keograms (like distinct positive-negative fronts located mostly in a near-horizontal direction). But even in this case when severely extended plasma irregularities from both the auroral and equatorial zones affect the ΔTEC maps, the revealed signatures of LSTIDs clearly indicate their southward propagation with respect to this quasi-stationary structure.

3.4. On the Spatial Extent of Plasma Depletions

The new open questions arise: How do these plasma depletions occur at midlatitudes, and what physical mechanism can be responsible for these processes? Was it a continuous development of a single bubble structure under the PPEFs action or a combination of several processes? To date, there are no model simulation results of this phenomenon.

Considering the possible driving mechanisms of the plasma depletions observed on 8 September 2017, Aa et al. (2019) emphasized contribution of two major processes: (1) PPEFs action over the magnetic equator and (2) merging with TIDs wave structures at midlatitudes. They also mentioned that the plasma depletions reached very high latitudes (46° MLAT) that map to an apex altitude of ~6,800 km over the magnetic equator, and a need in further modeling work to specify the major mechanisms responsible for such structure occurrence and dynamics.

In Figure 7, we compare signatures of the midlatitude plasma depletions as they are seen in TEC and ROTI observations for different time instants during two considered storms. All plots also include projections of the magnetic field lines. For the 27–28 May 2017 storm, the first irregularities were registered within ±15–20° MLAT (30°S–10°N) around the magnetic equator at ~00:35 UT on 28 May 2017; these signatures have a symmetrical extension from the magnetic equator and were well aligned along the magnetic field lines direction (Figure 7b, first plot). At ~01:35 UT, plasma depletions start to extent further poleward, and a clear isolated depletion extends to ~30°N, 75°W, ~39° MLAT (Figure 7a, second plot); the corresponded ROTI map (Figure 7b, second plot) reveals the following: (1) signatures of this extension had a larger amplitude of phase scintillations than those of the original source staying in the equatorial region; (2) the extension was pronounced in the northward direction only; and (3) the extended plasma depletion started to incline from the magnetic field lines direction. At ~02:20 UT, the extended plasma depletion reached ~36°N, 90°W, ~46° MLAT (Figure 7a, third plot). The direction of this structure became more northwestward and considerably deviate from the magnetic field lines direction; this effect is clearly seen in both the absolute TEC and ROTI maps. One hour later at ~03:30 UT, the plasma depletion reached ~40°N, 105°W, ~48° MLAT (Figure 7a, fourth plot); the direction of this plasma depletion became obviously across the magnetic field.

As is known, signatures of equatorial bubbles particularly in satellite optical observations can have an inverse C-shape form in a latitude-longitude domain (e.g., Kelley et al., 2003; Kil et al., 2009). The bubbles are typically oriented in the north-south direction, but its C shape can slightly deviate from the magnetic field line direction (usually within a narrow longitudinal band of several degrees). This effect is explained by specifics of optical peak emission and by a plasma bubble tilt. Initially, the upward \( E \times B \) drift of the equatorial ionosphere plays a major role in the transportation of plasma bubbles to higher altitudes, and as a result, magnetic flux tubes with a higher apex height may be depleted and plasma bubbles may have a larger latitudinal extent (in a poleward direction). The formation of the shell-like structure (C shape) can be explained by the creation of polarization electric field inside the depleted region or by the zonal shear flow of the ionosphere (Kil et al., 2009). For both mechanisms, the plasma-depleted flux tubes with different apex heights are supposed to drift with different velocities; thus, the depleted flux tubes at lower apex heights move farther from an initial location (where the bubble was originated) than those at larger apex heights.

So, even in the presence of a strong zonal drift in the equatorial region, the zonal shear velocity varies with
Figure 7. Comparison of total electron content (TEC) and rate of total electron content index (ROTI) observations over the American sector for specific time intervals of the 26–27 May and 7–8 September 2017 events. Grey shading illustrates nighttime. Thick black line shows the magnetic equator, and thin black lines show the magnetic field lines.
an altitude, and the upper plasma-depleted flux tubes (with a higher apex height) have slower zonal drift velocities and their displacement from the bubble's origin location would be retarded.

For the 27–28 May 2017 event, we observe quite an opposite situation. Initially, under the action of PPEFs, the equatorial ionosphere was uplifted and postsunset plasma bubbles were developed over the equatorial region with an enhanced latitudinal extent (up to 20° MLAT) and with symmetrical signatures in ROTI. Later, the most northern part of the plasma bubble depletion started to drift fast in the northwestern direction, traversing in ~2 hr in the continental United States and reaching ~48° MLAT. One can suppose that this depletion extension was done within a scenario of a further development of the same bubble structure, namely, plasma depletion reached higher altitudes and covered upper plasma flux tubes with higher apex heights. If so, several crucial questions arise: (1) when this altitudinal extent took place and why it did not occur within the same plane (an altitude-longitude origin location of the plasma bubble); (2) how the "possibly depleted" plasma flux tubes with larger apex heights (footprints poleward of 20°MLAT) and larger volume were able to drift much faster than all inner flux tubes; (3) if the "single" plasma bubble structure extended to ~40°N, 105°W, ~48° MLAT, it should have a conjugate point at ~54°S, 128°W, while the bubble's base with the innermost flux tubes drifted slowly near ~70°W–75°W. Thus, it would be a huge inverse C-shaped structure with a strange orientation with respect to magnetic field lines, and its longitudinal span would be more than 50° (from ~75°W to ~125°W). How can such an enormous shear of the shell-structure of the single plasma bubble that is typically very narrow in a longitudinal span (several degrees) be explained? (4) If it is an absolutely new bubble and from the northernmost point of the plasma depletion at ~40°N, 105°W, ~48°MLAT, we estimate that the uppermost depleted plasma flux tube should have an apex height at ~6,000 km using the IGRF (International Geomagnetic Reference Field) model. It is logical to expect that the whole plasma bubble should also be observed near this magnetic field line (equatorial cross section at ~110°W) at other depleted plasma flux tubes below the uppermost one, but we did not see it. Also, this new bubble should be inclined in the opposite, northeastward direction at midlatitudes of the continental United States. Why did we observe that this depletion was still connected with its original base at ~75°W?

From the arguments above, it seems to be a rather unlikely scenario with a further altitudinal evolution of the single plasma bubble. We suggest that probably, there took place a two-stage process: (1) extension of the plasma bubble in the altitudinal/latitudinal domains up to ~20°–25° MLAT under the action of PPEFs effects and (2) horizontal transportation of the depleted plasma across the magnetic field lines in the northwestern direction. Analysis of TEC maps (Movies S2–S3) reveals an occurrence of the SED structure signature during first hours of geomagnetic storms (during 23–01 UT on 27 May and 22–24 UT on 7 September) over subauroral latitudes of central-western North America. At later hours, the western edge of the SED plume disappeared and only the eastern edge of the plume still remained with a gradually decreased TEC magnitude and it drifted to the west of continent. We emphasize that there were no signatures of high ROTI values that corresponded to sharp density gradients along this eastern edge across the continental United States until the first plasma depletions appeared over Florida from the south. At that time, the plasma density depletions appeared from the subequatorial region and moved in the northeastern direction approximately following the eastern edge of SED. A narrow well-defined plasma depletion channel (Figure 4a–4b) was formed, and large gradients defined by high ROTI values were detected at both edges of this channel (Figure 7).

There is an obvious similarity that such a horizontal transportation of the plasma depletions across the continental United States is rather identical to the northwestern path of narrow SED plumes transported from the SED base at low-latitudes to the MIT location. Most likely, the poleward-streaming plasma depletions have also moved along the still remained eastward edge of SED. So, the same physical processes can support transportation of both SED and plasma depletions, particularly SAPS electric fields and enhanced westward plasma drifts.

For the case of the 7–8 September 2017 (Figures 7c–7d), we observe a similar pattern of plasma depletion behavior at midlatitudes. This storm represents an excellent example of a dramatic development of equatorial irregularities under PPEFs action. After ~23 UT, EPBs occurred over the South America sector in a rapid, burst-like mode and speedily expanded toward higher latitudes (Figure 6, Movie S2). Before ~00:10 UT, their development has a very symmetrical expansion within ±20–25° MLAT with respect to the magnetic equator (Figures 7c–7d, first to second plots). After 00:20 UT, the northernmost part of the plasma depletion with the
equatorial base near 75°W started to extend further northward with an increased deviation from the field-aligned direction (Figures 7c–7d, third plot). At ~01:30 UT, the plasma depletion is substantially extended in the northwestward direction, and the depleted channel was located in a zonal (near-horizontal) direction at ~35°–37°N, across the magnetic field direction (Figures 7c–7d, fourth plot). For these time instants, it is clearly seen that the extended plasma depletion reaching ~40°N, 110°W was still connected with the plasma depletion origin at ~75°W of low and equatorial region. Thus, these results clearly indicate that for the ~2-hr duration, the original location of plasma bubble near the magnetic equator (lowest depleted plasma flux tubes) did not drift noticeably from ~75°W, while the northern part of depletion drifted for ~30°–35° in longitudes, mostly in the zonal direction. Such a huge horizontal displacement and its zonal direction support an idea of the plasma horizontal transportation from its source near low latitudes in a similar way like for SED plumes. Thus, the September 2017 storm provides an example with a rapid development of very intense storm-induced plasma bubbles and occurrence of a deeper channel with plasma depletions extended toward midlatitudes.

So, both cases of the May and September 2017 geomagnetic storms revealed an appearance of stream-like structures with embedded depletions and strong ionospheric irregularities that were transported in a very similar way like SED/TOI phenomenon previously reported (e.g., Foster, 1993; Foster & Coster, 2007). Under specific conditions, the plasma depletions extended toward low latitudes of the American sector can be involved in the same electrodynamics mechanism as SED plume (whose source has the very similar latitudinal location) and transported with the high speed in a northwestward, poleward direction.

### 3.5. Westward Drifts and Poleward-Streaming Plasma Density Depletions

In Figures 8a–8b, we plot TEC maps in a polar view with superimposed SuperDARN global convection contours for both events. We note an expanded dusk convection cell; its equatorward edge coincided well with location of a deep MIT, well extended to the sunlit ionosphere. The dusk cell convection velocities (not shown here) indicate strong westward flows.

Analysis of DMSP measurements for both events (Figures 2, 3, right column) demonstrates presence of large subauroral zonal ion drifts within and poleward of the MIT location. For 28 May 2017, the westward ion drifts reached ~500–1,000 m/s. For 8 September 2017, the DMSP F17 (Figure 3a) crossed the American sector near 01:10 UT and registered the following: (1) westward ion drift of ~1,600 m/s near 40°N; (2) MIT at 40–45°N; and (3) plasma depletion at 34–37°N just equatorward from the MIT position. Such characteristics of plasma flow correspond to definition of intense SAPS (Foster & Vo, 2002). Taking into account that horizontal transportation of the plasma depletions across the continental United States was rather similar to the northwestern path of SED plumes transported from the SED base at low latitudes to MIT and SAPS is believed to be a major driving mechanism, we can suggest that SAPS can play an important role in driving plasma depletions that were extended toward much higher latitudes under PPEFs action. For both storms, the plasma depletion channel occurs equatorward of the SAPS region. The poleward electric fields associated with SAPS expand equatorward (or leak to lower latitudes) and result in northwest plasma transportation equatorward of the SAPS region.

Additionally, we analyze the plasma drifts of the ionospheric F layer derived from digisonde measurements provided by the Global Ionospheric Radio Observatory (Reinisch & Galkin, 2011). The Pt Arguello (34.8°N, 120.5°W) and Eglin (30.5°N, 86.5°W) digisondes located at the western and eastern coasts of the United States were in a close vicinity from the streamed irregularities. The Digisonde Portable Sounders operate essentially as radar systems, that is, they measure radar distances, Doppler shift, and angles of arrival of the received echoes. For the May 2017 storm (Figure 8e), the F layer drift measurements over the Eglin digisonde demonstrated a strong westward zonal drift during 01–06 UT on 28 May 2017 with a peak of ~270 m/s at ~03 UT. During 03–04 UT, the northward zonal drift reached its peak of ~160 m/s. At the western coast, the Pt Arguello digisonde showed a similar predominance of the F layer zonal drifts in the northwestward direction during 02–05 UT. At that time, the northward zonal drift reached its peak of ~180 m/s and the westward zonal drift reached its peak of ~150 m/s. For the September 2017 storm (Figure 8f), the Eglin and Pt Arguello digisondes also demonstrated westward/northwestward drifts during 01–06 UT on 8 September 2017. For the Eglin station at the east U.S. coast, the westward zonal drift with a peak of 120 m/s was registered during 23–00 UT on 7 September and then during 02–06 UT. Near 02–04 UT, the westward and northward drifts had a peak of ~180 and ~100 m/s, respectively. For the Pt Arguello, the westward
Figure 8. (a–b) Polar view total electron content (TEC) maps in geographical coordinates (0–90°N, local noon at the top) with superimposed SuperDARN global convection contours for both events; (c–d) rate of total electron content index (ROTI) maps; (e–f) digisonde-derived eastward and northward drifts in the F region for Pt. Arguello and Eglin stations (marked by magenta circles on TEC maps above); (g–h) precise point positioning errors in east, north, and up direction for GPS station chain near Florida (marked by black crosses on maps above).
Drift was observed during 00–06 UT with peak values of ~175 m/s. Similar to EGLIN, here the northward drifts had a peak of ~100 m/s near 02–04 UT. Thus, the digisonde-derived plasma drifts confirmed that even equatorward of SAPS and midlatitude plasma depletion channels, the ionospheric F2 region plasma drifted predominantly in westward or northwestward directions over the continental United States in the nighttime sector (02–06 UT) during both considered events.

Analysis of the plasma drifts from SuperDARN, DMSP, and digisonde observations demonstrates that the westward plasma drift increases from low latitudes (~200 m/s at 30°N) to subauroral ones (~500–1,500 m/s at 45–50°N), so the plasma depletion channel moves quickly in the northwestward direction when it reaches higher midlatitudes.

3.6. Impact of Midlatitude Plasma Depletions on Precise Positioning

Figures 8c–8d show a polar view of the ROTI maps for the same epochs as for TEC maps above (Figures 8a–8b). With high ROTI values (red color), there are recognized signatures of (1) the auroral irregularities oval at high latitudes and (2) midlatitude ionospheric irregularities stretched from low latitudes (0–20°N) toward the convection zone. We emphasize that comparison of the TEC and ROTI maps clearly demonstrates that strong irregularities specified by high ROTI values occurred exactly over both edges of plasma depletion channel at midlatitudes.

Considering operational sustainability during both geomagnetic storms, a decrease in positioning accuracy was registered for Wide Area Augmentation System base-stations (FAA GPS Performance Analysis Reports, 2017). For a single-frequency mode, GPS provides a meter-level positioning accuracy in best conditions. For 28 May 2017 (Report#98), maximum horizontal/vertical accuracies were 2.9/8.2 m for Miami (25.8°N; 80.3°W) and 3.1/5.8 m for Atlanta (33.4°N; 84.2°W) stations. For 8 September 2017 (Report#99), maximum horizontal/vertical accuracies were 5.2/8.0 m for Miami and 5.1/8.0 m for Atlanta—which is two to three times larger than the quarter statistics. For dual-frequency mode, GPS precise point positioning (PPP) accuracy is typically at the cm–dm level. We selected a chain of several GPS receivers from Florida to Missouri located exactly within or close the plasma depletion channel. Figures 8g–8h show PPP errors calculated for these stations using the JPL Automatic Precise Positioning Service (http://apps.gdgps.net/). After the storm commencement, PPP errors remained within cm–dm levels at all stations. When plasma depletions occurred over Florida and further north-westward, PPP errors abruptly raised to several meter. Thus, both the single-frequency and dual-frequency GPS positioning accuracy degrade at various stations within 35–45°MLAT that were on the way of the poleward-streaming plasma depletions.

4. Summary

We report evidence of a new pattern of storm-induced ionospheric irregularities that can adversely affect midlatitudes during geomagnetic storms. This new phenomenon represents a new challenge for the ionospheric community about the midlatitude ionospheric structuring during geomagnetic storm periods to understand physical processes and mechanisms of these structures’ development and evolution. It is unknown how often such poleward-streaming plasma depletions occur during space weather events and if they occur concurrently with the SED plume, afterwards, or in absence of SED.

They are quite similar to SED plumes in their northwestward transportation path across the continental United States. These plasma depletions seem to be related to storm-induced intensification of the postsunset EPBs in the American region, plasma bite-outs near the magnetic equator, and further extension of plasma bubbles toward low latitudes. If these depletions of equatorial origin can be involved into the similar transportation mechanisms (as SED) at low latitudes to midlatitudes, they can be stretched poleward toward the MIT location at much higher latitudes similar to SED behavior reported by Foster and Vo (2002). In detrended TEC maps, these plasma streams can form an illusion of TID-like signatures moving in the opposite direction (poleward, from the equator to high latitudes) with respect to typical storm-induced LSTIDs that propagate from auroral zone toward the equator. As reported by Cherniak and Zakharenkova (2018), the ROTI technique is very sensitive for detecting rapid ionospheric gradients and irregularities but could not reveal signatures of the typical LSTIDs structures at midlatitudes—which confirms a new pattern of storm-induced ionospheric irregularities behavior different from LSTIDs phenomena and its propagation characteristics.
We suggest that similar favorable conditions to promote such EPBs occurrence at higher latitudes of the American sector can be related to the fact that both storms developed at rather similar time (after 21–22 UT). Also, Foster and Coster (2007) suggest that if during severe storms (Dst < ~300 nT) Dst reaches its minimum at 20–00 UT, it can lead to the most dramatic redistribution of plasma density, including SED formation, in the American sector. For both considered storms, Dst reached a minimum of only ~145 nT and later than 20–00 UT. However, PPEFs effects associated with a rapid IMF southward turning occurred at similar UTs (after 21–22 UT) when the dusk sector moved from Atlantic to American longitudes, thus promoting the favorable conditions for a stronger ionospheric uplift and postsunset EPBs generation due to South Atlantic Anomaly proximity. Thus, other geomagnetic storms with a similar IMF Bz configuration during 21–01 UT can support an appearance of plasma depletions at low latitudes and midlatitudes of the American sector. The channels of poleward-streaming plasma depletions were stretched from low-latitude base toward higher latitudes; they are found to occur for geomagnetic storms under specific combination of steady southward IMF, SAPS electric fields, and enhanced westward drifts at midlatitudes, resulting in northward plasma transportation equatorward of the SAPS region. Besides the considered two geomagnetic storms in May and September 2017, we have found several other storm cases with a similar pattern, but further investigation is needed to determine whether this type of plasma depletions occurs predominantly during low solar activity only or not and whether they can occur separately or accompanying the SED plume.

The presented results can provide a clue in understanding some atypical plasma depletion with anomalously high estimates of an apex height of the uppermost depleted plasma flux tube. For example, Huang et al. (2007) reported the high-latitude plasma bubble registered near the plasmapause during the 29 October 2003 geomagnetic storm. The authors suggested that the plasma bubble, which caused the emptied flux tube at 46° MLAT, should reach ~6,800-km apex altitude over the magnetic equator. Probably, this storm-induced plasma depletion might also occur initially at much lower latitudes, and further, it was transported horizontally toward 46° MLAT in a similar way that we discussed in this paper. For a better understanding of an occurrence and evolution of plasma depletions moving across the magnetic field at midlatitudes and to identify a leading mechanism or their combination, proper physics-based model simulations should be conducted using a global ionosphere model capable to reproduce both the SED transportation and EPB development.

The streamer plasma depletions persisted for several hours over the continental United States, creating a localized threat for strong plasma gradients and GPS scintillation effects. We should emphasize that not only extreme space weather events or super-storms but also moderate-to-strong geomagnetic storms (Dst about ~145 nT) can lead to an occurrence of strong ionospheric irregularities at midlatitudes that pose a significant space weather threat for GPS-based systems operationality.

References


