Mid-latitude plasma bubbles over China and adjacent areas during a magnetic storm on 08 September 2017

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Abstract. This paper presents observations of post-sunset super plasma bubbles over China and adjacent areas during the second main phase of a storm on 08 Sep 2017. The signatures of the plasma bubbles can be seen or deduced from: 1) deep field-aligned total electron content (TEC) depletions embedded in regional ionospheric maps derived from dense Global Navigation Satellite System (GNSS) networks; 2) significant equatorial and mid-latitudinal plasma bite-outs in electron density measurements onboard Swarm satellites; 3) enhancements of ionosonde virtual height and scintillation in local evening associated with strong southward interplanetary magnetic field (IMF). The bubbles/depletions covered a broad area mainly within 20°-45°N and 80°-110°E with bifurcated structures and persisted for nearly 5 hours (∼13-18 UT). One prominent feature is that the bubbles extended remarkably along the magnetic field lines in the form of depleted flux tubes, reaching up to mid-latitude of around 50°N (MLAT: 45.5°N) that maps to an altitude of 6600 km over the magnetic equator. The maximum upward drift speed of the bubbles over the magnetic equator was about 700 m/s, and gradually decreased with altitude and time. The possible triggering mechanism of the plasma bubbles was estimated to be storm-time eastward prompt penetration electric field (PPEF), while the traveling ionospheric disturbance (TID) could play a role in facilitating the latitudinal extension of the depletions.

1. Introduction

Plasma bubbles refer to irregular structures of plasma density depletion, which are typical characteristics of nighttime ionosphere over equatorial and low-latitude regions. Plasma bubbles with different scale sizes can manifest themselves as spread-F echoes on ionograms [*Abdu et al.*, 2003], plume-like structures in radar backscatter maps [*Woodman and La Hoz*, 1976], airglow density depletions in all-sky images [*Kelley et al.*, 2002], and VHF/UHF scintillations of satellites signals [*Bhattacharyya et al.*, 2001; *Basu et al.*, 2005]. It is widely considered that the plasma bubbles are generated by the Rayleigh-Taylor (R-T) instability in the bottom-side ionosphere after sunset and evolve nonlinearly penetrating the F peak to the topside ionosphere [*Kelley et al.*, 1976; *Ott*, 1978; *Fejer et al.*, 1999; *Ma and Maruyama*, 2006]. They sometimes form into wedge-like structures extended along the magnetic field lines [*Tsunoda*, 1980; *Tsunoda et al.*, 1982]. Although various mechanisms (such as electric field, neutral wind, and gravity waves) can play a role in triggering R-T instability, the most efficient seeding factor of plasma bubbles over equatorial/low-latitude regions is the zonal electric field [e.g., *Abdu et al.*, 1997; *Fejer et al.*, 1999; *Li et al.*, 2009a; *Kil*, 2015]. The post-sunset enhancement of eastward electric field, also known as pre-reversal enhancement (PRE), is responsible for the enhanced equatorial upward drift that causes density perturbations to grow by the R-T instability mechanism, which may lead to the formation of plasma bubbles [*Farley et al.*, 1986; *Retterer and Roddy*, 2014; *Abdu*, 2012; *Abadi et al.*, 2015].

During geomagnetic storms, the development of plasma bubbles can be enhanced or suppressed depending primarily on two types of perturbation electric fields: (1) the prompt penetration electric field (PPEF) created by solar wind-magnetosphere dynamo associated with southward turning of IMF B_z; (2) ionospheric disturbance dynamo electric field (DDEF) induced by changes in global thermospheric circulation due to auroral Joule heating, which may lead to the inhibition of post-sunset plasma bubbles occurrence [*Scherliess and Fejer*, 1997; *Li et al.*, 2009b; *Ramsingh et al.*, 2015; *Carter et al.*, 2016]. The PPEF can be superposed on the normal dusk PRE to cause larger ionospheric uplift and thus facilitate the development of plasma bubbles [*Abdu et al.*, 2003; *Basu et al.*, 2001, 2007; *Tulasi Ram et al.*, 2008; *Huang et al.*, 2010]. The storm effect of these two competing mechanisms on plasma bubbles is an important concern in ionosphere research community.

The occurrence of plasma bubbles and associated signatures of irregularities can even be observed at middle latitude, which could be caused either by an extension of equatorial plasma bubbles along the magnetic field lines after rising to a relatively high altitude, or by local Perkins instability [*Perkins*, 1973]. Recently, several studies have indicated that the equatorial plasma irregularities can reach high altitudes and extend to higher latitudes in the form of depleted flux tubes. For example, it was reported by *Kelley et al.* [2003] and *Makela and Kelley* [2003] that the equatorial plasma depletions can be viewed in all-sky airglow images at Maui, Hawaii (MLAT: 21.3°N). *Mendillo et al.* [2005, 2018] conducted simultaneous observation by using radar measurements and all-sky images at Arecibo observatory (MLAT: 30°N), and the study showed that the field-aligned structures in the images corresponding to the flux tubes of plasma density depletions. *Ma and Maruyama* [2006] reported a case in which a super plasma bubble could be detected at MLAT 31°N by using dense GPS network observations. *Foster and Rich* [1998] reported that the plasma depletions can be measured at MLAT 35°-37°N by using Millstone Hill incoherent scatter radar and the DMSP satellites. *Katamzi-Joseph et al.* [2017] found that the plasma bubbles can extend as far north as ∼42°N (MLAT: ∼39°N) using GNSS TEC and ion measurements from DMSP satellites. *Cherniak and Zakharenkova* [2016] reported super plasma bubbles in Europe for more than 8 h reaching ∼40°-45°N (MLAT: ∼35°-41°N), based on GNSS TEC as well as measurements from Swarm and DMSP satellites. *Huang et al.* [2007] reported that during intense storms, depleted flux tubes associated with large-scale plasma bubbles can extend to much higher latitudes (MLAT: ∼46°N).

In this paper, we present unique observations of super plasma bubbles at MLAT∼15°-45°N over China and adjacent areas during an intense storm on 08 Sep 2017. It was found that the storm-time PPEF contributed to the generation and migration of the super plasma bubbles, which were detected and recorded by using observations from ionosonde, dense GNSS network, and the Swarm satellites. Moreover, TID could also played a role in facilitating the latitudinal extension of the bubbles.

2. Data Description

Measurements from multiple instruments were analyzed to study the characteristics of plasma bubbles under the influence of the geomagnetic storm on 08 Sep 2017. The solar wind and geomagnetic conditions during the storm are described in Figure 1 by using solar wind speed, interplanetary magnetic field (IMF) B_z component, interplanetary electric field (IEF) E_y component, the longitudinal asymmetric index (ASY-H) that represents the auroral activity, and the symmetric index (SYM-H) as the high-resolution Dst index.

The most important information about plasma bubbles are provided by the TEC data from ground-based GNSS measurements. The GNSS data come from Crustal Movement Observation Network of China (CMONOC) and the International GNSS Service (IGS).

CMONOC consists of 260 GNSS receivers covering China mainland, and there are 38 stations of IGS located within China and adjacent regions. For more details on the distribution of GNSS stations and the procedures of TEC derivation, readers may refer to *Aa et al.* [2015].

Besides TEC data, the ionosonde measurements from Sanya (18.3°N, 109.4°E) and GNSS scintillation measurements from Kunming (24.2°N, 103.4°E) and Guangzhou(23.2°N, 113.3°E), as well as the in situ electron density measurements on board the Swarm A and Swarm C satellites at an orbit at altitude around 450 km are used to analyze the signature of plasma bubbles.

3. Observational Results

During the time periods of 07-08 Sep 2017, two coronal mass ejections (CME) passed Earth successively and generated an intense geomagnetic storm with a double main phase. Figures 1a-1e show the temporal variation of the solar wind speed, IMF B_z component, IEF E_y component, SYM-H index, and the ASY-H index for the above-mentioned periods. Figures 1a and 1b show that the IMF B_z turned southward at around 20:40 UT on 07 Sep and remained negative at nearly constant level for 2 hours, then suddenly decreased to a minimum value of -31.2 nT at 23:31 UT on 07 Sep, along with a sharp increase of the solar wind speed due to the compression and interaction of these two CMEs. Figure 1d illustrates that the minimum value of SYM-H for the first storm main phase reached -144 nT at 01:05 UT on 08 Sep. During the recovery phase, the next CME re-amplified the storm with a second main phase onset at 11:35 UT. The IMF B_z decreased to -17.4 nT at 11:55 UT on 08 Sep and remained negative for several hours. SYM-H dropped to a second minimum value of -111 nT at 17:05 UT on 08 Sep.

Figure 1f shows the corresponding variation of ionospheric virtual height (h'F) over a low latitude station Sanya (18.3°N, 109.4°E, dip angle: 11.3°). The local dusk to dawn intervals of the station on 08 Sep are marked by shaded areas. Figure 1f shows that compared with the previous evening, the h'F of Sanya station exhibited a considerable post-sunset increase at around 12:45 UT on 08 Sep, which was consistent with the pronounced increase (decrease) of IEF E_y (SYM-H). These near simultaneous enhancements of h'F and IEF E_y indicate that there was a prompt penetration of eastward electric field into middle and low latitude regions at local dusk hours on 08 Sep, which added onto the normal post-sunset PRE of zonal electric field, caused larger upward plasma drifts, and generated conditions favorable for the formation of plasma bubbles. Figures 1g and 1h show the measurements of L-band amplitude scintillations index S4 from GPS/Beidou satellites in the adjacent stations: Kunming (24.2°N, 103.4°E, dip angle: 17.7°) and Guangzhou (23.2°N, 113.3°E, dip angle: 16.7°). Weak to moderate scintillations started from around 11:45-12:00 UT on 08 Sep, illustrating the possible generation of plasma irregularities/bubbles induced by the geomagnetic storm.

TEC data can be used to further confirm the existence of plasma bubbles. Figures 2 and 3 show a series of gridded vertical TEC maps over China and adjacent areas at 15 min intervals during 12:45-17:00 UT on 08 Sep 2017. An elevation cutoff of 30° was used to avoid multi-paths effects. The resolution of the map is 1°×1° and was generated by selecting the median of all available measurements in each bin as the estimated grid value, with no interpolation being applied. The signatures of the plasma bubbles appeared in the form of TEC depletions embedded in the maps mainly within 20°-45°N and 80°-110°E, which originated from the equatorial latitudes and then expanded northwestward approximately along the geomagnetic field lines. The depth of TEC depletions varied in the range of 5-15 TEC Unit (TECU, 10^{16} el/m^2). As shown in Figures 2b and 2c, two separate parallel structures of TEC depletion initiated around 13:00 UT, which could correspond to bifurcated branches of plasma bubbles as previously reported [e.g., *Ma and Maruyama*, 2006; *Cherniak and Zakharenkova*, 2016].

In order to further illustrate the characteristics of plasma bubbles, the rate of TEC index (ROTI) [*Pi et al.*, 1997] was derived by using dual frequency phase measurements of navigation signals, which can be used to represent the severity of GNSS phase fluctuations and to characterize the ionospheric irregularities. The time derivative of TEC (Rate of TEC change, ROT) was first calculated for all visible satellites with elevation angle greater than 30°. ROTI is defined as the 5-min standard deviation of ROT. For more details about ROTI, readers may refer to *Pi et al.* [1997] and *Cherniak et al.* [2014]. Figures 4 and 5 present the ROTI maps with the same resolution and time interval as those of Figures 2 and 3. The irregularities were first seen in the low latitude regions between 95°E and 120°E longitudinal sectors at 12:45 UT, which approximately corresponded to a local time between 19:00 and 20:45. The bubble-like structures bifurcated and further extended northwestward in the form of depleted flux tubes. The west branch reached ∼45°N (MLAT: ∼41°N) at 13:30 UT, indicating that the plasma bubbles could rise to an altitude of ∼4800 km over the magnetic equator. Similarly, the east branch migrated to a maximum latitude of ∼50°N (MLAT: ∼45.5°N) that corresponded to an altitude of ∼6600 km over the magnetic equator, similar to those indicated in *Huang et al.* [2007]. TEC depletion and associated ROTI fluctuation continued for 5 hours and gradually subsided.

Figures 6a-6g show the temporal variation of ionospheric pierce points (IPP) vertical TEC at seven stations between 10-16 UT on 08 Sep 2017 for PRNs 10, 18, 21, and 24. The locations of these stations are shown in Figure 2i, which were selected to be evenly distributed along the latitudinal extension of the irregularities as much as possible. The color-bar represents the geographic latitudes of IPP, indicating that TEC depletions can be observed between 15°N to 50°N. Figures 6h-6n show the associated de-trended TEC results to better illustrate the plasma depletion. The de-trended TEC was calculated by subtracting the 1-hour moving average value of original TEC data. The inclined red thick line marks the trends of the negative wavefront. This can be used to calculate the horizontal phase speed of the depletion, which is estimated to be as much as ∼800 m/s with roughly a northwestward direction. Considering the previous analysis of Figures 2 and 4, the rate of latitudinal extension of the depletion/irregularities traces in TEC and ROTI maps can be used to estimate the vertical drift speed of equatorial plasma bubbles. The scintillation started at around 1145 UT at Kunming station (MLAT: 17.7°), which corresponded to ∼650 km altitude over magnetic equator; while the highest latitude reached by the TEC/ROTI at ∼1315 UT is 45°N (MLAT: 40.5°), which corresponded to ∼4600 km altitude over magnetic equator. It can be estimated that the upward drift speed of plasma bubbles over the magnetic equator was ∼700 m/s at around 13:15 UT and gradually decreased with increasing altitude and time.

Figure 7 shows satellite passes and the corresponding measurements of electron density from the Swarm constellation from 12 UT to 18 UT on 08 Sep 2017. Swarm A and Swarm C flew at an altitude of 440-460 km. They have nearby longitudes that approximately located in ∼10 LT (ascending) and ∼22 LT (descending) sectors. The geographic maps with different satellite orbit paths between 60°N-60°S are shown in Figures 7a and 7b for Swarm A and C, respectively. The right panels show the variation of in situ electron density (Ne) with respect to latitude along these paths. Swarm B is not shown here since its did not pass over China and adjacent sectors in the local post-sunset hours during this storm period. Swarm A measured no signatures of equatorial plasma bubbles in paths #1 (147°E) and #2 (123°E), though obvious plasma depletions were detected at ∼40°S. However, the satellite in path #3 (100°E) measured a wide and drastic density depletion near the equator as low as 2×10^3 el/cm^2, which was 2-3 orders of magnitude lower than normal Ne conditions. The coverage of major depletion was between 10°S and 20°N with several minor negative spikes distributed in the middle latitudes of both hemispheres, which can be clearly distinguished from the main ionospheric mid-latitude trough at around 50°-60°. Similar observations were made by Swarm C as shown in Figure 7b. The TEC results that coincide with path #3 (#8) at 15:15 UT and with path #4 (#9) at 16:45 UT are also superimposed on Figures 7a and 7b, respectively. Recall from Figures 3b and 3h that the same paths of Swarm were also shown there with four intersections between satellite paths and TEC depletions being marked. It can be seen that these intersections (X1-X4) correspond nicely to the mid-latitude bite-outs in the plasma profiles. This demonstrates that the latitudinal elongated plasma depletion was mainly associated with plasma bubbles, though another factor that the Swarm orbit being below the F layer peak might also play a role in it. This bubble-associated extension of depletion was also reported by several studies [e.g. *Basu et al.*, 2001; *Kil et al.*, 2006; *Huang et al.*, 2007; *Cherniak and Zakharenkova*, 2016]. These studies indicate that the plasma bubbles can be lifted to higher altitudes with depletions being extended along the magnetic field lines to higher latitudes, as can be seen in paths #4 (#9) and #5 (#10). The equatorial Ne depletions along these paths were less obvious and gradually subsided, yet the signatures of plasma bubbles that had drifted to much higher latitudes can be detected at ∼50°N and ∼40°S. The shaded areas indicate deep plasma depletions over China and adjacent regions in accord with TEC depletions in Figures 2 and 3 as well as ROTI fluctuations in Figures 4 and 5.

4. Discussion

Firstly, the results presented in the previous section indicate that there were significant equatorial plasma bubbles over China and adjacent sectors in local dusk hours on 08 Sep 2017, which were associated with strong PPEF as can be deduced from the simultaneously drastic change of IMF B_z, IEF, SYM-H, and ionosphere virtual height during the second main phase of the storm. It is generally assumed that PPEF is eastward (westward) during daytime through dusk sectors (midnight to dawn sectors), and can penetrate nearly instantly to low latitudes and has a relatively short duration (∼1-2 h); On the other hand, DDEF is westward (eastward) during daytime (nighttime), and the build-up time of the DDEF after storm onset is comparatively long (>3 h) such that it may take up to 1-2 days before the equatorial ionospheric response can be fully observed [*Fejer*, 1991; *Li et al.*, 2009b; *Horvath and Lovell*, 2013; *Tulasi Ram et al.*, 2015]. *Huang* [2008] and *Huang et al.* [2010] also pointed out that the PPEF is approximately proportional to the IEF during the storm main phase. Recall from Figures 1c and 1f that the IEF E_y drastically increased from -6.5 mV/m (11:35 UT) to 13.76 mV/m (11:58 UT) on 08 Sep 2017, and h'F at Sanya station exhibited considerable increase simultaneously. This eastward IEF corresponds to eastward PPEF. In addition, the evolution of TEC depletion and ROTI fluctuation were also consistent with the variation of IMF B_z, IEF E_y, and SYM-H, which collectively show that it was the PPEF that drove the development of equatorial plasma bubbles.

Secondly, recent studies have shown that the PPEF can persist with considerably longer durations of ∼8-10h if the IMF B_z is sustained southward for prolonged periods [*Huang et al.*, 2005; *Huang*, 2008]. Recall from Figure 1b that during the second main phase of the storm on 08 Sep, the IMF B_z suddenly dropped to -17.4 nT at 11:55 UT and remained southward for several hours, which suggests that there was a continuous PPEF since 12:00 UT. Moreover, some studies found that the PPEF could be eastward even at 22-23 LT [e.g. *Fejer et al.*, 2008; *Chakrabarty et al.*, 2015], which may be the case for this event that is evidenced in Figure 7, which shows that significant equatorial plasma depletions were measured along path #3 of Swarm A and path #8 of Swarm C at around 15.5 UT (∼22 LT). It appears therefore that a possible extension of the upward vertical drift towards longer duration due to the consistent PPEF might have contributed to the bubble growth rate.

Thirdly, one important aspect regarding the plots from Figures 2 to 5 is that the TEC irregularity traces were displaced westward in the successive plots and further the declination of the traces with the N-S meridian increases as time increases. These characteristics suggest that the irregularity structures drift westward with velocity increasing with increasing latitude. Since the observation of bubbles was preceded by the first main phase of storm event about 12 hours earlier, there is possibility of atmospheric gravity waves (AGWs) that generated in auroral zone and propagated equatorward, which could create traveling ionospheric disturbance (TID) that acted on the field-aligned bubble traces to shape such a latitude dependent drift.

Last but not least, mid-latitude plasma irregularities can either be an extension of depleted plasma bubbles from the equator [e.g., *Ma and Maruyama*, 2006; *Huang et al.*, 2007; *Cherniak and Zakharenkova*, 2016; *Katamzi-Joseph et al.*, 2017], or generated due to the AGWs and/or coupling between Perkins and sporadic E (E_s) layer instabilities, which will manifest in the form of TID [e.g., *Shiokawa et al.*, 2002, 2003; *Tsugawa et al.*, 2007; *Li et al.*, 2009a]. Considering nighttime medium-scale TID could generate stream-like structures with southwestward propagation direction, it is very likely that both mechanisms played a role in current study. The storm-time PPEF initiated the uplift of equatorial plasma bubbles and generated the latitudinal extension of the plasma depletions; while the TID might further facilitate the stretch of this structure and make it tilt more westward. Thus the vertical drift velocity and the highest altitude of the equatorial plasma bubbles that estimated in the previous section are likely to be the upper limit. More work need to be done in the future to distinguish the effects between plasma bubbles and TID.

5. Conclusion

This study presented unique observations of super plasma bubbles with bifurcated structures in the evening sector within China and adjacent areas (20°-45°N and 80°-110°E) during a storm on 08 Sep 2017. The existence and characteristics of the plasma bubbles were well indicated by the following results: 1) significant GNSS TEC decrease for 5-15 TECU and Swarm Ne depletions for 2-3 orders of magnitude; 2) enhancement of ionospheric h'F and associated equatorial plasma uplifts over certain stations after strongly southward turning of IMF; 3) severe regional irregularities in ROTI map that is aligned with the TEC depletion structure. It has been shown that the plasma bubbles and uplifts were triggered by eastward PPEF. The upward drift speed of equatorial plasma bubbles was as much as 700 m/s at around 13 UT and gradually decreased with altitude and time. This study provides useful evidence in demonstrating the link between equatorial and mid-latitude electrodynamics. The observed plasma depletions persisted for several hours and expanded northwestward along the magnetic field lines to mid-latitude regions, which could be attributed to both equatorial plasma bubbles and medium-scale TID. The highest latitude where the depletions reached was around 50°N (MLAT: 45.5°N), which suggest that the plasma bubbles might reach an apex height of 6600 km over the magnetic equator. However, this estimation is likely to be an upper limit since the transition of depletion signature from one of plasma bubbles to that of TID is not well defined, which need to be studied in the future.

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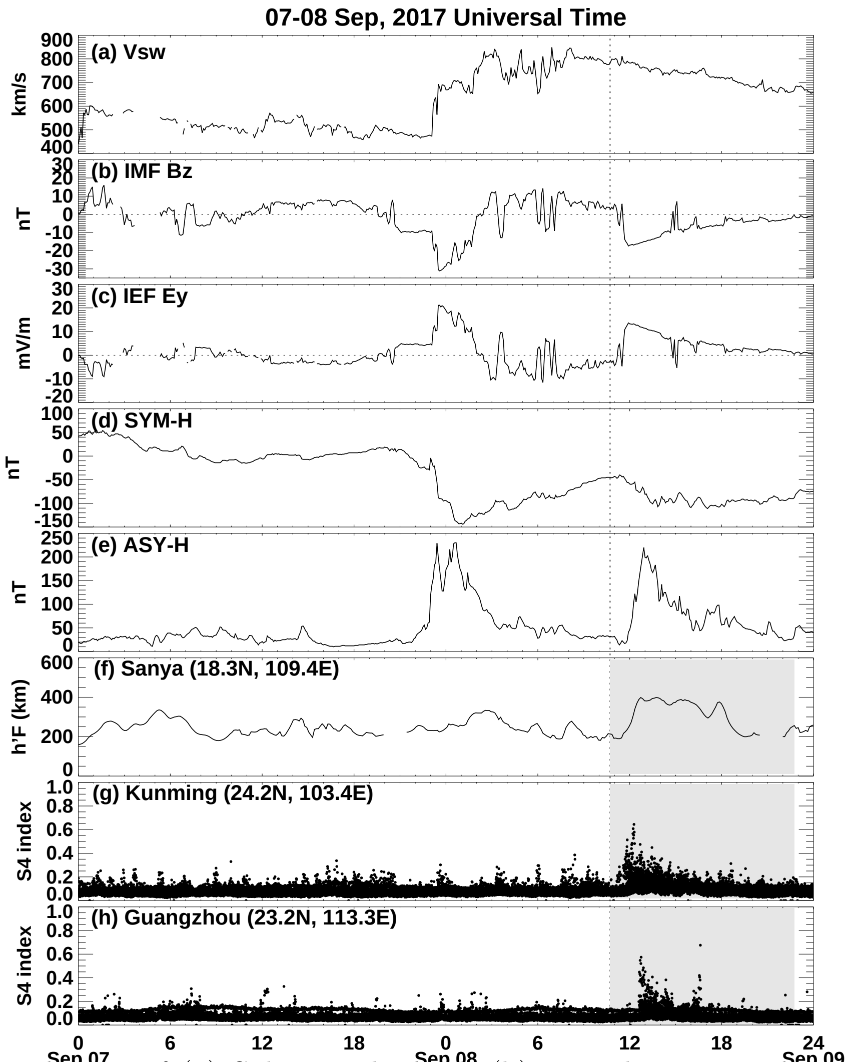

Figure 1. Time series of (a) Solar wind speed; (b) interplanetary magnetic field (IMF) B_z, (c) interplanetary electric field (IEF) E_y, (d) SYM-H index, (e) ASY-H index, (f) ionospheric virtual height (h'F) over Sanya, and S4 scintillation index during the period of 07-08 September 2017 for Kunming (g) and Guangzhou (h). The solar wind and IMF data have been shifted to the nose of the Earth's bow shock. The shaded areas represent the local dusk to dawn period at these stations.

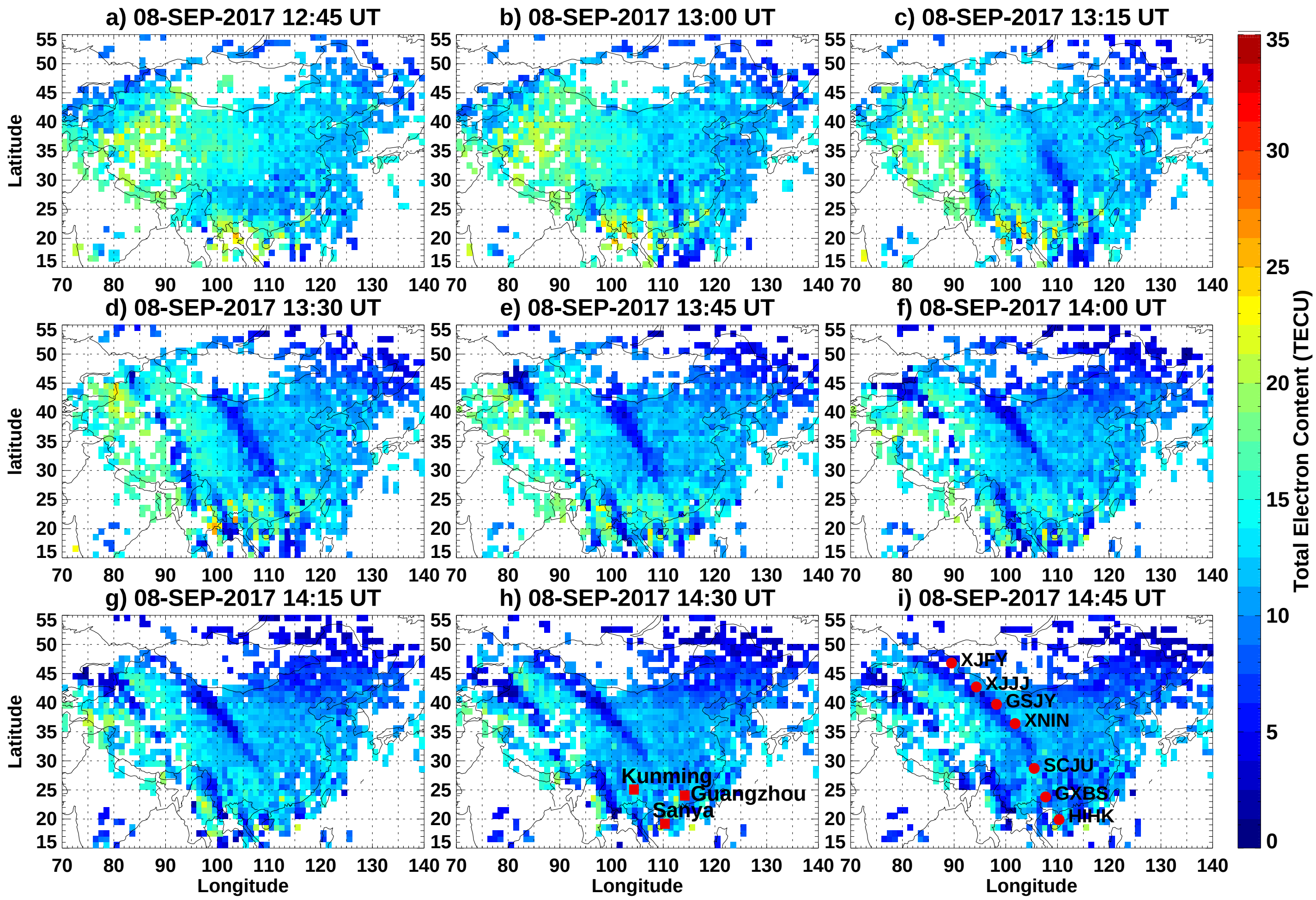

Figure 2. Gridded TEC maps over China and adjacent areas with 15 min interval during 12:45-14:45 UT on 08 September 2017. The distribution of ionosonde/scintillation stations used in current study are shown in Figure 2h. Seven GNSS stations are marked in Figure 2i to track the trace of irregularities.

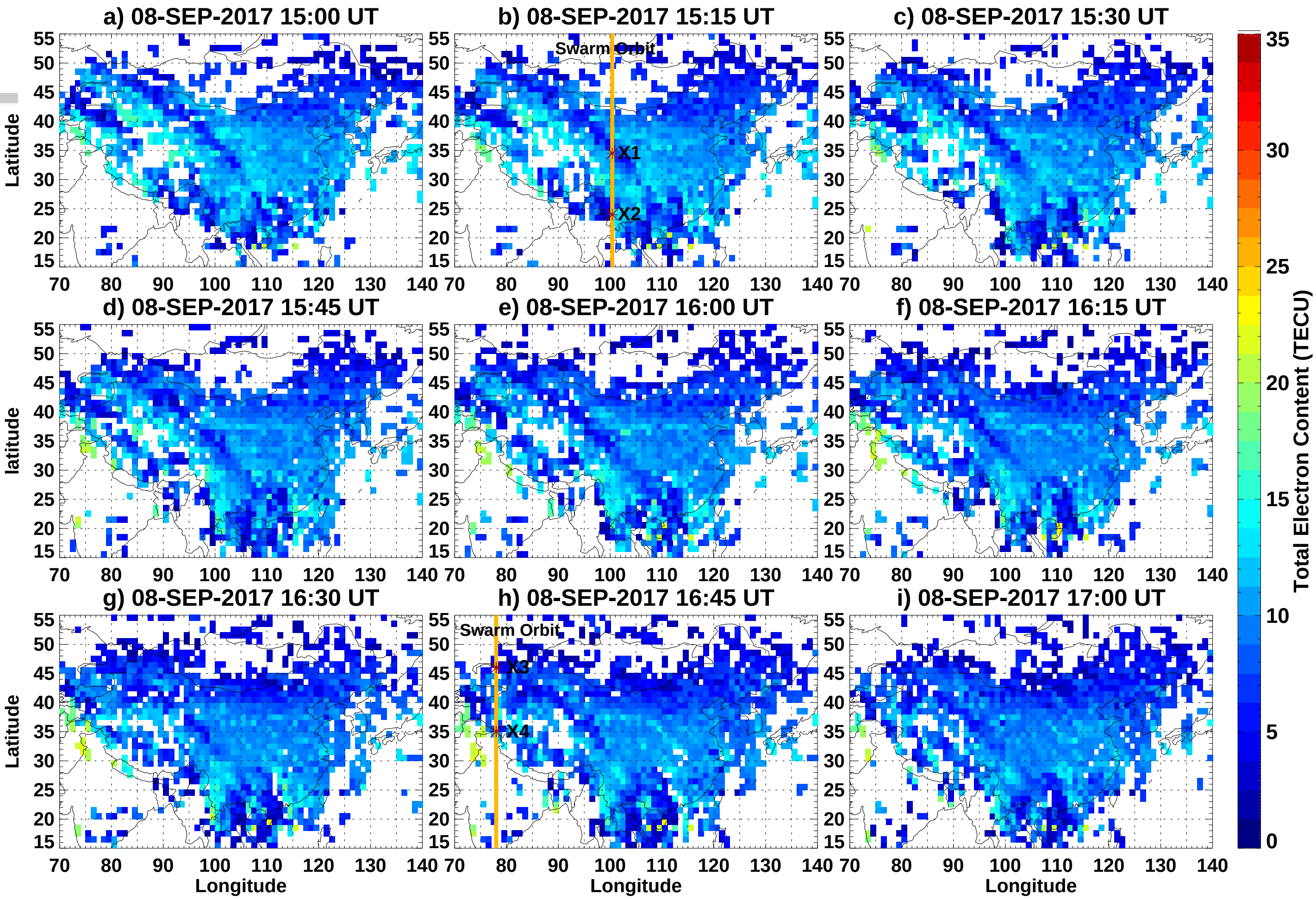

Figure 3. Same as Figure 2, but for time period of 15:00-17:00 UT on 08 September 2017. The Swarm satellite orbits are superimposed on TEC depletions for Figure 3b and 3h with four points of intersection being marked by asterisks.

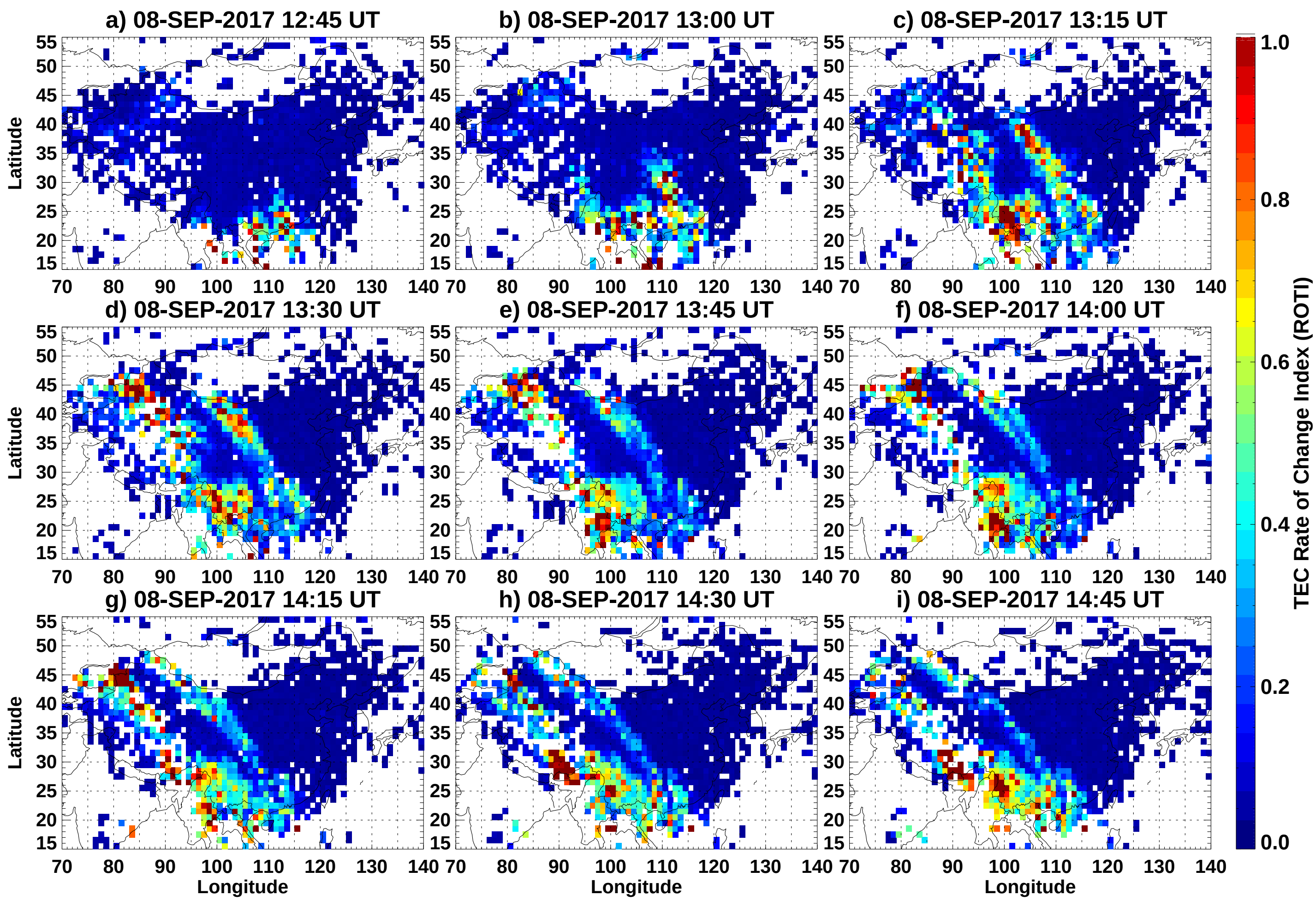

Figure 4. ROTI maps of ionospheric irregularities over China and adjacent areas with 15 min interval during 12:45-14:45 UT on 08 September 2017.

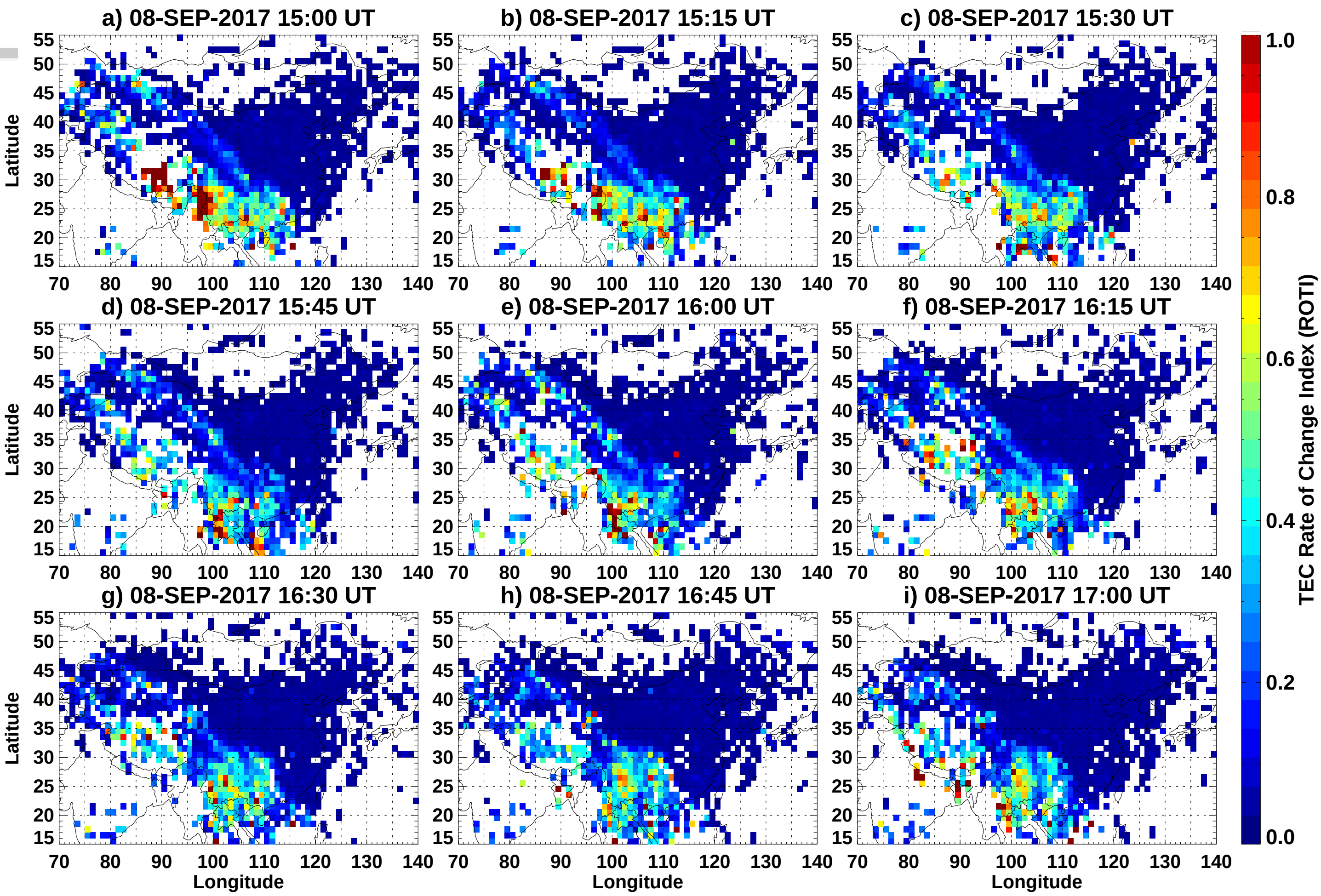

Figure 5. Same as Figure 4, but for time period of 15:00-17:00 UT on 08 September 2017.

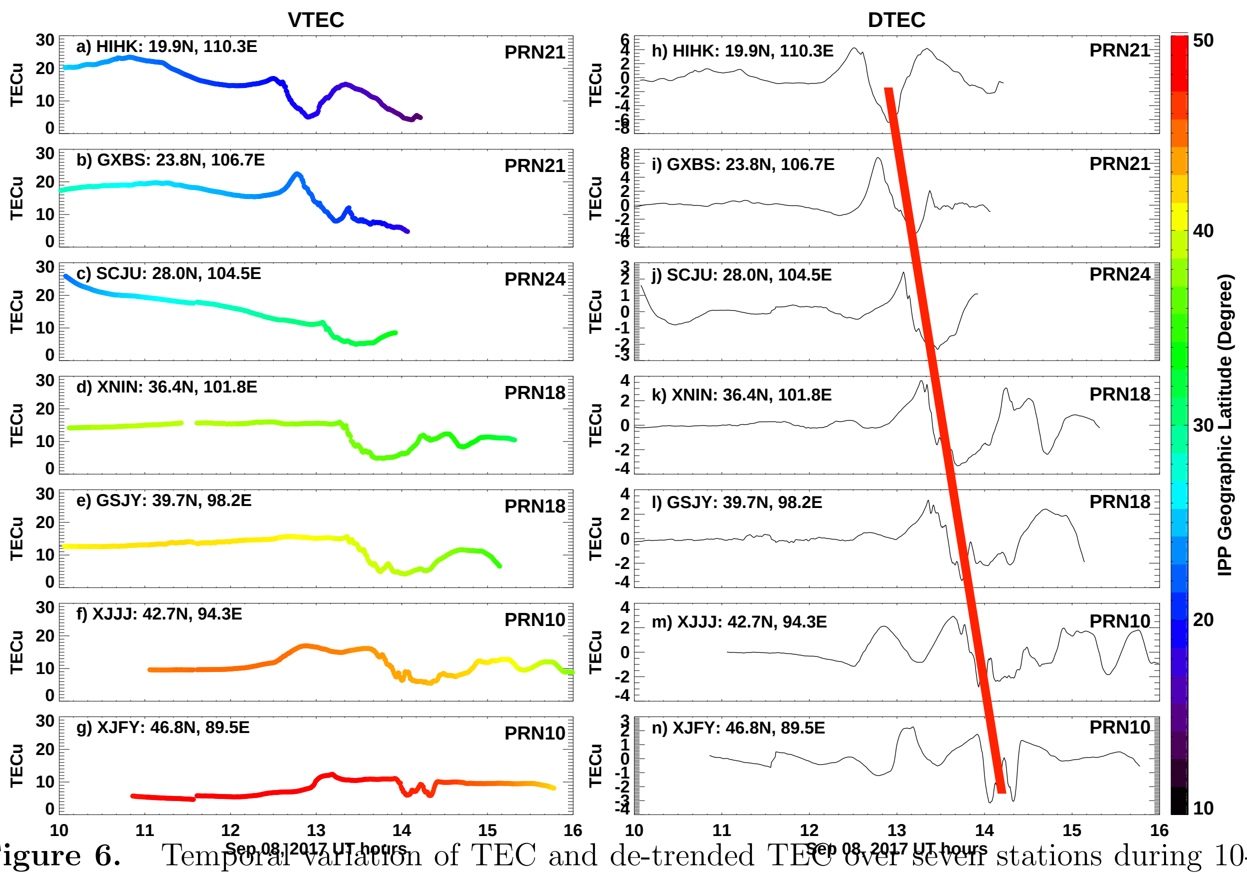

Figure 6. Temporal variation of TEC and de-trended TEC over seven stations during 10-16 UT on 08 September 2017. The color bar shows the geographic latitude range of the ionospheric pierce points (IPP). The red thick line marks the propagation of the depletions.

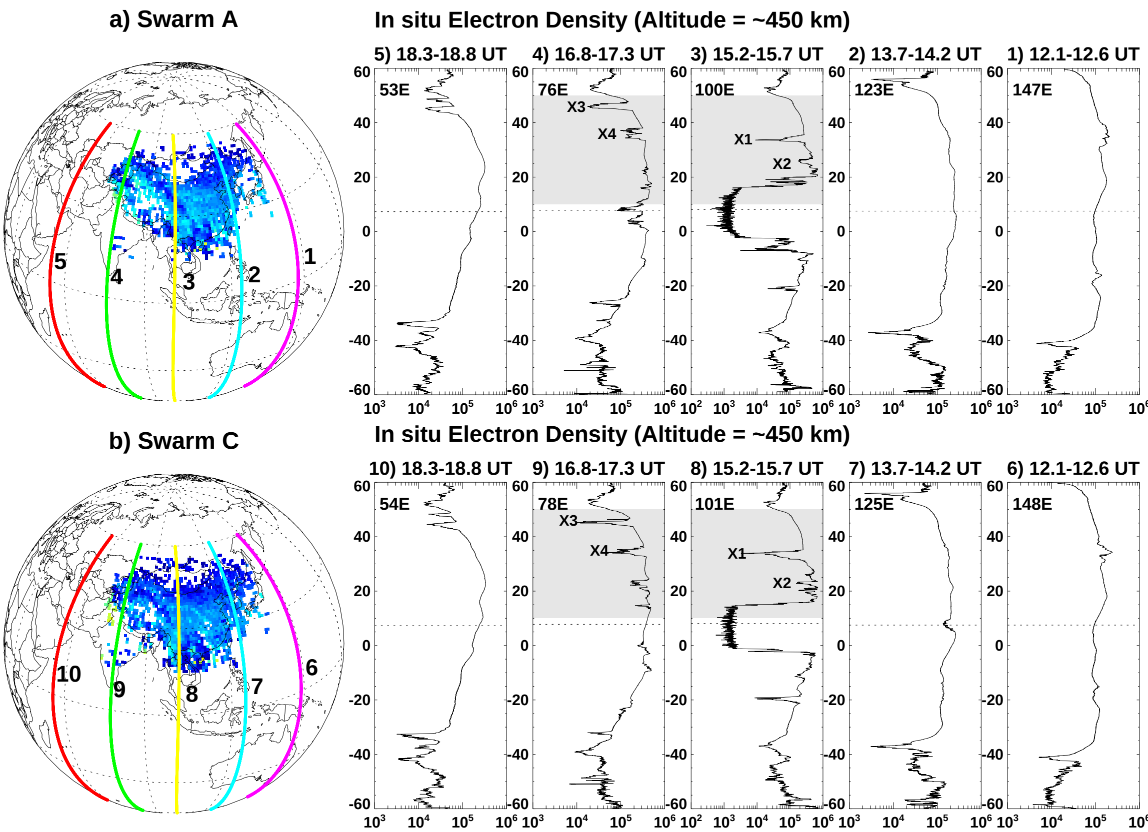

Figure 7. (a) (left) The global map with 5 different satellite orbit paths of Swarm A, with gridded TEC at 15:15 UT being superimposed; (right) variation of in situ electron density as a function of geographic latitudes along these paths. (b) the same as Figure 7a, but for Swarm C satellite with gridded TEC at 16:45 UT being superimposed. The shaded areas represent plasma depletions over China and adjacent regions. Four intersection points X1-X4 that marked in Figure 3b and 3h are also shown here. The magnetic equator is indicated by dotted horizontal lines on the density-latitude profiles.