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Key Points:
- This is the first report of double TOIs during a geomagnetic storm using both model simulations and observations
- One TOI is associated with the dusk convection cell, and the other one is from the dawn convection cell
- The morning TOI density originated from auroral precipitation and is then transported into the polar cap by the convection electric field

Supporting Information:
- Supporting Information S1
- Movie S1
- Movie S2

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Formation of Double Tongues of Ionization During the 17 March 2013 Geomagnetic Storm

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Abstract During geomagnetic disturbances, enhanced high-latitude convection transports ionospheric F_2-region plasma from the dayside midlatitude region into the polar cap, leading to structures such as tongues of ionization (TOIs) and patches. In this study, we investigate the dynamic evolution of TOIs during the 17 March 2013 storm using a high-resolution coupled thermosphere-ionosphere-electrodynamics model and Defense Meteorological Satellite Program (DMSP) satellite observations. Both model and observations show the occurrence of two TOIs simultaneously. One originates in the morning convection cell and the other one in the evening cell. DMSP observations also show similar signatures of two density peaks inside the polar cap. Further diagnostic analysis and control simulations show that the morning TOI is associated with auroral precipitation and is transported into the polar cap region by the convection electric field. This study reveals that the plasma transport in both the afternoon and morning sectors play critical roles in the dynamic evolution of polar ionospheric structures.

1. Introduction

During geomagnetic disturbances when the interplanetary magnetic field (IMF) *Bz* component is southward, a two-cell convection pattern is usually set up at high latitudes. This convection pattern has a distinct structure: The dawn cell has a counterclockwise circulation, and the dusk cell a clockwise one (e.g., Heppner & Maynard, 1987; Ruohoniemi & Greenwald, 1996).

This convection can transport plasma from the daytime midlatitudes into the polar cap region and cause a tongue of ionization (TOI), which is characterized by a longitudinally narrow region of enhanced plasma density from middle to high latitudes in the noon-midnight direction (Knudsen, 1974; Sato, 1959; Sato & Rourke, 1964). Ionospheric *F*-region TOIs and patches are often associated with the formation of plasma irregularities, which can disrupt trans-ionosphere communication and navigation in the polar region (Basu et al., 2002; Jin et al., 2017; Xiong et al., 2016). Hence, it is of critical importance to understand the formation and dynamic evolution of the TOIs in the polar ionosphere.

The TOI was first reported by Sato (1959) using maps of ground-based F_2-region critical frequency (f_oF_2). Using observations from multiple instruments including incoherent scatter radars, Global Position System (GPS) total electron content (TEC), Defense Meteorological Satellite Program (DMSP) satellites and Super Dual Auroral Radar Network (SuperDARN) radars, Foster et al. (2005) produced a global map of the TOI and showed that it originates from a region of storm-enhanced density (SED) and extends from the daytime midlatitudes into the nightside polar cap in the antisunward convection flow channel. After that paper, numerous studies were carried out to investigate the TOI evolution and its dependence on geophysical conditions (e.g., David et al., 2016; Middleton et al., 2005; Thomas et al., 2013). Most of these previous studies have concentrated on the TOI generated by the afternoon convection cell; the TOI associated with the morning convection cell has been seldom reported. Zhang, Zhang, Moen, et al. (2013) reported a TOI in the morning convection cell and investigated the polar cap patch segmentation from the morning TOI using GPS TEC and ground-based observations. Based on optical imaging from ground charge-coupled device (CCD) camera and IMAGE (Imager for Magnetopause-to-Aurora Global Exploration) satellites, Moen et al. (2007, 2015) showed that polar cap patches exit from both convection cells near the midnight.

In this paper, we report, for the first time, an event of double TOIs in the polar ionosphere during the 2013 St. Patrick's Day storm, utilizing the recently developed high-resolution Thermosphere Ionosphere Electrodynamics General Circulation Model (TIEGCM). The temporal evolution of TOIs and the formation mechanisms during the storm are examined. The DMSP observations are also compared with model results.

2. Methodology

The TIEGCM self-consistently solves time-dependent equations of momentum, energy, and continuity for the neutrals and ions of the coupled global ionosphere-thermosphere (I-T) system (Qian et al., 2014; Richmond et al., 1992; Roble et al., 1988). Recently, TIEGCM v2.0 has been upgraded to a high-resolution version, which has a horizontal resolution of $0.625° \times 0.625°$ in a geographic latitude-longitude grid and a vertical resolution of 1/4 scale height. The high-resolution TIEGCM has shown a good capability in simulating mesoscale structures of the ionosphere and thermosphere during the 2017 Great American Solar Eclipse (Dang, Lei, Wang, Burns, et al., 2018; Dang, Lei, Wang, Zhang, et al., 2018). In this study, we use the high-resolution TIEGCM to simulate the polar ionospheric responses to the 17 March 2013 geomagnetic storm. The time step of the model simulation for this study is 5 s. A subcycling technique is used in the O^+ continuity equation solver with a time step of 0.1 s. The convection pattern at high latitudes is specified by the Weimer model (Weimer, 2005), which is driven by the observed solar wind and IMF conditions. The auroral precipitation in the TIEGCM is specified by Roble and Ridley (1987) and Emery et al. (2008).

3. Results

Figures 1a–1c show the variation of solar wind and IMF parameters, as well as *Sym-H* indices during the 2013 St. Patrick's Day storm. At about 06:00 universal time (UT) on 17 March 2013, a shock driven by a coronal mass ejection arrived at the magnetosphere, characterized by the sudden enhancement of solar wind density and velocity and the southward turning of IMF *Bz*. The *Sym-H* index started to decrease at around 06:00 UT and reached a first minimum of around −110 nT at 10:00 UT. After that, it attained a second minimum of −132 nT at 20:00 UT before recovery.

Figures 1d–1k display the time evolution of the simulated electron densities at pressure surface 2.0 (near the F_2-region peak, ~300 km) in the Northern Hemisphere on 17 March during the storm. The polar maps of electron densities as a function of geographic latitude and local time (LT) are shown on the top side of each panel. The convection patterns with positive electric potential are shown as red and negative potentials with blue contours. The outer boundary is 50°N geographic latitude. At 06:00 UT, in the storm initial phase, the electron density started to increase in the noon sector, with a magnitude of 5×10^5 cm^{-3}. At 08:00 UT, the electron density enhancement occurred over a large part of the afternoon sector. An evident SED structure can be seen in the afternoon sector at around 60°N. The ionospheric plasma in the afternoon sector was transported in an antisunward direction into the polar cap region by the dusk cell of the convection pattern, as indicated by the blue solid lines. Consequently, a TOI occurred in a narrow region from 65°N at noon to latitudes greater than 80°N inside the polar cap, with a magnitude of 5.5×10^5 cm^{-3}.

As time progressed, at 10:00 and 12:00 UT, the electron density perturbation caused by the geomagnetic storm extended into the premidnight sector, leading to an electron density enhancement between 18 and 22 LT at middle latitudes. On the dayside, the electron density within the TOI structure in the afternoon sector increased to 8×10^5 cm^{-3}. This was associated with the enhanced convection pattern during the storm main phase. The storm-enhanced TOI in the afternoon sector has been investigated in great detail in previous studies (e.g., Foster et al., 2005; Liu et al., 2016, 2017). Interestingly, another TOI feature can also be clearly seen in the morning sector from ~10 UT. The morning TOI stretched from 9 LT at middle latitudes to 12 LT at around 75°N, with a magnitude of 5×10^5 cm^{-3} at 10 UT. The TOI in the morning sector was associated with the dawn cell of the ionospheric convection, which transported plasma from lower latitudes on the morning side into the polar cap region. The morning TOI had a lower electron density than had the afternoon TOI, and moved toward the noon, from about 8 LT at 10:00 UT to 10 LT at 12:00 UT. Note that the

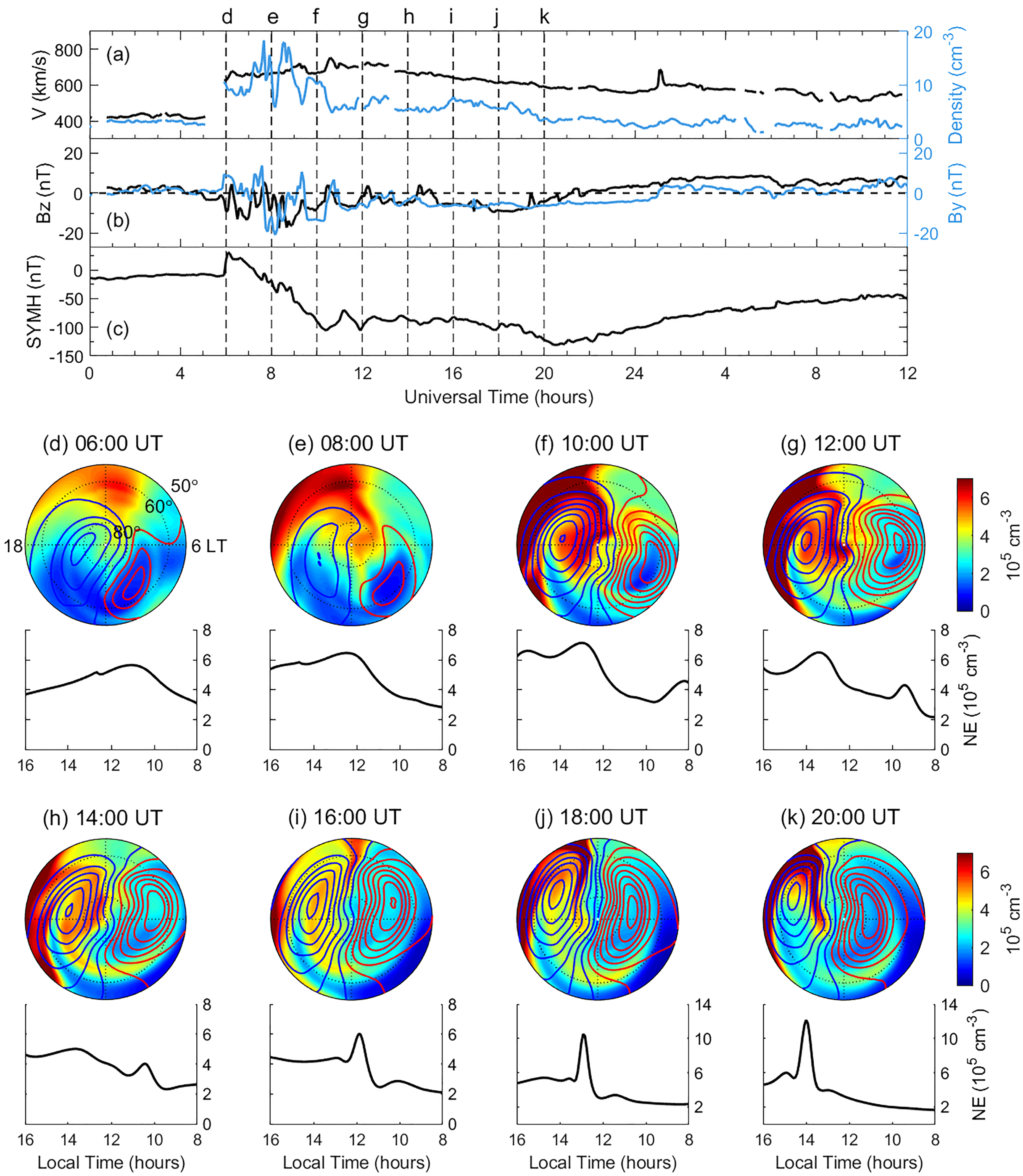

Figure 1. Variations of the (a) solar wind speed and density, (b) interplanetary magnetic field Bz and By components, and (c) SYM-H indices during the 17 March 2013 geomagnetic storm. (d–k) Polar maps of the simulated electron densities and their local time variations (times goes from right to left) at 65°N at pressure level 2 (~300 km) in the Northern Hemisphere on 17 March 2013.

simulated electron density within the morning TOI structure was higher than that at lower latitudes. This could be associated with both the local ionization enhancement due to the sunrise effect and the auroral electron precipitation in the morning sector, as will be explained in detail later.

The TOI associated with the dusk cell started to deplete at 14:00 UT with an electron density of about 2×10^5 cm^{-3} and disappeared around 16:00 UT. On the other hand, after 14:00 UT, the TOI associated with the

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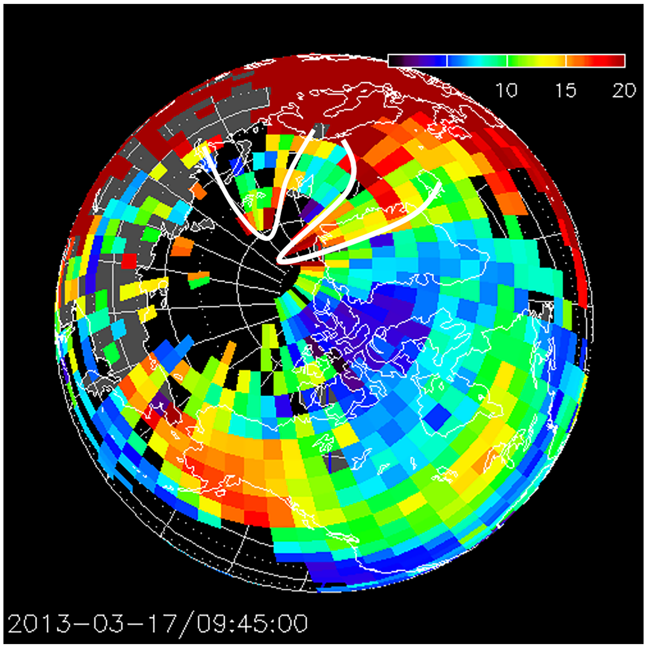

Figure 2. A polar map of the GPS TEC in the Northern Hemisphere at 09:45 UT on 17 March 2013.

morning convection cell also disappeared. However, a new TOI was formed at noon at 16:00 UT. This newly formed TOI structure associated with the dusk cell moved toward the afternoon sector and finally reached 15 LT at 20:00 UT. The TOI peak density varied from a magnitude of 5.8×10^5 cm^{-3} at 16:00 UT to one of 8×10^5 cm^{-3} at 20:00 UT.

Thus, the simulation results showed a complicated evolution of TOIs (also in the supporting information Movie S1) during the geomagnetic disturbances. During the main phase of the 2013 St Patrick's Day storm, two TOIs occurred simultaneously: one was located in the morning sector and the other in the afternoon sector. The TOIs in the morning and afternoon sectors were, respectively, associated with the dawn and dusk cells of the convection pattern and stretched from the dayside middle latitudes all the way into the polar cap region. To further illustrate the detailed evolution of the double TOIs during the storm, the bottom side of each panel in Figure 1 depicts the distribution of the electron densities at the $Zp = 2$ constant pressure surface (near the F_2-region peak) at 65°N at different UTs. The electron density was plotted from 8 to 16 LT for the dayside sector.

At 06:00 UT, during the storm initial phase, there was no evident TOI signature at 65°N. The electron density peaked at around 11 LT, with a magnitude of 5.6×10^5 cm^{-3}. As shown in Figure 1e, at 08:00 UT a TOI structure started to occur at 12:30 LT in the afternoon sector. The TOI at 10:00 UT moved to 13:30 LT and the electron density increased to 7.1×10^5 cm^{-3}. At the same time, the electron density also increased in the morning sector, and another TOI was generated, corresponding to the appearance of the TOI in the morning sector near 08 LT in Figure 1e. The electron density within the morning TOI was about two thirds of that in the afternoon TOI structure. Note that the *Ne* density enhancements at 65°N were equatorward of the polar cap region, and thus, these density enhancements were the plasma density sources that once transported through the cusp region did form the TOIs.

Then at 12:00 UT, as shown in Figure 1f, two prominent TOIs can be seen clearly. The TOI in the afternoon sector occurred at about 14 LT and the morning one at 9 LT. The structure of double TOIs continued to be seen until 14:00 UT. At 14:00 UT, the TOI in the afternoon was greatly reduced with an electron density of about 4.5×10^5 cm^{-3} and finally disappeared after 16:00 UT. The TOI in the morning sector also disappeared at 16:00 UT. However, a new TOI formed at noon, associated with the dusk convection cell. This TOI became stronger after 16:00 UT. It moved toward the duskside continuously and arrived at 14 LT at 20:00 UT with a magnitude of 6.2×10^5 cm^{-3}.

In order to confirm the existence of double TOIs over the polar ionosphere during the storm, we employed GPS TEC, NmF_2 data from the Qaanaaq ionosonde (77.5°N, 69.2°W), and measurements from the DMSP satellites. A polar map of GPS TEC at 09:45 UT during the storm is given in Figure 2. A TOI structure is clearly seen in the morning sector at around 10 LT, with a magnitude of 20 TEC units. For the afternoon sector, there were large gaps of GPS receivers over Russia, making it difficult to observe the full picture of double TOIs during this period. However, a TOI-like structure can still be noted at high latitudes on the afternoon side. Figure 3 shows a comparison of NmF_2 variations between ionosonde observations and TIEGCM simulations at Qaanaaq on 17 March 2013. At 14 UT (10 LT), there is an NmF_2 enhancement of around 4×10^5 cm^{-3} in the model results, corresponding to the morning TOI. Unfortunately, the large data gap in the same morning period prevents us from a direct comparison between the ionosonde data and model prediction. In the afternoon at around 20 UT (15 LT), both exhibit a prominent NmF_2 enhancement within the afternoon TOI region.

The DMSP consists of multiple polar-orbiting satellites, orbiting the Earth every 102 min at 835–850 km altitude. Data from the DMSP satellites have been utilized to identify the TOI structure over the polar cap by examining density enhancements along the orbit (e.g., Garcia et al., 2000; Hosokawa et al., 2009; Wang et al., 2016). Figure 4 shows the (a, e) spacecraft track, (b, f) ion density, (c, g) plasma temperature, and

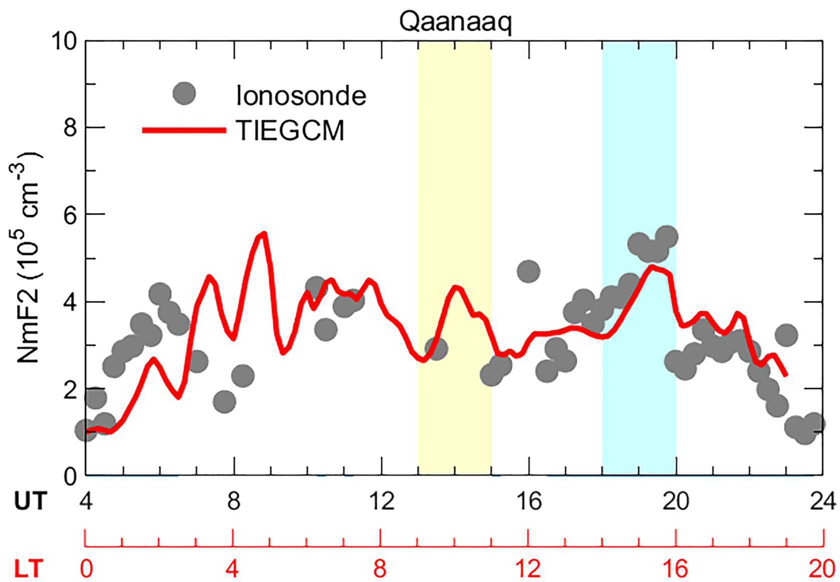

Figure 3. Universal time variations of N_mF_2 at Qaanaaq (77.5°N, 69.2°W) observed by the ionosonde and simulated by the TIEGCM on 17 March 2013.

(d, h) electron energy flux measured by DMSP F16 and F17 at around 10:00 UT. In Figure 4 (left column), DMSP F17 passed through the dayside polar ionosphere from 17 LT, 73°N, to around 6 LT, 62°N. Two strong ion density peaks were clearly seen in Figure 4b: one peak occurred at 10:05 UT and was located at 78°N and 13 LT with a density peak of 1.9×10^5 cm^{-3}, and the other occurred at 10:10 UT and was located at 68°N and 10 LT with a density peak of 1.5×10^5 cm^{-3}. The beginning and ending of the two regions of ion density enhancements were respectively denoted as "A," "B," and "C", "D". They were also labeled along the spacecraft track in Figure 4a. At 10:00 UT, the two regions of the observed ion density enhancements had a similar signature to the double TOIs in the TIEGCM results (Figure 1f). The DMSP ion density structure in "A-B" agreed well with the TIEGCM TOI structure in the dusk cell, which started from the middle-latitude afternoon sector and extended into the polar cap around noon. Note that ion densities are different between DSMP observations and TIEGCM simulations, as the DMSP orbit height is near 800 km, but TIEGCM results are near the F_2 peak. The second region of ion density enhancement (C-D) corresponded to the TOI structure in the morning sector. We have also overlaid the TIEGCM on the time sequence of DMSP observations, as shown by the red lines in Figure 4b. The simulated double-TOI structure generally agrees well with the DMSP observations, although the modeled ion density was much larger than the observations as the altitudes of the two data sets are different. The plasma temperatures from DMSP observations were shown in Figures 4c and 4g. They generally varied inversely to the ion density variations due to the electron cooling, which is a typical feature of the classical polar TOI (or patches) induced by the convection electric field. *Te* decreases with ion density enhancement within the double-band structures, while *Te* increases between the two-band structures. This is different from the "hot polar patches" defined by Zhang et al. (2017), in which the electron temperature increases with the ion density enhancement due to energetic electron precipitation. We also show electron and ion temperatures from the model in the supporting information (Figure S1), which gives similar characteristics.

We further examined the variations of precipitating electron energy flux to exclude the possibility of DMSP-observed density peaks being caused directly by auroral precipitation. As shown in Figure 4d, significant auroral electron precipitation can be seen before 10:02 UT and after 10:10 UT, which represented the auroral oval on the duskside and dawnside. Neither two regions of the observed ion density enhancements were located within these auroral regions. The energy flux of precipitating electrons in the regions of double TOIs (A-B and C-D) was low, showing that no strong electron precipitation occurred within the regions of ion density enhancement. One can note that in Figure 4b an ion density enhancement also occurred between B and C in the polar cap, which might be associated with the polar rain electrons from the solar

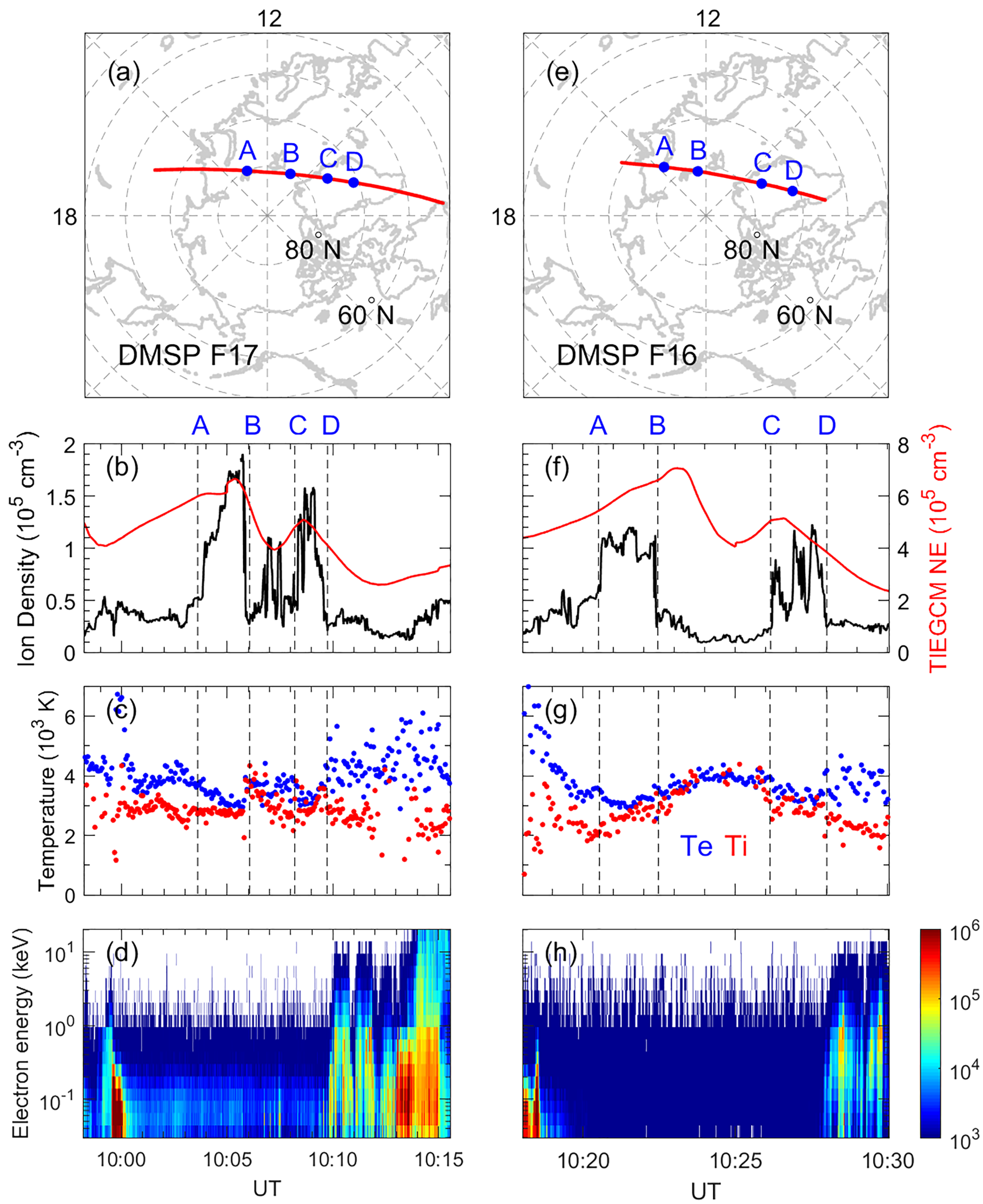

Figure 4. (a, e) The satellite tracks and the measurements of (b, f) ion density, (c, g) electron and ion temperature, and (d, h) precipitating electron energy flux of the overpassing DMSP (left) F17 and (right) F16 satellites on 17 March 2013.

wind (e.g., Zhang et al., 2007). The observations from DMSP F16 are in Figure 4 (right column). Both DMSP F16 satellite observations and the overlaid TIEGCM simulations show a double-TOI structure that agrees with that seen by DMSP F17. Note that the DMSP observation in Figure 9n in Hosokawa et al. (2010) also exhibited a double-band structure of ion density, which agrees with our result. Our result indicates that the two regions of enhanced ion density observed by DMSP were associated with TOI structures that were transported by the convection cells, instead of being produced by local precipitation.

4. Discussion and Conclusions

As indicated in Figures 1 and 4, TOIs occurred simultaneously in the morning and afternoon sectors during the 2013 St. Patrick's Day storm. Most of the TOIs reported in previous studies were found to be associated with the dusk convection cell (e.g., Foster et al., 2005; Hosokawa et al., 2010; Thomas et al., 2013), due to the relatively dense plasma at middle latitudes in the afternoon sector. In the past decade, global GPS TEC maps have been widely used to study the structure of the polar ionosphere, including TOIs and polar cap patches (e.g., Foster et al., 2005; Liu et al., 2015; Zhang, Zhang, Lockwood, et al., 2013; Zhang, et al., 2015). However, lack of a full data coverage and low spatial and temporal resolution of the GPS TEC maps have limited the identification of smaller-scale structures like the double TOIs described in this paper. During the St. Patrick's Day event, there was a large gap of GPS receivers over Russia in the afternoon sector, and there were many smaller gaps in the morning sector around 9-12 UT, making it difficult to compare GPS data with the model results and validate the existence of double TOIs. Besides the observations, numerical models are also utilized to investigate the behavior and evolution of the TOI structure during storms (e.g., Liu et al., 2016, 2017; Sojka et al., 2012). These models, however, usually had a spatial resolution larger than 2° in longitude and latitude and so cannot resolve mesoscale structures such as double TOIs in the polar ionosphere well. In this study, the measurements made by the DMSP satellites have also provided a similar signature of double TOIs, showing two bands of ion density enhancements when they passed through the polar cap region from local afternoon to the morning sector.

The formation of double TOIs is closely related to ion convection and plasma density variations at lower latitudes, that is, the TOI source region. The variations of the IMF configuration during storm time impact the magnetic reconnection between the IMF and the geomagnetic field. This process further affects the ionospheric convection pattern and the dynamics of TOIs (Deng & Ridley, 2006; Weimer, 1996). As shown in Figure 1, the convection pattern changed greatly during the storm in response to IMF variations. During 10:00–14:00 UT, in the dawn convection cell, there were poleward $\mathbf{E} \times \mathbf{B}$ drifts along the potential line from middle and auroral latitudes into the polar cap region, leading to the antisunward transport of the plasma and thus the TOI structure in the morning sector.

Regarding the afternoon TOI source region, as shown in Figure 1, the electron density at middle latitudes and auroral regions changed at different UTs and different stages of the storm. TOIs can be more easily formed if there is a larger electron density in the lower-latitude source region. Sojka et al. (2012) showed that the longitudinal dependence of ionospheric electron density at middle latitudes during storms is mainly caused by the longitudinal variations of both neutral winds and electric fields. Heelis et al. (2009) and David et al. (2011) showed that lifting of plasma to higher altitudes contributes to the SED formation in the afternoon, which is suggested to be the source of the TOI structure. In terms of the plasma velocity observed by high-frequency coherent radars, Milan et al. (2002) found that the plasma transport in the polar cap provides plasma sources from both dawn and dusk sectors with the radar scans. Using model simulations, Zou and Ridley (2016) found that the plasma from both dawn and dusk sectors contributes to the formation of SED.

On the other hand, the formation of double TOIs, especially the morning TOI, is complicated and associated with both the electron density in the source region and the ionospheric convection pattern. Furthermore, the finding of the occurrence of double TOIs and their evolution in this study point to a new source of polar ionization, as almost all previous studies suggest that TOI and polar patches are the results of transportation of plasma from the afternoon/noon sector, whereas our results show that plasma can also be transported into the polar cap from the middle latitude and auroral regions through the morning sector, as shown in Figure 1. The importance of identifying and studying TOI and patches, including double TOIs, is also related to their potential space weather application in that radio scintillation tends to occur near the edges of these mesoscale structures. For this purpose, we carried out a diagnostic analysis of the ion continuity equation to explore the physical mechanisms responsible for the formation of the morning TOI. Since near the F_2 peak ionospheric ion composition is dominated by O^+, the ion continuity equation can be described as

$$\frac{\partial N_{O^+}}{\partial t} = q_{O^+} - \beta N_{O^+} - \nabla \cdot \left(N_{O^+} \vec{V}_{O^+} \right) \quad (1)$$

Similar to Lei et al. (2008), for convenience, the terms $\frac{\partial N_{O^+}}{\partial t}$, q_{O^+}, and βN_{O^+} are referred as op_dt, prod, and loss. The transport term $-\nabla \cdot \left(N_{O^+} \vec{V}_{O^+} \right)$ is split into the transport processes by electric fields (trans_E×B), neutral winds (trans_wind), and ambipolar diffusion (amb_diff). Thus, equation (1) is further written as

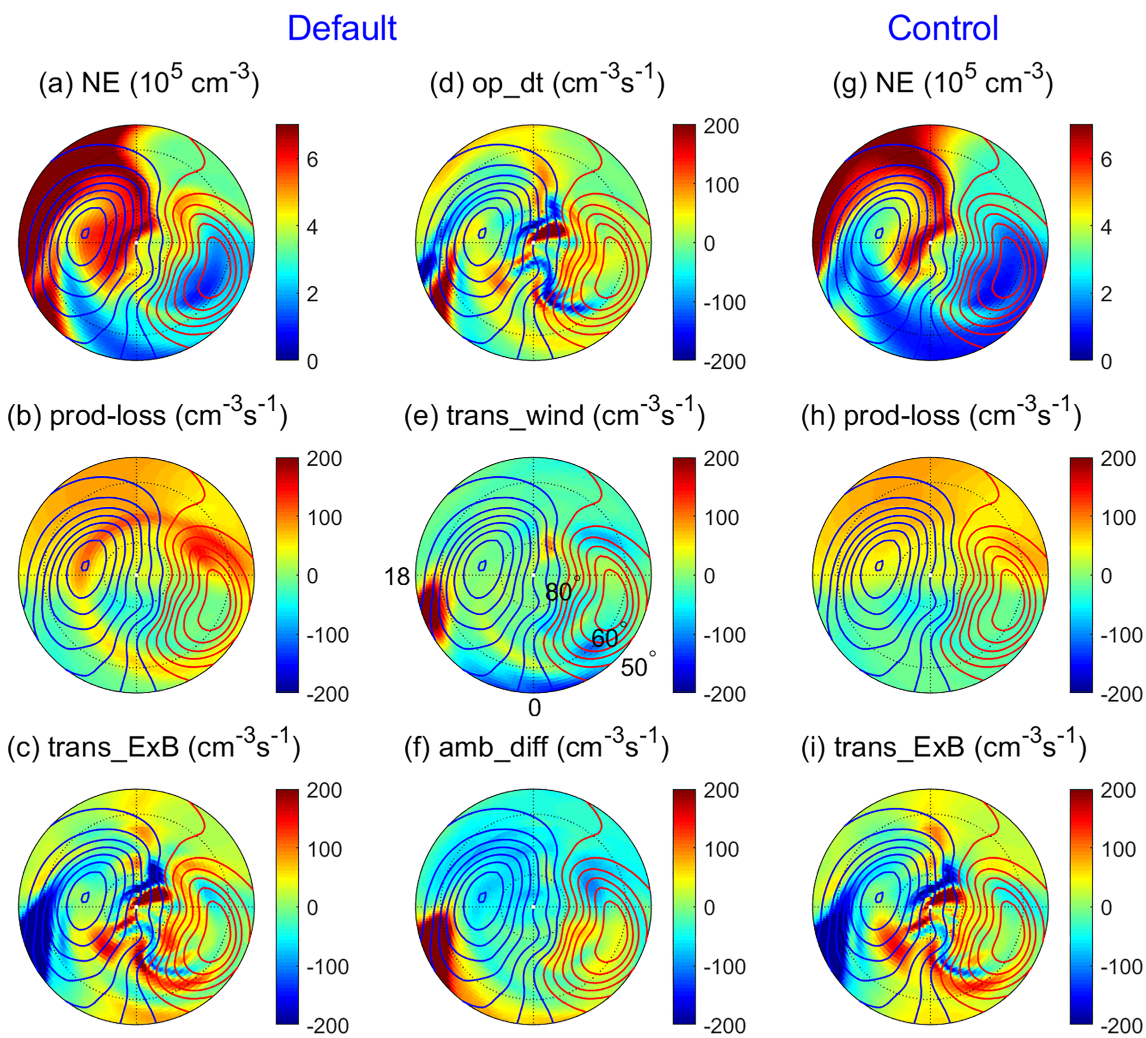

Figure 5. Polar maps of (a) electron densities and (b–f) terms simulated by the TIEGCM at 10:00 UT on 17 March 2013. (g–i) Similar to (a)–(c), respectively, but for the simulation results with 1/5 auroral electron precipitation of the default values.

$$\text{op\_dt} = \text{prod}-\text{loss} + \text{trans\_E}\times\text{B} + \text{trans\_wind} + \text{amb\_diff} \quad (2)$$

Figures 5a–5f show a snapshot of the polar maps of electron density and the terms (time rate of change of O^+) in equation (2) at pressure surface 2 at 10:00 UT. The change of O^+ (op_dt) in Figure 5d is generally consistent with the term trans_ExB (Figure 5c), which represents the transport effect by the convection pattern. In the morning sector, there is an evident transport of O^+ induced by the convection electric field from the auroral zone into the polar cap region. The production of O^+ by precipitation (Figure 5b) is also a significant contributor. At around 6–10 LT between 60°N and 80°N in Figure 5b, a large production of O^+ occurred, which is mainly associated with the electron precipitation. Compared to the effects of O^+ production and electric field transport, neutral winds and ambipolar diffusion in Figures 5e and 5f contribute less to the TOI. The term analysis illustrates that auroral precipitation and electric field transport play major roles in the formation of the morning TOI.

Ionization due to auroral particle precipitation has long been suggested as a source of polar cap patches (TOIs are continuous structures) (Weber et al., 1984). MacDougall and Jayachandran (2007) suggested that auroral precipitation actually dominates polar cap patch production. We also conducted a control simulation to examine the auroral effect on the morning TOI, in which the auroral precipitation was decreased to one fifth of the original values. The results are shown in the right panels of Figures 5g–5i. Figure 5h shows a great

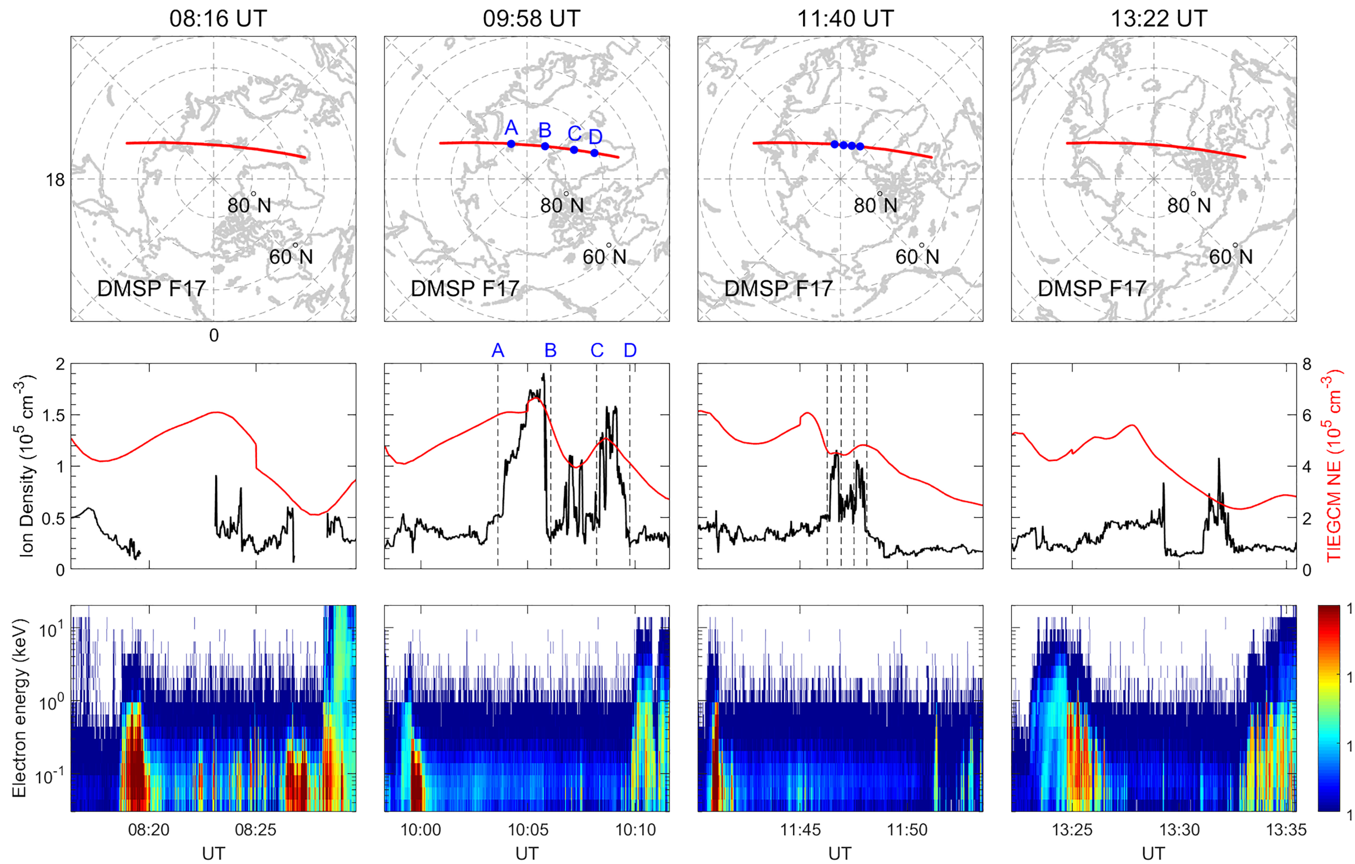

Figure 6. (top row) The satellite tracks and the measurements of (middle row) ion density and (bottom row) precipitating electron energy flux for four flybys of the DMSP F17 satellite on 17 March 2013. The TIEGCM electron density simulations at pressure surface 2 (~300 km, near the F_2-region peak) are overlaid on the DMSP ion density with red lines in the middle-row panels. The beginning universal time of each flyby is marked on the top.

decrease in O^+ production due to the reduction of auroral precipitation. Consequently, the morning TOI in Figure 5g almost disappeared. The TOI structure in the afternoon sector does not change much, since the source of the afternoon TOI is the large plasma density at middle latitudes and is not influenced greatly by the change of auroral precipitation. This indicates that the source of the morning TOI is associated with dayside auroral precipitation and the transportation of the plasma into the polar cap region by dawnside convection electric field.

The electron density changes within the regions of double TOIs can directly modulate the variation of the polar ionospheric conductivity/conductance, which has been suggested to play a significant role in the electrodynamic coupling in the magnetosphere and ionosphere system (Cowley, 2000; Lotko et al., 2014; Ridley et al., 2004). Moreover, the ionospheric conductance variations caused by TOIs could also influence local Joule heating and ion drag, which are directly linked to the dynamic and energetic processes in the coupled I-T system. Using coupled I-T models, Sheng et al. (2015) and Zhang, et al. (2015) showed that thermospheric winds and density at high latitudes can be significantly disturbed by the effect of Joule heating and ion drag. Therefore, the ionospheric conductance changes associated with double TOIs may have a potential impact on the dynamics, electrodynamics, and energetics of the coupled magnetosphere-ionosphere-thermosphere system and is therefore worthy of further exploration.

As illustrated in the TIEGCM simulations, the double TOI structure can last for more than 2 hr. In Figure 6, we display four consecutive passes of DMSP F17 satellites during its passing through the polar region in the Northern Hemisphere. Generally, the DMSP observations again agreed well with the model results, as shown in Figure 6 (middle row). No double-TOI structure appeared before the orbit of 10:00 UT, as shown in Figure 6 (first column) around 08:16 UT. For the subsequent flybys after 10:00 UT, the double-TOI structure at 11:40 UT still existed in both ion density observations and TIEGCM simulations. As compared with the features at 10:00 UT, the measured ion density at 11:40 UT was much smaller and the double-band structures were located closer together, indicating that the double-TOI structure was weakening as time progressed. Finally, the double-TOI structure disappeared during the pass that occurred around 13:22 UT from the results of DMSP ion density and simulated electron density. We have also examined the temporal variations of GPS TEC, which, however, did not show a prominent double-TOI structure after 10:00 UT (not shown here). The deviations of the continuation of the morning TOI between simulations and GPS TEC could be associated with several aspects. On one side, as given by the DMSP observations in Figure 6, the magnitude of double TOIs was only one third of the values at 10:00 UT and the spatial coverage was much smaller. Hence, GPS TEC may not be capable of perfectly catching such an F_2-region mesoscale structure within several longitude degrees, due to its relatively low spatial resolution and the height integration of electron density. On the other hand, based on the empirical convection and auroral model, the TIEGCM results cannot perfectly agree with the observations. Therefore, whether and how long the double TOI-structure can last during the storm time is still worth further exploration, possibly by conducting more comprehensive and statistical studies of double TOIs for different storm events.

It should be noted that an empirical convection model (Weimer, 2005) driven by the observed solar wind/IMF conditions was used in the TIEGCM here to represent the convection pattern in the high latitudes. The comparison between the Weimer model and SuperDARN observations (Movie S2 in the supporting information) show that the Weimer model generally reproduced the observed features regulated by IMF *Bz* and *By* during the storm. The SuperDARN structures are, however, more dynamic and finer than the Weimer ones. This deviation may cause the simulation results to depart from the actual dynamic and complicated ionospheric convection (such as the pulsed reconnections). In this respect, the simulated double-TOI structure associated with the Weimer convection model is more steady and continuous; however, the observed double-TOI structure (such as DMSP observation) in realistic conditions might be more like a series of polar cap patches rather than a continuous TOI. Also, the potential pattern of the Weimer model might not represent well plasma trajectories, especially in the middle-latitude region. The ionospheric trough in the midlatitudes is a region where the counterclockwise corotation electric field cancels the dusk-sector clockwise electric field, leading to plasma stagnation and hence density depletion in darkness (e.g., Moffett & Quegan, 1983; Rodger, 2013). The formation of the midlatitude trough is closely related to both the convection and corotational electric fields, of which the latter is not reflected in the Weimer model. Here the Weimer pattern does not properly define the plasma trajectories outside the polar cap associated with the ionospheric trough due to the lack of representation of corotational field. However, inside the polar region where the corotation electric field is weak, the Weimer potential contours are still reasonable. Thus, this weakness of the Weimer model does not influence the overall findings and analysis of double TOIs in this paper. To provide a more accurate and dynamic polar electric field, a solar wind-driven, two-way coupled magnetosphere-ionosphere-thermosphere model is desired. Furthermore, the auroral model used in TIEGCM is from Roble and Ridley (1987) and Emery et al. (2008), which is based on the estimated hemispheric power of precipitating electrons and can also introduce uncertainties from the actual conditions. A more accurate auroral model is also required to better simulate the auroral ionosphere. Meanwhile, the upper boundary of the model is around 600–700 km, depending on solar activity. Lack of the coupling with the plasmasphere might induce an underestimated TEC and an inaccurate plasma flux at the model's upper boundary. Nevertheless, by comparing the simulation results with DMSP observations, this study clearly shows the existence of double TOIs during geomagnetic storms and suggests its possible influence on the dynamic and energy processes in the coupled magnetosphere-ionosphere-thermosphere system in the polar region.

In summary, we have investigated the dynamic evolution of TOIs during the 17 March 2013 geomagnetic storm, using a high-resolution coupled thermosphere-ionosphere-electrodynamics model. This high-resolution modeling capability allows us to simulate better the mesoscale structures of the ionosphere. We show, for the first time, that double-TOI structures can occur in the polar cap during the storm main phase: one is seen in the afternoon sector and the other one in the morning sector. Double TOIs are each driven by the dusk and dawn cells of the ionospheric convection electric fields. The DMSP observations also showed a similar signature of double TOIs in the polar ionosphere. The diagnostic analysis and control simulations indicate that the morning TOI plasma originates from the auroral electron precipitation and transported into the polar cap region by convection.

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Reference

Basu, S., Groves, K. M., Basu, S., & Sultan, P. J. (2002). Specification and forecasting of scintillations in communication/navigation links: Current status and future plans. *Journal of Atmospheric and Solar-Terrestrial Physics*, *64*, 1745–1754. http://doi.org/10.1016/S1364-6826(02)00124-4

Cowley, S. W. H. (2000). Magnetosphere-ionosphere interactions: A tutorial review. In *Magnetospheric Current Systems* (pp. 91–106). Washington DC: American Geophysical Union. http://doi.org/10.1029/GM118p0091

Dang, T., Lei, J., Wang, W., Burns, A., Zhang, B., & Zhang, S.-R. (2018). Suppression of the polar tongue of ionization during the 21 August 2017 solar eclipse. *Geophysical Research Letters*, *45*, 2918–2925. https://doi.org/10.1002/2018GL077328

Dang, T., Lei, J., Wang, W., Zhang, B., Burns, A., le, H., et al. (2018). Global responses of the coupled thermosphere and ionosphere system to the August 2017 Great American Solar Eclipse. *Journal of Geophysical Research: Space Physics*, *123*, 7040–7050. https://doi.org/10.1029/2018JA025566

David, M., Sojka, J., Schunk, R., Liemohn, M., & Coster, A. (2011). Dayside midlatitude ionospheric response to storm time electric fields: A case study for 7 September 2002. *Journal of Geophysical Research*, *116*, A12302. http://doi.org/10.1029/2011JA016988

David, M., Sojka, J. J., Schunk, R. W., & Coster, A. J. (2016). Polar cap patches and the tongue of ionization: A survey of GPS TEC maps from 2009 to 2015. *Geophysical Research Letters*, *43*, 2422–2428. http://doi.org/10.1002/2016GL068136

Deng, Y., & Ridley, A. (2006). Role of vertical ion convection in the high-latitude ionospheric plasma distribution. *Journal of Geophysical Research*, *111*, A09314. http://doi.org/10.1029/2006JA011637

Emery, B. A., Coumans, V., Evans, D. S., Germany, G. A., Greer, M. S., Holeman, E., et al. (2008). Seasonal, Kp, solar wind, and solar flux variations in long-term single-pass satellite estimates of electron and ion auroral hemispheric power. *Journal of Geophysical Research*, *113*, A06311. http://doi.org/10.1029/2007JA012866

Foster, J. C., Coster, A. J., Erickson, P. J., Holt, J. M., Lind, F. D., Rideout, W., et al. (2005). Multiradar observations of the polar tongue of ionization. *Journal of Geophysical Research*, *110*, A09S31. http://doi.org/10.1029/2004JA010928

Garcia, F. J., Kelley, M. C., Makela, J. J., Sultan, P. J., Pi, X., & Musman, S. (2000). Mesoscale structure of the midlatitude ionosphere during high geomagnetic activity: Airglow and GPS observations. *Journal of Geophysical Research*, *105*, 18,417–18,427. http://doi.org/10.1029/1999JA000306

Heelis, R., Sojka, J. J., David, M., & Schunk, R. (2009). Storm time density enhancements in the middle-latitude dayside ionosphere. *Journal of Geophysical Research*, *114*, A03315. http://doi.org/10.1029/2011JA016988

Heppner, J., & Maynard, N. (1987). Empirical high-latitude electric field models. *Journal of Geophysical Research*, *92*, 4467–4489.

Hosokawa, K., Tsugawa, T., Shiokawa, K., Otsuka, Y., Nishitani, N., Ogawa, T., & Hairston, M. R. (2010). Dynamic temporal evolution of polar cap tongue of ionization during magnetic storm. *Journal of Geophysical Research*, *115*, A12333. http://doi.org/10.1029/2010JA015848

Hosokawa, K., Tsugawa, T., Shiokawa, K., Otsuka, Y., Ogawa, T., & Hairston, M. R. (2009). Unusually elongated, bright airglow plume in the polar cap F region: Is it a tongue of ionization? *Geophysical Research Letters*, *36*, L07103. http://doi.org/10.1029/2009GL037512

Jin, Y., Moen, J. I., Oksavik, K., Spicher, A., Clausen, L. B. N., & Miloch, W. J. (2017). GPS scintillations associated with cusp dynamics and polar cap patches. *Journal of Space Weather and Space Climate*, *7*, A23. https://doi.org/10.1051/swsc/2017022

Knudsen, W. C. (1974). Magnetospheric convection and the high-latitude F_2 ionosphere. *Journal of Geophysical Research*, *79*, 1046–1055. http://doi.org/10.1029/JA079i007p01046

Lei, J., Wang, W., Burns, A. G., Solomon, S. C., Richmond, A. D., Wiltberger, M., et al. (2008). Observations and simulations of the ionospheric and thermospheric response to the December 2006 geomagnetic storm: Initial phase. *Journal of Geophysical Research*, *113*, A01314. https://doi.org/10.1029/2007JA012807

Liu, J., Nakamura, T., Liu, L., Wang, W., Balan, N., Nishiyama, T., et al. (2015). Formation of polar ionospheric tongue of ionization during minor geomagnetic disturbed conditions. *Journal of Geophysical Research: Space Physics*, *120*, 6860–6873. http://doi.org/10.1002/2015JA021393

Liu, J., Wang, W., Burns, A., Liu, L., & McInerney, J. (2017). A TIEGCM numerical study of the source and evolution of ionospheric F-region tongues of ionization: Universal time and interplanetary magnetic field dependence. *Journal of Atmospheric and Solar-Terrestrial Physics*, *156*, 87–96. http://doi.org/dx.doi.org/10.1016/j.jastp.2017.03.005

Liu, J., Wang, W., Burns, A., Solomon, S. C., Zhang, S., Zhang, Y., & Huang, C. (2016). Relative importance of horizontal and vertical transports to the formation of ionospheric storm-enhanced density and polar tongue of ionization. *Journal of Geophysical Research: Space Physics*, *121*, 8121–8133. http://doi.org/10.1002/2016JA022882

Lotko, W., Smith, R. H., Zhang, B. Z., Ouellette, J. E., Brambles, O. J., & Lyon, J. G. (2014). Ionospheric control of magnetotail reconnection. *Science*, *345*(6193), 184–187. http://doi.org/10.1126/science.1252907

MacDougall, J., & Jayachandran, P. T. (2007). Polar patches: Auroral zone precipitation effects. *Journal of Geophysical Research*, *112*, A05312. https://doi.org/10.1029/2006JA011930

Middleton, H. R., Pryse, S. E., Kersley, L., Bust, G. S., Fremouw, E. J., Secan, J. A., & Denig, W. F. (2005). Evidence for the tongue of ionization under northward interplanetary magnetic field conditions. *Journal of Geophysical Research*, *110*, A07301. http://doi.org/10.1029/2004JA010800

Milan, S. E., Lester, M., & Yeoman, T. K. (2002). HF radar polar patch formation revisited: Summer and winter variations in dayside plasma structuring. *Annales de Geophysique*, *20*(4), 487–499. https://doi.org/10.5194/angeo-20-487-2002

Moen, J., Gulbrandsen, N., Lorentzen, D. A., & Carlson, H. C. (2007). On the MLT distribution of *F* region polar cap patches at night. *Geophysical Research Letters*, *34*, L14113. https://doi.org/10.1029/2007/GL029632

Moen, J., Hosokawa, K., Gulbrandsen, N., & Clausen, L. B. N. (2015). On the symmetry of ionospheric polar cap patch exits around magnetic midnight. *Journal of Geophysical Research: Space Physics*, *120*, 7785–7797. https://doi.org/10.1002/2014JA020914

Moffett, R. J., & Quegan, S. (1983). The mid-latitude trough in the electron concentration of the ionospheric *F*-layer: A review of observations and modelling. *Journal of Atmospheric and Terrestrial Physics*, *45*, 315–343. https://doi.org/10.1016/S0021-9169(83)80038-5

Qian, L., Burns, A. G., Emery, B. A., Foster, B., Lu, G., Maute, A., et al. (2014). The NCAR TIE-GCM: A community model of the coupled thermosphere/ionosphere system. In *Modeling the ionosphere-thermosphere system*, (pp. 73–83). Washington, DC: American Geophysical Union. http://doi.org/10.1002/9781118704417.ch7

Richmond, A. D., Ridley, E. C., & Roble, R. G. (1992). A thermosphere/ionosphere general circulation model with coupled electrodynamics. *Geophysical Research Letters*, *19*, 601–604. http://doi.org/10.1029/92GL00401
Ridley, A. J., Gombosi, T. I., & DeZeeuw, D. L. (2004). Ionospheric control of the magnetosphere: Conductance. *Annales Geophysicae*, *22*, 567–584. http://doi.org/10.5194/angeo-22-567-2004
Roble, R., & Ridley, E. (1987). An auroral model for the NCAR thermospheric general circulation model (TGCM). *Annales Geophysicae*, *5*, 369–382.
Roble, R. G., Ridley, E. C., Richmond, A. D., & Dickinson, R. E. (1988). A coupled thermosphere/ionosphere general circulation model. *Geophysical Research Letters*, *15*, 1325–1328. http://doi.org/10.1029/GL015i012p01325
Rodger, A. (2013). The mid-latitude trough—Revisited. In *Midlatitude ionospheric dynamics and disturbances*, (pp. 25–34). Washington DC: American Geophysical Union. http://doi.org/10.1029/181GM04
Ruohoniemi, J., & Greenwald, R. (1996). Statistical patterns of high-latitude convection obtained from Goose Bay HF radar observations. *Journal of Geophysical Research*, *101*, 21,743–21,763. http://doi.org/10.1029/96JA01584
Sato, T. (1959). Morphology of ionospheric F2 disturbances in the polar regions. *Report of Ionosphere and Space Research in Japan*, *13*, 91–95.
Sato, T., & Rourke, G. F. (1964). *F*-region enhancements in the Antarctic. *Journal of Geophysical Research*, *69*, 4591–4607. http://doi.org/10.1029/JZ069i021p04591
Sheng, C., Deng, Y., Wu, Q., Ridley, A., & Häggström, I. (2015). Thermospheric winds around the cusp region. *Journal of Geophysical Research: Space Physics*, *120*, 1248–1255. http://doi.org/10.1002/2014JA020028
Sojka, J., David, M., Schunk, R., & Heelis, R. (2012). A modeling study of the longitudinal dependence of storm time midlatitude dayside total electron content enhancements. *Journal of Geophysical Research*, *117*, A02315. http://doi.org/10.1029/2011JA017000
Thomas, E. G., Baker, J. B. H., Ruohoniemi, J. M., Clausen, L. B. N., Coster, A. J., Foster, J. C., & Erickson, P. J. (2013). Direct observations of the role of convection electric field in the formation of a polar tongue of ionization from storm enhanced density. *Journal of Geophysical Research: Space Physics*, *118*, 1180–1189. http://doi.org/10.1002/jgra.50116
Wang, B., Nishimura, Y., Lyons, L. R., Zou, Y., Carlson, H. C., Frey, H. U., & Mende, S. B. (2016). Analysis of close conjunctions between dayside polar cap airglow patches and flow channels by all-sky imager and DMSP. *Earth, Planets and Space*, *68*(1), 1–12. http://doi.org/10.1186/s40623-016-0524-z
Weber, E. J., Buchau, J., Moore, J. G., Sharber, J. R., Livingston, R. C., Winningham, J. D., & Reinisch, B. W. (1984). F layer ionization patches in the polar cap. *Journal of Geophysical Research*, *89*(A3), 1683–1694. http://doi.org/10.1029/JA089iA03p01683
Weimer, D. (1996). A flexible, IMF dependent model of high-latitude electric potentials having "space weather" applications. *Geophysical Research Letters*, *23*, 2549–2552. http://doi.org/10.1029/96GL02255
Weimer, D. (2005). Improved ionospheric electrodynamic models and application to calculating Joule heating rates. *Journal of Geophysical Research*, *110*, A05306. http://doi.org/10.1029/2004JA010884
Xiong, C., Stolle, C., & Lühr, H. (2016). The *Swarm* satellite loss of GPS signal and its relation to ionospheric plasma irregularities. *Space Weather-the International Journal of Research and Applications*, *14*, 563–577. http://doi.org/doi:10.1002/2016SW001439
Zhang, B., Varney, R. H., Lotko, W., Brambles, O. J., Wang, W., Lei, J., Wiltberger, M., &Lyon, J. G.(2015). Pathways of *F* region thermospheric mass density enhancement via soft electron precipitation. *Journal of Geophysical Research: Space Physics*, *120*, 5824–5831. http://doi.org/10.1002/2015JA020999
Zhang, Q.-H., Lockwood, M., Foster, J. C., Zhang, S.-R., Zhang, B.-C., McCrea, I. W., et al. (2015). Direct observations of the full Dungey convection cycle in the polar ionosphere for southward interplanetary magnetic field conditions. *Journal of Geophysical Research: Space Physics*, *120*, 4519–4530. http://doi.org/10.1002/2015JA021172
Zhang, Q.-H., Ma, Y.-Z., Jayachandran, P. T., Moen, J., Lockwood, M., Zhang, Y.-L., et al. (2017). Polar cap hot patches: Enhanced density structures different from the classical patches in the ionosphere. *Geophysical Research Letters*, *44*, 8159–8167. http://doi.org/10.1002/2017GL073439
Zhang, Q.-H., Zhang, B.-C., Lockwood, M., Hu, H.-Q., Moen, J., Ruohoniemi, J. M., et al. (2013). Direct observations of the evolution of polar cap ionization patches. *Science*, *339*(6127), 1597–1600. http://doi.org/10.1126/science.1231487
Zhang, Q.-H., Zhang, B.-C., Moen, J., Lockwood, M., McCrea, I. W., Yang, H.-G., et al. (2013). Polar cap patch segmentation of the tongue of ionization in the morning convection cell. *Geophysical Research Letters*, *40*, 2918–2922. http://doi.org/10.1002/grl.50616
Zhang, Y., Paxton, L. J., & Lui, A. T. Y. (2007). Polar rain aurora. *Geophysical Research Letters*, *34*, L20114. http://doi.org/10.1029/2007gl031602
Zou, S., & Ridley, A. J. (2016). Modeling of the evolution of storm-enhanced density plume during the 24 to 25 October 2011 geomagnetic storm. In *Magnetosphere-ionosphere coupling in the solar system* (pp. 205–213). Washington DC: American Geophysical Union. http://doi.org/10.1002/9781119066880.ch16