A TIEGCM Numerical Study of the Source and Evolution of Ionospheric F-region Tongues of Ionization: Universal Time and Interplanetary Magnetic Field Dependence

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Abstract

The National Center for Atmospheric Research Thermosphere-Ionosphere Electroynamics General Circulation Model (TIEGCM) has been employed to systematically study the source and evolution of the ionospheric F-region Tongue of Ionization (TOI), which is electron density enhancement in the polar region. The model is run for different Universal Times (UT), season and Interplanetary Magnetic Field (IMF) conditions. It is found that: (1) The TOI formation is critically dependent on UT, preferentially near 2000 UT in the Northern Hemisphere (NH) and near 1600 UT in the Southern Hemisphere (SH). These are the intervals when the high-latitude ion convection throat is closer to the middle-latitude high plasma density source region, so that more plasma can be directly transported into the polar cap region; (2) this different UT dependence between the two Hemispheres occurs, not only because of the different separation of the magnetic poles from the geographic poles in the two hemispheres, but also because of the UT dependence of the mid-latitude source locations (local time, latitude) and the magnitude of plasma density enhancements; (3) the TOI is generally stronger in the SH than it is in the NH, and in winter than in summer; (4) IMF By operates in the opposite sense in the two hemispheres in terms of the TOI pattern such that positive/negative IMF By tends to deflect the TOI toward the morning/afternoon sector in the NH. The opposite condition occurs in the SH.

1. Introduction

The Interplanetary Magnetic Field (IMF) components of B_z and B_y have great influences on the polar ionosphere and thermosphere since IMF B_z determines the cross polar cap potential and ion convection pattern, and IMF B_y controls the dawn-dusk asymmetry of this ion convection. There are a number of papers devoted to studying IMF B_y effects on the polar ion convection pattern [e.g., Heppner, 1977; Heelis, 1984; Weimer, 1995, 2005; Ruohoniemi and Greenwald, 2005]. Generally speaking, a large positive (negative) IMF B_y tends to increase the dusk (dawn) convection cell relative to the convection pattern with small B_y in the Northern Hemisphere (NH), and the opposite effect occurs in the Southern Hemisphere (SH). The IMF B_z and B_y components also have important impacts on high-latitude Joule heating, neutral circulation through ion-neutral collision, neutral composition (e.g., O/N_2), neutral density, and electron density [e.g., Thayer et al., 1987; Immel et al., 1997; Richmond et al., 2003; McHarg et al., 2005; Liu et al., 2012a]. McHarg et al. [2005] investigated the high-latitude Joule heating response to different IMF conditions based on the NH Joule heating pattern derived from data assimilation and concluded that hemispheric-integrated Joule heating increases with the IMF magnitude during southward IMF conditions, and the IMF B_y effect on the Joule heating pattern is unremarkable. Immel et al. [1997] investigated the IMF B_y effects on the far-ultraviolet dayglow observed by the Dynamics Explorer-1 imaging photometer and demonstrated that there was a dependence of the 6300 Å (O I) dayglow brightness on the sign of B_y . IMF dependence of the high-latitude ionosphere has also been examined with theoretical models [e.g., Roble et al., 1988; Crowley et al., 2006]. Roble et al. [1988] ran the National Center for Atmospheric Research (NCAR) Thermospheric General

Circulation Model (TGCM) for positive IMF By conditions and compared the results with the Dynamics Explorer-2 neutral wind data, revealing a By dependent mechanism that can transport the neutrals from the NH polar cap to middle latitudes at favorable local times. Crowley et al. [2006] studied IMF By effects on polar thermospheric neutral density and composition using NCAR Thermosphere Ionosphere Mesosphere Electrodynamics General Circulation Model (TIMEGCM) results. They showed that there is a clockwise rotation of the convection potential pattern, neutral wind, density, and composition as IMF By changes from negative to positive.

The offset between the geomagnetic and geographic latitudes might give rise to a systematic UT/longitude dependence of high latitude ionospheric and thermospheric phenomena during both geomagnetically quiet and disturbed conditions [Gasda and Richmond, 1998; Sojka et al., 1994, 2012; Xu et al., 2013]. de la Beaujardiere et al. [1985] studied the nighttime F-region density enhancements measured by EISCAT, Chatanika and Millstone Hill Incoherent Scatter Radar (ISR) observations during solar maximum. They showed that those density enhancements exhibited pronounced UT effects, which can be explained by the offset between the geographic and geomagnetic poles. Sojka et al. [2012] performed a numerical simulation of the longitudinal dependence of storm-time mid-latitude dayside Total Electron Content (TEC) enhancements using the Utah State University Time Dependent Ionospheric Model (TDIM) and found that this enhancement favors the American sector. Xu et al. [2013] revealed strong longitude variations under geomagnetic quiet conditions in the daily mean neutral density measured by CHAMP and GRACE satellites during the years 2003-2008 and attributed these longitudinal structures to heating of magnetospheric origin.

There are persistent electron density enhancements at high latitudes, individually referred to as a Tongue of Ionization (TOI) or polar cap patch. A TOI is a high latitude, large-scale (~1000 km) phenomenon that occurs regularly. It is a “tongue”-like high electron density structure that is elongated in the noon-midnight direction. A polar cap patch is a small-scale or medium-scale discrete high plasma density (at least double the background density) structure with a spatial scale of 100-1000 km [Carlson, 2012]. Liu et al. [2015] compared TOI occurrence at different UTs in the 14 October 2012 geomagnetic storm and postulated that the occurrence of TOIs depends on UT when geomagnetic activity was moderate. Sojka et al. [1994] studied the UT dependence of polar cap patches in the NH polar ionosphere by changing the IMF By direction using the TDIM. Their model revealed that patch intensities are stronger between 2000-2400 UT and absent between 0800-1200 UT in the winter solstice. Since both IMF and UT regulate high-latitude plasma flow, neutral wind, neutral composition and density, it is anticipated that the TOI depends on the equatorward expansion of polar ion convection and that poleward plasma transport may also have a strong association with TOIs. Several questions arise naturally here: what are the UT and IMF dependencies of TOIs? Is the UT dependence of TOI simply a consequence of the UT variations of the geographic location of the magnetic pole and ion convection; that is, stronger/weaker TOIs occur when the magnetic pole and convection are tapped sunward/toward midnight? Most recently, David et al. [2016] statistically analyzed the seasonal and UT dependence of polar cap patches based on GPS TEC data during 2009-2015. It will be fruitful to make a thorough data-model comparison to give a complete picture of the IMF and UT dependence of TOIs. To date, no first-principles modeling has been performed to fully examine the IMF

and UT effects on TOIs as well as the association with polar cap patches. In this paper, we address this issue by deploying the state-of-the-art, high-resolution NCAR Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIEGCM) to study the occurrence and intensity of TOIs at different UTs under different IMF Bz and By conditions. The remainder of this article will be arranged as follows. Numerical experiment settings will be explained in the section 2. The UT, IMF, seasonal and solar activity dependence of TOIs will be introduced in the section 3, followed by the discussion and summary.

2. Numerical Experiment Settings

The NCAR TIEGCM is a time dependent, 3-dimensional, thermosphere-ionosphere coupled model solving the fully coupled, nonlinear, hydrodynamic, thermodynamic, and continuity equations of the neutral gas self-consistently with the ion energy, ion momentum, and ion continuity equations as well as the neutral wind dynamo [Roble et al., 1988; Richmond et al., 1992; Qian et al., 2014]. The model resolution is 2.5° in latitude and longitude and has 60 pressure surfaces in altitude ranging from 97 km to 500 km, with a vertical resolution of 1/4 scale height. This high-resolution version of the TIEGCM has a better capability to resolve high-latitude ionospheric structures and responses. For example, Wang et al. [1999] compared the high- and low-resolution model results from the Thermosphere-Ionosphere Nested Grid (TING) model, which is an extension of the thermosphere-ionosphere general circulation model (TIGCM), and revealed that the high-resolution model produces a well-defined polar cap TOI and coarse resolution model tends to smooth out the patches and TOI. The input parameters for the

TIEGCM are solar EUV and UV spectral fluxes, parameterized by the solar F10.7 cm index, and high latitude auroral particle precipitation and convection electric fields, which are specified by the Weimer model [Weimer, 2005]. The amplitudes and phases of tides from the lower atmosphere are specified by the global-scale wave model at the model's lower boundary [Hagan and Forbes, 2002]. In this paper, we present the results of numerical experiments for September equinox at solar medium conditions (F10.7=120). All model runs start from the initial state of IMF $B_z = 0$ and IMF $B_y = 0$ for 24 hours to reach a steady state. Then we change IMF B_z abruptly from 0 to -10 nT at different UTs to investigate the UT dependence of the high latitude ionosphere response to IMF changes. In order to reveal IMF effects on the high latitude ionosphere, we sort IMF B_y and B_z at the UT when the TOI is most prominent.

3. Results

3.1 Evolutions and UT Dependence of TOIs

Figure 1 shows the evolution of ionospheric F2 region peak density (NmF_2) for the NH in geographic latitude (above 40°) and local time (LT) coordinates. The superimposed electrostatic potential is from the Weimer model [Weimer, 2005]. As IMF B_z changes from 0 to -10 nT at 0000 UT, a pronounced two-cell plasma convection pattern expands toward lower latitudes. Two hours later at 0200 UT, positive storm effects (enhanced electron densities) appear at middle latitudes in the afternoon sector. The positive storm effects become stronger and expand to higher latitudes in the following 2 hours. At 0300 UT, a TOI appears between 70° and 80° geographic latitude at about 1300 LT along the plasma anti-sunward convection channel that runs from noon to midnight. This TOI

173 becomes stronger with UT until 0600 UT. Compared with NmF2 at 2300 UT, the high-
174 latitude low electron density region (the blue colored region, negative storm effect) starts
175 to expand towards the early morning sector and afternoon sector after IMF B_z turning
176 southward at 0000 UT. For instance, the red-blue separatrix at 2300 UT locates at round
177 0600 LT, whereas it moves gradually to about 1000 LT at 0700 UT. The last panel of
178 Figure 1 gives NmF2 at 0700 UT, when a strong negative storm effect occurs at high
179 latitudes, especially in the post-midnight to early morning sector and the TOI becomes
180 weaker than it was from 0300 UT to 0600 UT. In addition, the magnetic pole and ion
181 convection pattern rotate counterclockwise with respect to the geographic pole.

182 Figure 2 is for the SH in the similar format of Figure 1. Similar to the NH, both the
183 convection pattern and the magnetic pole rotate counterclockwise with UT with respect to
184 the geographic pole. The latitudinal distance between the magnetic and geographic poles
185 is larger in the SH than that in the NH, which makes the UT effect on polar ion
186 convection larger in the SH. The SH convection pattern is more displaced towards the
187 daytime ionization between 2300 and 0700 UT in Figure 2. The middle latitude positive
188 storm effects in the noon-2000 LT sector occur at 0200 UT, which is earlier than they
189 were in the NH case. A TOI occurs at 0200 UT and becomes stronger at 0400 UT. TOIs
190 only appear in limited regions and do not extend into the nighttime. As shown in Figures
191 1 and 2, the TOI signatures are stronger 4 hours after the southward IMF B_z turning.

192 Figure 3 shows the UT dependence of NmF2 for the NH in geographic latitude (the
193 outer circle is 40 degrees) and local time coordinates after imposing IMF $B_z = -10$ nT for
194 4 hours for a number of different starting times. Universal Times listed above each panel
195 are the simulation starting time plus 4 hours. There is a clear UT dependence of the

middle latitude high electron density “reservoir”. In addition, relative locations between the two-cell plasma convection and the geographic pole also change with UT. For example, the positive storm effects in the noon-2000 LT sector are stronger and wider in LT at 2000 UT than at earlier or later UT hours. The dayside convection throat is located in the morning sector during 0400-1200 UT, whereas it is located at the afternoon sector, closer to the afternoon positive storm effect region during 1600-2400 UT. Furthermore, the high-latitude plasma convection pattern in the throat region moves to about 58° geographic latitude at 2000 UT, but it locates at 70° geographic latitude at 0400 UT. Because of the favorable relative location between the high electron density reservoir at middle latitudes caused by the positive storm effects in the afternoon sector and the dusk convection cell and the throat region, the TOI is stronger at around 2000 UT, and weakest at around 0800 UT. The UT variation of the positive storm effects is another interesting phenomenon and will be studied in a separate publication.

Figure 4 is the same as Figure 3 but for the SH. SH TOIs are generally stronger than NH TOIs (see Figure 3 for the NH). In the SH, the two-cell convection throat is located in the afternoon sector between 0400-1600 UT and in the morning sector between 2000-2400 UT. In addition, the high electron density region stretches further across the polar cap towards the nightside at 1600 UT, as compared to other UTs. As a result of the overlap between the two-cell convection pattern and the middle-latitude high plasma density reservoir, the TOI intensity is strongest at about 1600 UT, and weakest in the early morning and near midnight UT hours.

3.2 Season dependence of UT effects

In order to investigate the seasonal dependence of UT effects on TOI, Figure 5 shows seasonal variations of NH NmF2 as a function of geographic latitude and local time at different UTs. At equinox, TOIs have similar structures and intensities. TOIs, having similar shapes, are much weaker in summer than they are in other seasons. TOI is hardly discerned during 0400-1600 UT in summer, which has almost the same local time dependence but different seasonal dependence with respect to the polar cap patch as revealed by Sojka et al. [1994] and David et al., [2016]. They showed that polar cap patches are weakest or disappear during 0600-1300 UT in winter. We will interpret this discrepancy in the discussion part. To avoid repetition, we do not show the SH, in which TOIs have similar seasonal dependence.

3.3 IMF Dependence of TOI

Figure 6 illustrates the IMF B_y effects on TOIs in the two hemispheres for southward IMF B_z conditions. We set IMF $B_z = -10$, $B_y = \pm 10$, and examined the model results after running the simulation for 4 hours. The top and bottom panels are for the NH at 2000 UT and SH at 1600 UT, respectively. The reason for choosing these two UTs is that the TOIs are more prominent at those UTs. As can be seen from this figure, the dusk plasma convection cell is larger relative to the dawn counterpart in the NH, and the throat region locates at an earlier local time when B_y is positive (upper right panel), compared to the convection pattern for the B_y negative case (upper middle panel). Thus, the TOI is stronger and pushed more toward the duskside and middle latitudes when B_y is negative. For positive B_y , the TOI is weaker in the NH because the convection convergence region is further away from the afternoon electron density peak, so it is more difficult to

transport the plasma from the afternoon sector into the throat region. The opposite conditions apply for the SH. The dawn cell is much better defined, and the TOI moves closer to the pre-midnight sector for positive B_y , compared with what it does for the negative B_y . One common feature in both hemispheres is that TOI intensity tends to be weaker when IMF B_y has a magnitude that is close to that of B_z in our simulations. The reason for this is that IMF B_y tends to twist the two-cell convection pattern making it more difficult to advect the plasma into and across the polar cap. Further studies are needed to fully evaluate the effect of relative strength between B_y and B_z on the occurrence, location, and intensity of TOIs.

Figure 7 depicts the IMF B_z effects on the TOI in the two hemispheres. We set IMF $B_z = -10, -5$ and 10 nT with a constant IMF B_y (IMF $B_y = 0$). The middle latitude ionospheric NmF_2 was less increased, the two-cell convection pattern is more confined to high latitudes, and the TOI is weaker when IMF B_z has a smaller southward component. The convection is much weaker and more distorted during northward IMF conditions than during southward conditions. For northward IMF B_z , the convection exhibits a more complex structure and has multi-cells. No obvious TOI can be observed under northward IMF conditions. In the SH, the electron density is smoothly distributed. For both hemispheres, the convection patterns are confined to higher latitudes and away from the middle latitude source region for northward IMF B_z conditions. At the same time, there are no or small positive storm effects to build up the source. Therefore, the TOI is thus non-exist or very weak.

Figure 8 shows the solar activity dependence of the TOI for southward IMF B_z at 2000 UT at September equinox. NmF_2 is overall larger at higher solar activity. Generally, TOIs

are weaker and become wider at low solar activity ($F_{10.7} = 70$) than they are at the higher solar activity ($F_{10.7}=180$). This agrees with the study of David et al. [2016], in which they show tongue-to-background ratio is much lower at solar minimum. In the NH, TOI disappears at the lowest solar activity ($F_{10.7}=70$). In the SH, TOIs are similar in shape for different solar activities.

4. Discussion

4.1 UT and IMF Dependence of TOI Intensity

The expanded two-cell ion convection pattern under southward B_z conditions transports the plasma from mid-latitudes into the high latitudes to form the TOI structure.

There are three main factors contributing to the UT dependence of TOIs, including:

(1) The UT variations of the magnetosphere reconnection between the solar wind magnetic field and the geomagnetic field at the magnetopause due to the UT variation of the geomagnetic tilt angle. This affects the cross polar cap potential, $\mathbf{E} \times \mathbf{B}$ plasma drifts and the dynamics of the TOI [Weimer, 1996, Deng et al., 2006]. Taking the SH as an example in Figure 9, the positive and negative potential cells rotates around the geographic pole with UT, and shifts more toward middle latitudes near noon at 0400 UT and at midnight at 1600 UT. The $\mathbf{E} \times \mathbf{B}$ upward ion drift peaks change with UT and vary from two peaks at 0000 UT to a single peak at 2000 UT.

(2) The UT variations of the middle latitude high plasma density reservoir. The latitudinal locations of maximum electron density and the magnitudes of the electron density enhancement change with UT (Figures 3 and 4). In the NH, maximum electron densities typically occur at around $40\text{-}50^\circ$ at different local times, whereas they can appear at a

larger latitude range from 40° to 60° in the SH. Liu et al. [2016b] showed that the enhanced plasma densities at subauroral middle latitudes around noon are mainly caused by the $\mathbf{E} \times \mathbf{B}$ upward ion drifts that lift the ionosphere to higher altitudes where chemical recombination is slower. Sojka et al. [2012] studied the longitudinal dependence of storm-time middle latitude electron density enhancement and ascribed this to longitudinal variations of both the neutral winds and the electric fields. The longitudinal dependence of neutral wind effects may either enhance or counteract the effect of the expanded high-latitude convection electric fields.

(3) The UT variations of the relative position between the twin-cell polar plasma convection, especially for the throat region, and the middle latitude plasma reservoir. This arises from the relation between the two principal coordinate systems of ionosphere-magnetosphere interaction: solar geomagnetic coordinates in which the ion convection pattern occurs and solar-terrestrial coordinates (geographic latitude/LT) in which solar heating produced plasma generally resides. These coordinate systems vary with respect to one another with UT, determining the amount of electron transport from mid-latitudes to high latitudes. It would be expected that the UT at which the noon portion of the auroral oval is at its lowest geographic latitude should correspond roughly to the time when the plasma drifting across the polar cap contains the largest electron densities. Currently, the south and north magnetic poles are located at about 64°S , 140°E and 81°N , 110°W in geographic coordinates, respectively, which corresponds to ~ 0300 UT and 1900 UT at noon. However, the expected relationship between the UT when the auroral oval at local noon is at its lowest geographical latitude and the strength of the tongue does not occur in the SH. In this case, the TOI is stronger at 1600 UT when the mid-latitude positive storm

effects are stronger and at higher latitudes than they are at 0400 UT when the above-mentioned condition is met. Thus, in the SH, the ion convection throat region is most efficient at tapping plasma into the polar cap to form a TOI in the presence of an intense plasma reservoir at a relatively higher geographic latitude even though the magnetic pole and almost the entire polar convection pattern are located on the nightside. On the other hand, the NH does behave as expected. That is, the TOI is stronger at 2000 UT when the convection pattern is closer to the high electron density region. To some extent, the IMF B_y and UT effects on TOIs operate in a similar way by modifying the relative location between the two-cell convection configuration, including the convection throat region, and the middle latitude high plasma density reservoir. In the NH, as shown in Figure 5, it is interesting to note that, for negative B_y , the dawn cell ion convection velocities become faster than for zero IMF B_y condition. When IMF B_y is positive, the dusk cell is larger relative to its dawn counterpart than it is when B_y is negative. This change in IMF B_y direction also shifts the dayside plasma convection entry point to an earlier local time. The plasma density is larger at around 1400 LT, which is closer to the entry local time for negative IMF B_y than that for positive IMF B_y , which facilitates the poleward plasma transport. Thus, the NH TOI is stronger during negative IMF B_y than that during the positive IMF B_y conditions. Another process may also contribute to a weaker TOI for the positive B_y case. The negative storm effects (decreased electron densities) caused by neutral composition changes typically commence in the post midnight and early morning sector at high latitudes [Prolss, 1995; Liu et al., 2010]. These negative storm effects tend to destroy or weaken the TOI.

4.2 Seasonal Dependence of UT Effects on TOI Intensity

Our NH results showed that TOIs are weaker or almost disappear in summer, which is in general agreement with Sojka et al. [1994] and David et al. [2016]. Sojka et al. [1994] used the convection pattern of Heppner and Maynard [1987] as a driver to TDIM to investigate the UT and seasonal dependence of TOI and patches under moderate geomagnetic disturbed conditions ($K_p = 3.5$) at solar maximum ($F_{10.7} = 210$). They showed that summer hemisphere TOIs/patches disappear during the 0600-1300 UT and patches have the largest intensity in winter between 2000-2400 UT. Based on GPS TEC maps of the Northern Hemisphere from the years 2009 to 2015, David et al. [2016] concluded that TOIs or patches were absent for winter days from about 0500-1200 UT. It should be cautioned to make a direct comparison between our results and previous two results that are drawn from samples at a fixed local time (~ 23 LT) and close to magnetic pole. The common features are that TOIs/patches are strongest at around 2000 UT in winter hemisphere. This could be related to the stronger plasma source in winter. It would be expected that daytime mid-high latitude electron density is larger in summer than winter given the fact that dayside ionosphere electron content has a strong dependence on solar zenith angle. However, middle latitude winter anomaly is a phenomenon in which F2 region electron density is larger in the winter hemisphere than that in the summer hemisphere [e.g., Rishbeth and Garriott, 1969; Burns et al., 2014]. This winter anomaly brings about larger electron density in the winter hemisphere allowing more plasma transport from the middle latitude ionosphere source region into the polar cap to form TOI or patch. Our current results were drawn from the geomagnetic storm condition (constant IMF $B_z = -10$ nT). As shown in Figures 1 and 2, positive storm effects are

gradually built up at middle latitudes, which have a strong seasonal dependence. Positive storm effects on the dayside are more likely to occur in the winter than in the summer, which can be viewed as an exaggeration of geomagnetic quiet time winter anomaly. The daytime O/N_2 at high latitudes suffers more reduction in the summer hemisphere than in the winter hemisphere as a consequence of a larger joule heating [Liu et al., 2012]. Zonal-mean summer-to-winter transequatorial winds facilitate the neutral composition equatorial propagation in summer and hinder it in winter. In addition, the neutral winds tend to converge at middle latitudes in the winter hemisphere, resulting in an increase in O/N_2 and thus increase electron density there. The storm-time higher middle latitude daytime electron density in the winter hemisphere is favorable for generating TOI.

4.3 Hemispheric Asymmetry of TOI Intensity

The hemispheric asymmetry of TOI intensity is probably caused by the difference of the location of the magnetic poles relative to the geographic ones in the northern and southern hemispheres. The northern magnetic pole is closer to the northern geographic pole than the southern magnetic pole is to the southern geographic pole. The geographic latitude of the southern magnetic pole is near 64°S , whereas the northern magnetic pole is at about 81°N geographic latitude. Because the southern magnetic pole is located more toward geographic midlatitudes, the auroral region in the SH can have relatively smaller solar zenith angles than the auroral region in the NH in the daytime (and conversely has larger solar zenith angles 12 hours later). Thus, when the solar zenith angle is small, ionospheric plasma densities caused by solar ionization are larger in the auroral region of the SH. This solar zenith angle dependence of electron densities in the auroral region is

complicated by the longitudinal dependence of electric field induced upward plasma drifts as mentioned earlier (Section 4.1). The magnetic field intensity in the SH is generally weaker than that in the NH, which could produce larger vertical ion drift velocities ($\mathbf{V}=(\mathbf{E}\times\mathbf{B})/B^2$) and electron density enhancements, as suggested by Heelis et al. [2009]. For instance, in the South Atlantic Magnetic Anomaly region, because of the weak magnetic field intensity, the maximum NmF2 values are larger in the SH in Figures 4 and 6-7. These two factors (relative smaller zenith angles and larger upward drifts) increase plasma contents for the plasma source region for TOI. Therefore, the extended polar convection in the Southern Hemisphere, which is located more toward middle latitudes, is efficient at bringing the plasma from the mid to the high latitudes.

5. Conclusions

Based on the TIEGCM simulations of occurrence and intensity of TOIs and patches under different IMF and UT conditions, the main results are the following: (1) TOI intensity shows a clear UT dependence and is more prominent during 1600-2000 UT in the NH and 1200-1600 UT in the SH; (2) The UT and IMF orientation dependence of the TOI is different between the Northern and Southern hemispheres because of the different separations of the magnetic poles from the geographic poles in the two hemispheres and the different locations of the plasma source region for TOI; (3) IMF By modifies the plasma convection and TOI pattern in a way that positive/negative IMF By tends to shift the throat region toward the dawn/dusk side in the NH. The opposite condition holds in the SH; generally speaking, larger IMF By magnitude tends to decrease the TOI intensity;

(4) the middle latitude high-density region occurs at higher geographic latitudes in the SH than in the NH. The TOI is more salient in the SH than in the NH.

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Figures

Figure 1. A polar view of the N_mF_2 evolution in geographic coordinates in the Northern

Hemisphere. Superimposed is the electrostatic potential. The outer circle is 40° in geographic latitude.

Figure 2. Same as Figure 1, but for the Southern Hemisphere.

Figure 3. UT Dependence of TOIs for the Northern Hemisphere after 4 hours of constant southward IMF Bz (- 10 nT) conditions.

Figure 4. Same as Figure 3, but for the Southern Hemisphere.

Figure 5. Seasonal dependence of UT effects on the TOI in the NH. IMF $B_z = -10$ nT and $B_y = 0$ nT are used for this seasonal analysis.

Figure 6. IMF B_y dependency of TOIs for southward IMF B_z . The top panels are for the Northern Hemisphere at 2000 UT and the bottom panels are for the Southern Hemisphere at 1600 UT.

Figure 7. IMF Bz dependency of TOIs at 2000 UT. The top panels are for the Northern Hemisphere and the bottom panels are for the Southern Hemisphere.

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596 Figure 8. Solar activity dependence of TOI for Southward IMF Bz at 2000 UT.

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Figure 9. UT dependence of polar cap potential (contour line) and upward $\mathbf{E} \times \mathbf{B}$ drifts (contour color) in the Southern Hemisphere at pressure level 3.125 (~300 km). Cross polar cap potential drop are labeled in the title.