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Polar cap patches and the tongue of ionization: A survey of GPS TEC maps from 2009 to 2015

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Key Points:

- GPS TEC maps of the Northern Hemisphere from the years 2009 to 2015 have been studied to see when TOIs or plasma patches are present
- The TOI and plasma patches are seen to have a dependency on UT and season, which is consistent with that predicted by Sojka et al. (1994)
- The observed UT/seasonal dependency of plasma patches allows us to rule out patch source mechanisms that do not have such a time dependence

Supporting Information:

- Supporting Information S1

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Abstract The source and structuring mechanisms for *F* region density patches have been subjects of speculation and debate for many years. We have made a survey of mappings of total electron content (TEC) between the years 2009 and 2015 from the web-based Madrigal data server in order to determine when patches and/or a tongue of ionization (TOI) have been present in the Northern Hemisphere polar cap; we find that there is a UT and seasonal dependence that follows a specific pattern. This finding sheds considerable light upon the old question of the source of polar cap patches, since it virtually eliminates potential patch plasma sources that do not have a UT/seasonal dependence, for example, particle precipitation or flux transfer events. We also find that the frequency of occurrence of patches or TOIs has little to do with the level of geomagnetic activity.

1. Introduction

What is the source of the plasma in polar cap *F* region ionization patches? What is the mechanism by which the patches are structured? These are important and challenging questions, whose answers will provide guidance to the space weather community concerned with radio communications at high latitudes.

A key observation from the earlier times of patch study was the finding by *Buchau et al*. [1985] that patches, as seen at the polar cap location of Thule, Greenland, have a dependence on universal time (UT). A strong dependency on solar cycle was also noted.

During the 1990s the ionospheric research community held three workshops (1992, 1994, and 1996) to address the questions of the source and structuring of patches. The workshops were sponsored by the High Latitude Plasma Structures group of the Coupling Energetics and Dynamics of Atmospheric Structures program, funded by the National Science Foundation, and by the international Solar-Terrestrial Energy Program Global Aspects of Plasma Structures group. In these workshops, a variety of mechanisms were proposed as answers to the two questions posed above. Three special sections of *Radio Science* carried 35 papers, of which 18 focused on the polar cap patch phenomenon, without arriving at a definitive answer. Over the intervening years additional studies have refined the proposed mechanisms and provided improved observational capabilities, while still leaving the questions open to debate.

Historically, polar cap plasma density structures were identified through ionosonde observations; *Sato* [1959] proposed that the source of the enhancements was solar-illuminated plasma drifting into the polar cap. The work we describe in our present article gives very strong support to Sato's hypothesis; indeed, it leads us to speak of "patches" and the tongue of ionization (TOI) as being practically the same thing. (Note well that we are speaking of *F* region total electron content (TEC) patches; optical or airglow patches may be a completely separate phenomenon; it is possible that a region of the ionosphere may glow, for example at 6300 Å, without the electron density being any greater than that of its surrounding area. Also, soft precipitation in the cusp may produce slight enhancements in the *F* region which are not substantial enough to be observable in TEC; see *Carlson* [2012]. Observations by *Weber et al*. [1984] and *Foster and Doupnik* [1984] confirmed that solar-illuminated plasma may indeed drift into the cusp region, leading to the transport of enhanced plasma across the polar cap.

Another proposed source for the patch plasma was auroral precipitation in the cusp [*Knudsen*, 1974; *Tsunoda*, 1988; *Rodger et al*., 1994]. A third proposed source [*Valladares et al*., 1994] was an enhanced cusp electric field. *Weber et al*. [1984] argued that patches were not produced by local precipitation in the polar cap. *Crowley* [1996] provided a comprehensive review of the research literature on polar cap patches. *MacDougall and Jayachandran* [2007] have proposed that the plasma source is low-energy auroral precipitation in the dawnside convection cell, as plasma is transported back to the cusp region.

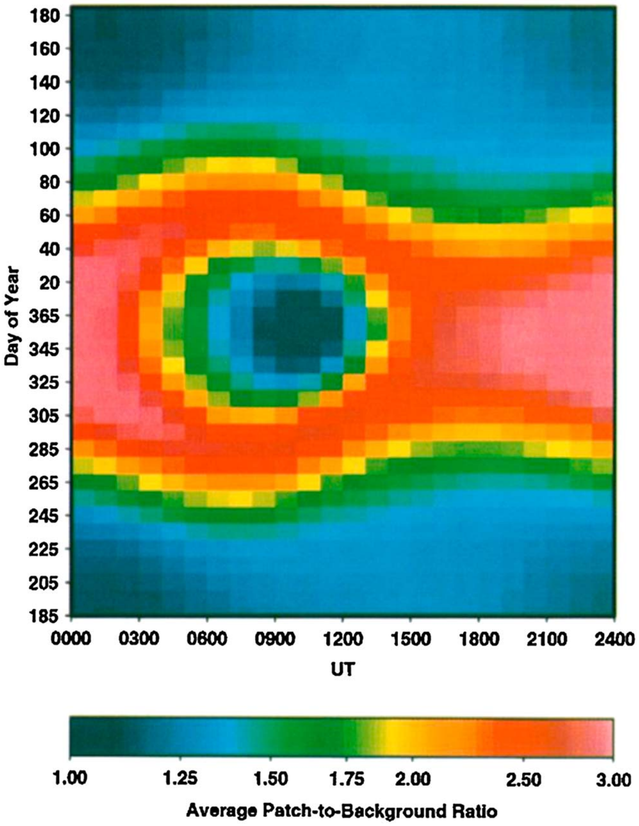


Figure 1. A reproduction of Plate 4 from *Sojka et al.* [1994], showing the model-based patch-to-background ratios as a function of day of year and universal time.

The mechanism for structuring existing plasma (such as the TOI) into discrete patches is also a source of ongoing debate. This article deals with the issue of the plasma source more or less independently of any structuring mechanism, and we will not list here the various mechanisms that have been proposed.

2. The 1994 Prediction of TOI and Patches

Sojka et al. [1994] carried out a modeling study of the UT and seasonal dependence of the formation of the tongue of ionization and its subsequent structuring into discrete patches. Using the Utah State University Time Dependent Ionospheric Model (TDIM) (see references in *Sojka et al.* [1994]), with the convection patterns of *Heppner and Maynard* [1987] as drivers, the formation of a TOI was simulated as dayside plasma is "caught" by the convection electric field and transported antisunward through the cusp and into the polar cap. This process exhibits a strong UT and seasonal dependency, owing to the fact that at certain times the solar terminator is too far equatorward for the magnetospheric electric field to be able to "catch" the dayside plasma, and at other times the entire polar cap is solar-illuminated and there is no tongue or patch structure because the whole polar region is ionized. The patch structuring mechanism used in the 1994 study was to "chop" the TOI by switching periodically between two of the Heppner and Maynard convection models corresponding to different orientations of the B_y component of the interplanetary magnetic field (IMF). (Both convection patterns corresponded to a southward orientation of the B_z component.)

Figure 1 is a reproduction of Plate 4 from *Sojka et al.* [1994], which presented a prediction, based on an extensive set of model runs, for the complete UT and seasonal dependency of the tongue of ionization and/or patches in the Northern Hemisphere. In order to generate the original figure, model runs were carried out at 1 h UT intervals at a 10 day spacing throughout an entire year; the run conditions were solar maximum and moderate geomagnetic activity. For each model run, a patch-to-background ratio (which could equally well have been called a tongue-to-background ratio) was computed and then plotted in the figure with a color representing the ratio; days/times colored red are highly favorable to the formation of TOIs and patches, while areas of blue are highly unfavorable to the formation of patches having dayside plasma as their source.

Salient features of the UT/seasonal dependency as depicted in Figure 1 include a "prime" condition for patch formation during the hours 1800–0300 UT in the winter months; an equinoctial band of patch availability during the hours of about 0400–1400 UT; an absence of patches in the summer; and most interestingly, a "hole" that is devoid of TOIs or patches during the dead of winter between the hours of about 0600 and 1300 UT.

At the time of writing the original paper (1994), there was little opportunity for testing the prediction by comparison with data, as such observations were rather scarce. *Coley and Heelis* [1998] carried out an analysis of patch occurrence as observed by the NASA DE 2 satellites and found a UT and seasonal dependency that was consistent with the *Sojka et al.* [1994] prediction. In a follow-up study to the 1994 paper, *Bowline et al.* [1996]

demonstrated that limited polar cap observation, such as would be available from a small number of ground-based stations, can yield only a portion of the UT/seasonal morphology, making a strong case that observational coverage of the entire polar cap region is needed for testing the prediction. In an interesting study, *Dandekar and Bullett* [1999] examined observations from ground-based locations in Greenland and found a seasonal dependence of patch occurrence consistent with that given by *Sojka et al.* [1994]; however, since their database lacked a longitudinal distribution, there was no opportunity for detecting a UT dependency.

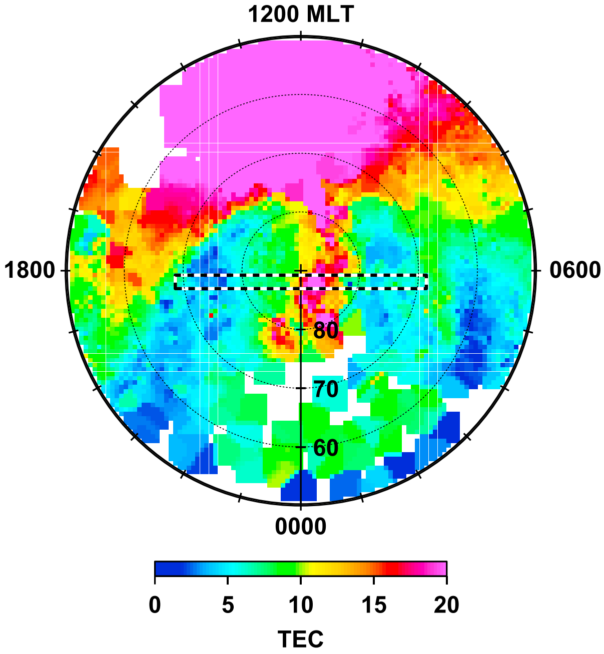


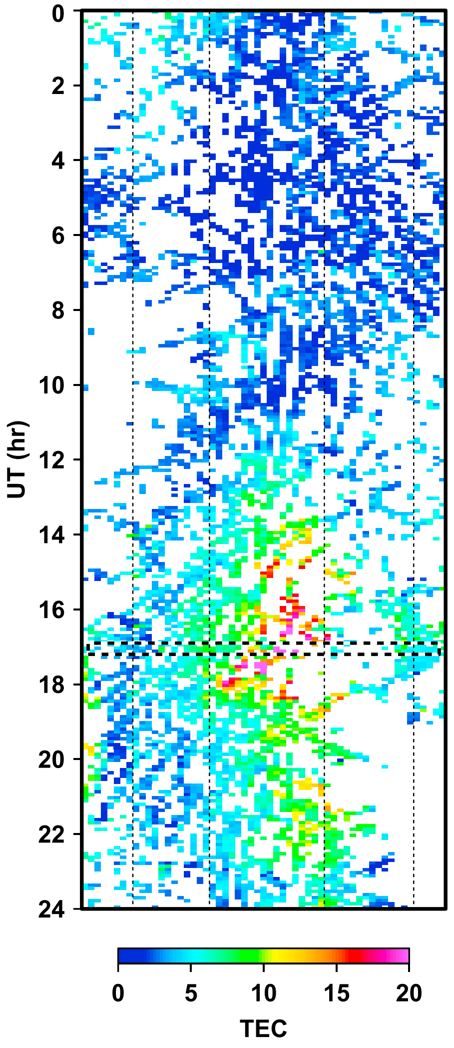
Figure 2. A GPS TEC map from the Madrigal database for 5 November 2012 near 1700 UT, plotted in coordinates of magnetic latitude and magnetic local time. A tongue of ionization (TOI) is plainly visible. The dotted line rectangle is discussed in section 4.

3. Polar Cap GPS TEC Maps

Data for total electron content (TEC) obtained from ground-based GPS receivers have been collected, calibrated, quality controlled, and archived by scientists at the MIT Haystack Observatory and made available online through the Madrigal webserver in the form of global TEC maps at a 5 minute cadence. While data are available from the year 2000 onward, we found polar cap coverage dense enough to be useful in the present context in the Northern Hemisphere TEC maps from the year 2009 onward.

The MIT Automated Processing of GPS (MAPGPS) software suite [*Rideout and Coster*, 2006] is used to calculate estimates of the total electron content (TEC) from the network of worldwide GPS receivers. Currently, Haystack processes over 5000 GPS receivers a day; for most of the time period prior to 2015, TEC processing was based on data from 2000–3000 receivers. TEC estimates are output in single-degree bins of latitude and longitude every 5 min where data are available and are stored in Haystack's Madrigal database. Madrigal is an open source distributed database system providing web-based data storage, retrieval, search, and visualization freely available to the space science community. Recently, the MAPGPS processing code was significantly enhanced to improve the handling of errors (W. Rideout and A. Coster, personal communication, 2015). GPS TEC data from 2001 to 2016 have been processed using the updated version of MAPGPS, and all of these data are available online within Madrigal. In 2015, Haystack's GPS TEC processing was enhanced and the method used now is described in *Vierinen et al.* [2015].

In the present study, the global TEC mappings supplied by Madrigal are recast into magnetic polar coordinates (Northern Hemisphere only); Figure 2 shows an example. (The purpose of the dotted rectangular outline in the center is discussed in the next section.) This is a GPS TEC map near 1700 UT on 5 November 2012, which was a day of very low geomagnetic activity, the average *Kp* being 0.6; the IMF B_z component was consistently southward during the latter half of the day, varying between about −2 and −5 nT. To improve the appearance of the figure, we have used a simple algorithm for interpolating and filling in small areas that are without GPS TEC data points; Figure S1 of the supporting information shows what Figure 2 looks like with no interpolations or filling in. Features evident in this dial plot include the high-density solar-illuminated plasma on the sunward side (toward the top of the dial), lower TEC values on the nightside, a midlatitude trough beginning at 60° magnetic latitude at 2000 MLT and extending round the night sector to 0600 MLT, and last but not least, a beautiful TOI structure extending in an antisunward direction across the polar cap.



T	B	R
2.6	3.9	0.66
2.1	3.1	0.69
2.1	2.7	0.78
1.7	2.0	0.87
1.4	1.8	0.78
1.5	1.7	0.87
1.5	2.2	0.70
2.8	2.6	1.04
3.0	2.8	1.08
2.8	3.0	0.96
2.5	3.3	0.76
3.7	2.9	1.27
5.2	3.3	1.57
6.9	3.9	1.75
8.1	5.0	1.63
8.6	5.7	1.52
11.0	5.9	1.86
11.7	5.6	2.11
9.1	5.6	1.64
7.1	4.8	1.48
6.8	4.1	1.65
6.7	5.3	1.27
6.5	5.0	1.29
4.8	4.7	1.01

Figure 3. From the Madrigal GPS TEC maps for the entire day of 5 November 2012, the tongue-to-background calculation strips such as the dotted line rectangle in Figure 2 are extracted and displayed in a single plot, as discussed in detail in section 4. Dotted vertical lines indicate the locations of the "tongue" or "patch" segment (center), and the two "background" segments used in the TBR calculations. Tongue (or patch), background, and ratio values are printed on the right hand side of the figure.

4. Identification of Polar Cap Patches and TOI

While the tongue of ionization in the dial plot of Figure 2 is readily apparent to the eye, it is necessary to have the capability for an automated search by computer through many thousands of such dials. The goal is to determine exactly when there was, and was not, a TOI (or patches) in the Northern Hemisphere polar cap throughout all days and times for the years from 2009 to 2015 and, having collected this information, to display it in the same format as in *Sojka et al.* [1994] (Figure 1 of this article). No selection based on the IMF or geomagnetic activity is made; all solar cycle conditions, IMF orientations, and activity levels are included together, and only the UT/seasonal dependency is considered. The fact that we must work with TEC, while the 1994 study was based on the *F* region peak density NmF2, is not a problem; NmF2 and TEC tend to be closely related to one another (see, for instance, *Davies* [1990]).

We now describe the procedure we developed in order to enable a computer-automated search for TOIs and/or patches throughout several years' worth of TEC maps. In Figure 2, a dotted line rectangle is drawn in the center, just below the magnetic pole. It is within this strip that the search for TOIs or patches takes place. As part of our testing of the robustness of the method, we moved the location of the strip up and down through several degrees of latitude, without a significant change in the results. The GPS TEC maps are available at 5 min intervals; therefore, there are 288 maps per day. The center strips from these 288 dials can be collected and put together in one plot; an example is given in Figure 3, again for 5 November 2012. This figure, unlike Figure 2, shows only the uninterpolated GPS TEC data without any filling in of empty areas; all of our tongue-to-background ratio figures (Figure 4 here, as well as those in the supporting information) are calculated from such uninterpolated data sets. The one strip that was shown in Figure 2, for 1700 UT, is also shown in this figure, and each line of pixels going across is another such strip for a different universal time. Vertical dotted lines show the locations of the "tongue" segment and the two "background" segments. In Figure 3, we can see that the TOI structure in Figure 2 began to appear at about 1400 UT, remains strongly present until about 1800 UT, and continues to persist weakly until about 2300 UT. For many hours the structure is stable and well defined.

Within each of the 288 strips that constitute one day's worth of TEC maps, we need to identify both a background density level and a tongue (or patch) density level. With 288 strips per day, and 365 days per year, it is clearly desirable that the process be automated. A considerable amount of this work was initially done "by hand," in

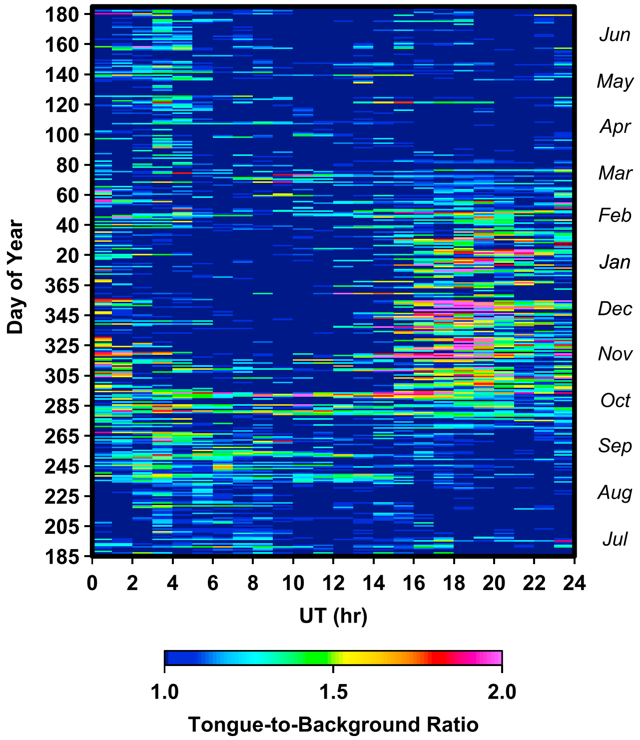


Figure 4. Based on the Madrigal GPS TEC maps for the year 2013, the tongue- (or patch-) to-background ratio (TBR) is plotted as a function of day of year and universal time. The method by which the TBR values are calculated is explained in section 4.

order to learn what procedure might work best, and when a procedure was finally settled on, its robustness was tested by varying the parameters of the method to ensure that significant changes in the results did not occur. In the supporting information we have included several examples in which the parameters have been varied by a considerable amount, showing that the end result is substantially the same; see, in particular, Figures S3 and S4. The method is relatively simple. We hope in the future to introduce a more sophisticated scheme, perhaps based on information about the convection electric field via the Super Dual Auroral Radar Network (SuperDARN) convection patterns [*Ruohoniemi and Baker*, 1998].

Each strip is divided into three segments of roughly similar length, each being about 1200 km. The center segment is considered to represent the tongue (or patch), and the left and right segments represent the background. TEC averages are computed within each segment, we take the ratio of the TEC average in the center segment to the average of the two background segments, and we call that our “tongue-to-background ratio” or TBR. This is repeated for each of the 288 strips for the day and for all days of the year. The method differs somewhat from the patch-to-background computation used by *Sojka et al.* [1994], but in that case, since it was based on model runs, the patch locations were known in advance.

5. UT and Seasonal Dependence of the Tongue-to-Background Ratio

Using the procedure outlined in the previous section, we computed the tongue-to-background ratio at 1 h intervals for every day of each of the years from 2009 to 2015. In all seven years the results are very similar, though there is an overall scaling correlated with solar cycle. The years 2009 and 2010 could be said to be solar-minimum years, and the TBR is significantly lower during these years. In this brief article, we will look in detail at only one year; we will use 2013 as our representative year. However, tongue-to-background ratio figures for the other years from 2009–2015 are included in the supporting information; see Figure S2.

Figure 4 shows the TBR for 2013 drawn up in the same format as the prediction by *Sojka et al.* [1994] (Figure 1). The most notable feature of the 1994 figure is the “hole”, or absence of patches, in the winter during the UT range of about 0500–1200. This hole is also evident (and in fact is somewhat larger) in the TBR plot based on the Madrigal GPS TEC maps for 2013; it is also present in the TBR figures for the other years from 2009 to 2015. Another feature that is seen in both the 1994 figure and in Figure 4 is that for the same range of winter days that constitute the hole; at other UTs these same days constitute the prime time for patch or TOI formation. Since Figure 1 was based on model runs, it has a much “cleaner” look, but its basic structure is clearly reproduced in Figure 4. There is one interesting difference which is not readily explainable at this time; Figure 1 indicates intense patch presence during winter days from 1800 to 0300 UT, while in Figure 4 (as well as the other years not shown here) the patch presence trails off after 2200 or 2300 UT and is almost nonexistent during the hours 0000 to 0300. An explanation of this discrepancy

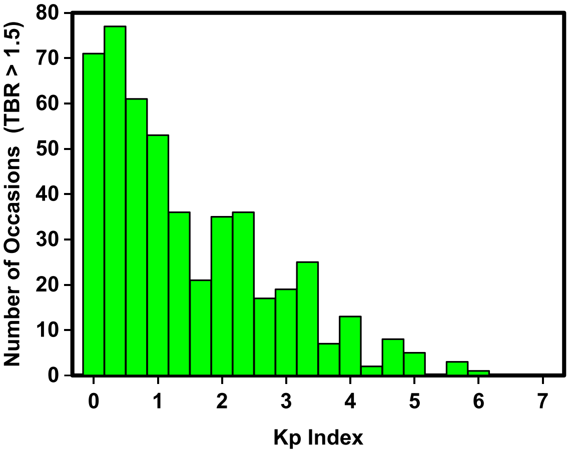


Figure 5. Based on the tongue-to-background ratios for the year 2013 as displayed in Figure 4, a histogram showing the number of occurrences in which the TBR is at least 1.5, plotted against the level of geomagnetic activity as represented by the *Kp* index. Here an "occurrence" is one "cell" from Figure 4, that is, a 1 h period during which the average TBR is as high as 1.5.

will have to await further study; a revisiting of the 1994 modeling study is planned, with the latest version of the TDIM model driven by updated convection electric field models; perhaps some light will be shed on this issue.

It may be noticed that there is a difference in the overall absolute values of the ratios in Figures 1 and 4, with that of the 1994 study reaching and occasionally exceeding a value of 3.0, while the TBR shown in Figure 4 reaches only 2.0. This is accounted for by recalling that when the ratios were computed in the 1994 study, it was known in advance exactly where the patches would be (since it was all based on model runs), and therefore the patch and background values were quite pure, thereby optimizing the ratio; see the original 1994 paper for a detailed explanation of the method that was employed in that case.

6. Discussion and Summary

The tongue-to-background ratios (TBR) extracted from the Madrigal TEC maps for the years 2009–2015 show a good morphological agreement with the prediction made by *Sojka et al*. [1994], which was based on model runs. The most salient feature seen in the TBR figures, as well as the 1994 study, is the "hole" for winter days between about 0500 and 1200 UT; during this time patches and/or TOIs are absent. The great importance of this fact lies in what it can tell us about the much disputed issue of the source for plasma patches: *any source mechanism that does not have this UT/seasonal dependency may be ruled out*. This hole represents the time when a tongue of ionization cannot form because the solar terminator is too far away from the pole for the convection electric field to catch the dayside plasma and bring it into the polar cap. Thus, this would be precisely the time when, if patches were seen, it would be known that these were patches not having dayside plasma as their source. However, with this hole occurring year after year, we see that when the TOI disappears, patches also disappear. For this reason, mechanisms relying on particle precipitation, motion of the cusp, electric field variations, or flux transfer events do not appear to be candidates as major sources for plasma patches (except perhaps for patches of such low density that they are not observable in a height-integrated measurement like TEC, such as might be caused by soft precipitation in the cusp region).

The source mechanism that stands out as passing the test is the one originally proposed by *Sato* [1959], that the patches consist of high-density plasma from the solar-illuminated dayside which has been entrained by the magnetospheric electric field and transported into the polar cap. (This is the mechanism used in the modeling of *Sojka et al*. [1994].) This permits us to speak of the TOI and patches as being practically the same thing; patches are just a TOI that has been structured or "chopped" into discrete units. We reiterate here that these words apply to *F* region *density* patches; optical or airglow patches may represent a different phenomenon altogether.

A close look at Figure 4 reveals one cell in the very center of the wintertime hole having a high value (about 1.4) for the TBR; is this a patch that has formed at a time when a TOI cannot exist? In fact, this high ratio can be traced to an unusually low background density level being present at that time; see Figure S5 in the supporting information.

The mechanisms responsible for patch structuring are still open to question; an upcoming study of the Madrigal TEC maps based on a comparison of days when a smooth TOI is present, versus days with patchy structures, may shed light on this issue.

We close with a word about the tongue of ionization and geomagnetic activity. A review of the literature reveals a widespread belief in a correspondence between high levels of geomagnetic activity and the existence of a TOI (and therefore, according to our conclusions, also patches). For example, *Thomas et al.* [2013] state that a tongue of ionization is transported into the polar cap by “enhanced convection electric fields”; likewise, *Hosokawa et al.* [2010] state that “expansion of the high-latitude convection” is a necessary condition for the formation of a TOI. A notable exception is the above mentioned paper by *Dandekar and Bullett* [1999], who state in their conclusion section, “The polar cap patch occurrence does not seem to depend much on the magnetic activity measured in *Kp* units.” In fact, the idea that the TOI or patches must be associated with high activity is untenable in the light of the survey of Madrigal GPS TEC maps from 2009 to 2015. There are many examples like the one in Figure 2, of excellent TOI formations lasting for hours, on days when *Kp* never exceeds 1+ or 2−. Figure 5 shows a histogram of the number of occurrences in Figure 4 where the tongue-to-background ratio is 1.5 or higher, plotted according to the level of activity as represented by the *Kp* index. We see that there are many patch or TOI occurrences during periods of low activity. Whether there is a TOI and patch dependency on the polarity and/or magnitude of the IMF remains to be seen; this will be the topic of a future study.

Acknowledgments

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