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Key Points:

- Ionospheric data coverage in the Southern Hemisphere is now comprehensive enough to allow a multiyear survey of polar cap density patches
- The seasonal and diurnal distributions of patches in the SH are like those of the NH, but are shifted by 6 months and 12 hr
- Our results differ in very significant ways from what has been reported in several recent studies using other methodologies

Supporting Information:

- Supporting Information S1

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Hemispherical Shifted Symmetry in Polar Cap Patch Occurrence: A Survey of GPS TEC Maps From 2015–2018

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Abstract Much theoretical and observational work has been devoted to studying the occurrence of *F* region polar cap patches in the Northern Hemisphere; considerably less work has been applied to the Southern Hemisphere. In recent years, the Madrigal database of mappings of total electron content (TEC) has improved in Southern Hemisphere coverage, to the point that we can now carry out a study of patch frequency and occurrence. We find that Southern Hemisphere patch occurrence is very similar to that of the Northern Hemisphere with a half-year offset, plus an offset in universal time of approximately 12 hr. This is further supported by running an ionospheric model for both hemispheres and applying the same patch-to-background technique. Further, we present a simple physical mechanism involving a sunlit dayside plasma source concurrent with a dark polar cap, which yields a patch-to-background pattern very much like that seen in the TEC mappings for both hemispheres.

Plain Language Summary The tongue of ionization (TOI) is a stream of high-density plasma flowing antisunward across the polar cap; it may be present as one continuous structure, or it may be fragmented into discrete density patches. There is a well-studied climatology of when the TOI (and patches) may appear in the Northern Hemisphere polar cap; it has been harder to study this issue for the Southern Hemisphere because observational data there has been comparatively scarce but has improved considerably in recent years. We carry out a systematic search for TOIs and patches in both hemispheres throughout the years 2015–2018 and find that the pattern of patch occurrence in the Southern Hemisphere is very much like that in the Northern Hemisphere, but is seasonally shifted by 6 months and diurnally shifted by 12 hr. This finding, which is based on the use of two-dimensional grids of observations of total electron content, is very different from results reported in studies that have been based on the use of one-dimensional satellite tracks.

1. Introduction

F region density patches in the polar cap can be studied via various observational systems, including ground-based radar, and in situ density-measuring instruments aboard satellites such as SWARM or DMSP. When the goal is to establish patterns of patch occurrence based on season or universal time, the databases generated by these systems have definite drawbacks. In the case of using data along a satellite path, in addition to the disadvantage of having information only along the one-dimensional track of the satellite, there is the problem of being unable to sample a full set of longitudes independently of universal time due to the fact that the satellite will transit the polar cap at only certain times. In the case of using observations from ground-based radar stations, it would be necessary to have data from a large number of stations monitoring the ionosphere at the same time.

These drawbacks can be largely avoided by using the maps of total electron content (TEC) derived from the GPS network of satellites, available online from the Madrigal data server (Rideout & Coster, 2006). This database has provided continuous coverage of the Northern Hemisphere polar cap for more than a decade, and, in recent years, a much improved coverage of the Southern Hemisphere polar cap as well. The great advantage of using these TEC maps will be evident from Figure 1. Here we show, by way of an example, an interesting event from the Southern Hemisphere in which a tongue of ionization (TOI) is formed, and then an hour later a patch separates from the TOI, and then after another hour, while progressing antisunward, the patch and the TOI appear to have rejoined each other. It would be very difficult to track the history of a patch like this from a single ground-based station or a series of satellite passes. (See also Figure S1 in the supporting information.) It can be seen in Figure 1 that there are substantial

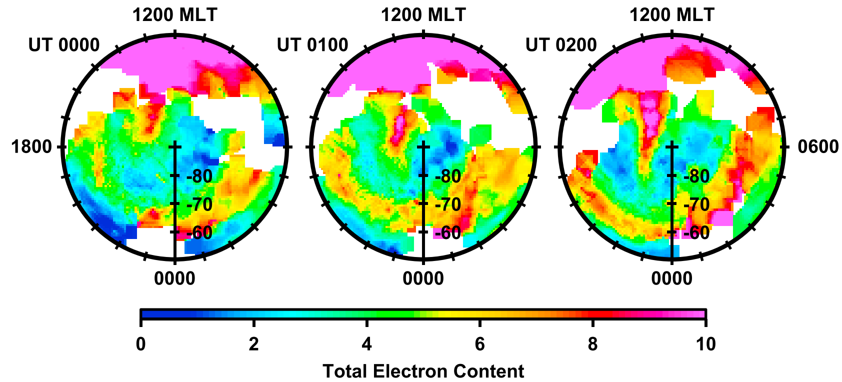

Figure 1. Examples of GPS total electron content maps from the Madrigal data server in magnetic polar coordinates, for the Southern Hemisphere on 28 May 2017 spaced 1 hr apart. The formation of a tongue of ionization is evident.

areas where data coverage is not available; perhaps 20% of the dial plot is left blank. (The gaps are less prominent in the Northern Hemisphere data.) Even so, it is possible to clearly discern features and structures within the polar cap. Until recent years, the coverage in the Southern Hemisphere had too many large gaps, making a study like this infeasible.

Historically, among the first publications to discuss polar cap patches were Buchau et al. (1983) and Weber et al. (1984), while the TOI was described by Sato (1959). The observational platform that led to their work was based on all-sky cameras and photometers. An early instance of patch research based on TEC in the Northern Hemisphere is Weber et al. (1986), and an early study of TEC patches in the Southern Hemisphere is Krankowski et al. (2006). Pedersen et al. (2000) and Carlson et al. (2002) studied patches in the Northern Hemisphere from databases of incoherent scatter radar observations, while Coley and Heelis (1995) studied patches in data from in situ satellite measurements of electron density. The latter study presented a quantitative definition of a patch that was based on N_e along a satellite track and a detailed algorithm to search for and identify patches. An early study using a physics-based model of the ionosphere was Sojka et al. (1993), which showed that the TOI could serve as the source of plasma for *F* region patches, while Sojka et al. (1994) gave a model-based highly detailed picture of the seasonal and universal time dependence of patch occurrence in the Northern Hemisphere. David et al. (2016), which first made a large-scale study of polar cap patches based on the Madrigal GPS TEC maps, showed that the seasonal/UT morphology presented by Sojka et al. (1994) was essentially correct; this work was, again, for the Northern Hemisphere only. An early work classifying patches in both the Northern and Southern Hemispheres is Coley and Heelis (1998); working with data from Dynamics Explorer 2 and DMSP satellites, they found a seasonal patch distribution pattern in both hemispheres with more patches in local winter than in summer. Due to the limitations of satellite data, there was no detailed study of a UT dependency.

More recent studies in which the in situ electron density measurements from the CHAMP and SWARM satellite systems have been used to compare the morphology and frequency of patch occurrence in the Northern and Southern Hemispheres include Noja et al. (2013) and Chartier et al. (2018). The results reported in these two studies are distinctly different from those we obtain here in the present study; both conclude that patches in both hemispheres occur most frequently during the same months of the year, and not in each hemisphere's winter months. In Chartier et al. (2018) data are first presented based on a patch detection algorithm which produces a patch distribution that is consistent with our results here (i.e., more patches in local winter in both hemispheres), though they reject this, and go on to employ a new algorithm which finds more patches in both hemispheres during the same months of the year, rather than in local winter. We defer any effort to give a detailed account of why the results are so different, but we expect that diversity in the definition of what it means to be a “polar cap patch” may account for a large part of the discrepancy. Noja et al. (2013), for example, have included regions at 55° magnetic latitude in their patch search algorithm; this goes far outside the polar cap area. Not only might there be patch-like density structures in the region outside the polar cap, but even high-density midlatitude dayside corotating plasma could be detected by the algorithm, to be reported as a “patch”. Interestingly though, Chartier et al. (2018) have shown that the pattern reported by Noja et al. (2013) persists even if the latitude cutoff is brought up

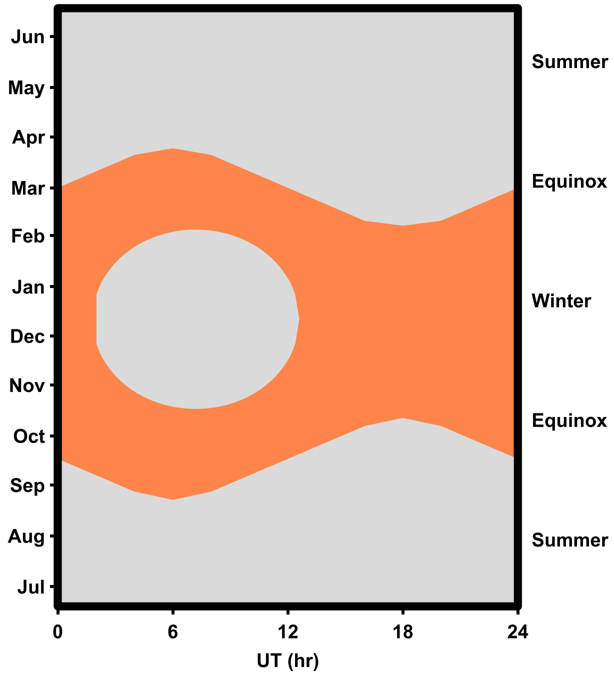

Figure 2. A schematic diagram showing the universal time and seasonal dependence that was found to exist in the Northern Hemisphere for *F* region polar cap patches and the tongue of ionization, based on a survey of GPS total electron content maps from 2009–2015 (David et al., 2016). The most salient feature is the "hole" that is present during the winter at universal times from about 0300 to 1200.

to 78°. Since we are limiting our study to polar cap patches, we do not go equatorward of 68°. In David et al. (2016), and particularly in the supporting information file for that paper, we carried out extensive tests to confirm that our patch-to-background calculation was not particularly sensitive to the precise value of this latitude boundary (nor to other parameters either), though in all cases our boundaries were well confined to what might be labeled as being within the "polar cap." If one looks at Figure S2 in the supporting information file, it is evident that if the patch search "strip" were extended to 55°, the dayside plasma which has corotated to the dusk side at 1800 MLT could end up being selected as a "patch". We further expect that the GPS TEC maps inherently provide a more robust platform for patch searches than the CHAMP and SWARM satellite trajectories.

Another recent study, based on SWARM satellite data, is Spicher et al. (2017); they have reported finding more patches in local winter in both hemispheres and have pointed out that, in the Southern Hemisphere at least, the findings of Noja et al. (2013) were inconsistent with both their results and those of Coley and Heelis (1998). Again, due to the nature of satellite databases, it was not possible to make a study of any UT dependency. (For more about the difficulty of looking for a UT dependency in satellite data, please see Figure S3 in the supporting information.)

In previous work (David et al., 2016) we carried out a systematic search for patches and/or TOIs in the Northern Hemisphere based on the GPS TEC maps for the years 2009–2015. A procedure for calculating a patch-to-background ratio (or TOI-to-background ratio) was devised and described therein, and was applied to the Northern Hemisphere GPS TEC maps, providing a database of polar cap patch-to-background ratios for 24 hr/day for a period of 6 years. We found a specific and repeatable pattern when the TOI-to-background ratio was plotted in a frame of universal time versus day of year; this pattern is shown schematically in Figure 2. The colored region shows those days and times when patches or a TOI may be seen; the gray areas are those days/times when the seasonal and UT dependence of the TOI does not permit patches to appear (except under unusual geophysical conditions). Patches or TOIs are absent during the summer months, due to the fact that the whole polar cap is sunlit.

The pattern is characterized most notably by a "hole" or absence of TOIs or patches in the winter months during a universal time window of about 0400–1200 hr. In David et al. (2016) we made much of this winter hole, as its presence demonstrates that the plasma source for polar cap patches is strongly UT-dependent in a specific way and that other non-UT-dependent mechanisms, which might be proposed as a plasma source for patches, could not be considered as major contributors to patch formation. In other words, this allowed us to make the claim that *within the context of studying polar cap patch climatology in its seasonal and universal time dependence, we could use the terms "patch" or "tongue-of-ionization" interchangeably*, since the TOI was shown to be by far the largest contributor of plasma in forming patches in the polar cap. (We reiterate here the caveat from the original paper, that we are speaking of density patches; other entities such as optical or airglow patches might perhaps represent some entirely different phenomenon.) This has allowed us to state that there is the potential for patches to appear when two conditions are met: (i) that solar-created plasma has been transported from the dayside into the polar cap and (ii) that the polar cap is in darkness.

Our TEC map database has been obtained from the Madrigal web server at this site (http://cedar.openmadrigal.org). Madrigal is an open source distributed database system providing web-based data storage, retrieval, search, and visualization freely available to the science community. The MIT Automated Processing of GNSS (MAPGPS) software (Rideout & Coster, 2006) is used to compute estimates of the TEC from the network of worldwide GPS receivers. Currently, Haystack processes more than 6,000 GNSS receivers a day; for most of the years prior to 2015 TEC processing was based on 2000–3000 receivers. There are now two TEC products stored in NSF's CEDAR Madrigal database; the first consists of single-degree bins of latitude and longitude at a 5-min cadence. The second is the new line-of-sight (LOS) TEC product, which includes observations of TEC for each satellite-receiver pair every 20–30 s. In 2015, Haystack's GNSS TEC processing was enhanced and the method now being used is described in Vierinen et al. (2015). The GNSS TEC binned data products from 2001 to 2016 have all been processed with the updated version of MAPGPS and are available online within Madrigal. Since April 2019, Haystack's GNSS TEC processing has been expanded to include GLONASS data.

To serve the purposes of this study, the GPS TEC maps obtained from the Madrigal database were recast into magnetic polar coordinates, in which a 105 × 105 grid covers the region centered on the magnetic pole and extending down to 50° magnetic latitude. A simple filling and interpolating algorithm is employed; see section 3 of David et al. (2016) for details.

2. The Patch-to-Background Ratio

2.1. "Patches" or "Tongue of Ionization"?

It seems the literature lacks a word to mean "high-density *F* region plasma transported by *E*×*B* from the dayside into the polar cap," regardless of whether it is a single large continuous structure (like a TOI) or a stream of discrete "islands" or patches. In this work, as before in David et al. (2016), we find ourselves trying to fill this lack by using the terms "patches" and "tongue of ionization" interchangeably. We could perhaps invent a new term, or employ yet another unmemorable acronym, but that might only clutter the issue and cloud the message we wish to get across.

To be very precise, what we are studying is the pattern of times and seasons when the polar cap contains a diversity of plasma regions or structures, including both low-density areas (the "background"), and at the same time, high-density areas (the "foreground," or "patches," or "TOI"). We do not make the assumption that these high-density areas or plasma structures originated on the dayside, but we do find that the observed pattern does closely match the pattern of those times and seasons when the relative geometry of the solar terminator and the high-latitude convection electric field is such that dayside plasma can be *E*×*B* transported into a dark (i.e., low density) polar cap. This is the pattern shown in Figure 2.

A variety of mechanisms have been proposed for the in situ generation of high-density plasma in the polar cap or cusp region, but the lack of a seasonal or universal time dependency of any such mechanism seems to virtually guarantee that it will be only a minor contributor to the patch population; this is the real significance of the wintertime hole that occurs in the pattern around 0300–1200 UT (in the Northern Hemisphere). The real-world observations show more "noise" occurring in the winter hole as compared with the clean contour produced by model runs; the identification of individual events where patches or TOI structures are seen within the boundaries of the hole will provide opportunities for highly interesting case studies to be carried out.

2.2. Calculation of the Patch-to-Background Ratio

In David et al. (2016) we described in detail our definition of and procedure for computing a ratio of the "patch" total electron content and the "background" TEC from the GPS TEC maps. In the supporting information pdf file for that paper, we gave several examples to show that the method is robust, in the sense that it is not sensitive to the values chosen for parameters such as the width of the inspection area or the positioning of the inspection strip (within reasonable bounds). We make use of the same procedure for computing our patch-to-background ratios in this article, this time in both the Northern and Southern Hemispheres. Our use of a ratio, rather than an on/off or 1/0 criterion for patches is in contrast with the methodology of several recent publications on the topic, such as Noja et al. (2013), Chartier et al. (2018), and Spicher et al. (2017), as well as Coley and Heelis (1995).

A very brief description of our patch-to-background procedure is as follows: We define an "inspection area" of a GPS TEC map, which when plotted looks like a horizontal "strip" going from the duskside to the dawnside, a few degrees of latitude nightward of the magnetic pole, extending on each side by about 15° of latitude. (See Figure S2 in the supporting information.) We look for a "foreground" high density within the middle part of this inspection area, and a "background" low density out toward either side of that. Again we refer the reader to our above-mentioned publication of 2016 for full details.

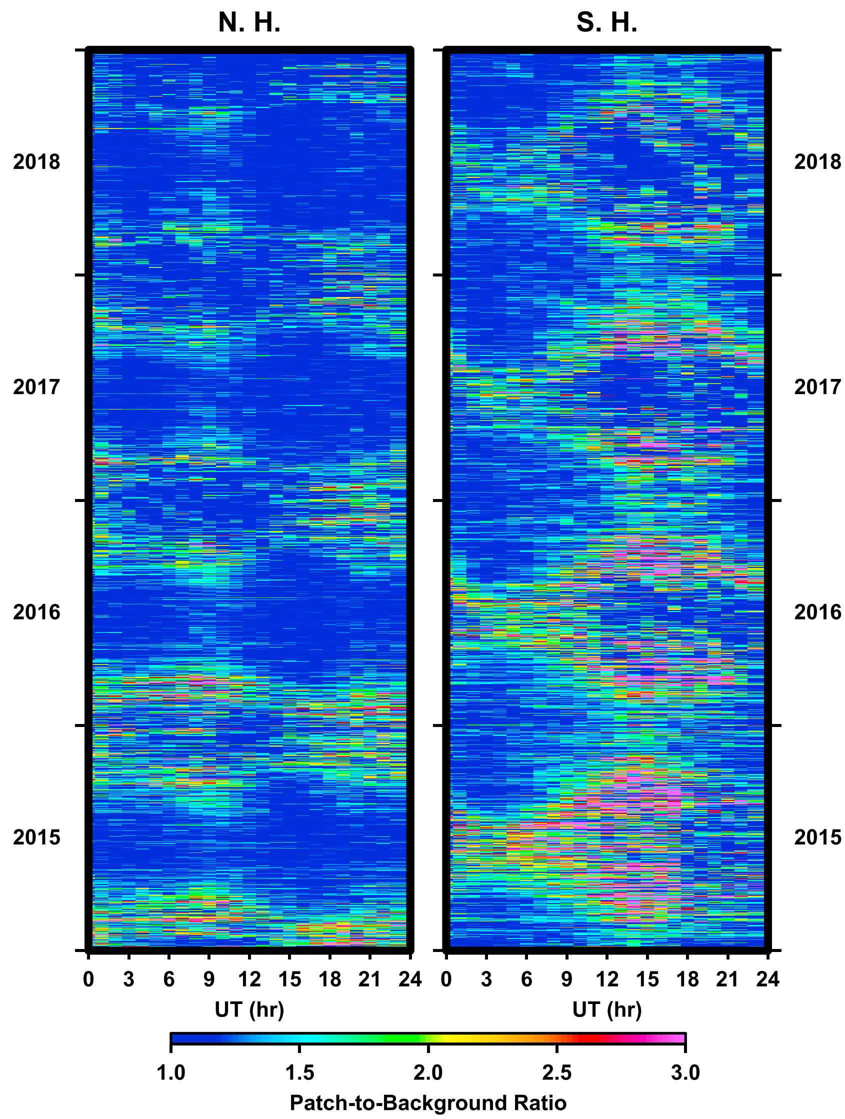

Figure 3. Our calculated patch-to-background ratios for both the Northern and Southern Hemispheres, from the GPS total electron content maps for the years 2015–2018.

Additionally, in David et al. (2016), and in its supporting information file, we went into detail as to why we speak of polar cap patches and the tongue of ionization practically interchangeably, and how this point of view is justified by the analysis of the GPS TEC maps, particularly the wintertime hole in the UT/seasonal dependence. In the present article we will continue to speak of the TOI and patches as being essentially interchangeable; indeed, we could consider the TOI itself to be one big patch.

3. Results

For the 4 years of data that we are using in this study, we have computed the patch-to-background ratio for each day at 1-hourly intervals for both hemispheres; the results are plotted in Figure 3. If the reader will first look at the left panel of the figure, for the Northern Hemisphere, it will be noticed that there occurs a series of shapes like the one shown schematically in Figure 2, including the hole that occurs each winter during a UT window of about 0300 to 1200 hr. It will also be noticed that there is an absence of patches or TOIs during the summer months. Highly favorable times for patches/TOIs in the Northern Hemisphere are found during equinox around 0000–1200 UT, and during winter around 1500–2400 UT.

The patch-to-background ratios for the Southern Hemisphere from the GPS TEC maps are plotted side-by-side with those for the Northern Hemisphere. Again we see the familiar repeated shape, though this time shifted by 12 hr of universal time (the *x* axis), and by 6 months (the *y* axis). (Note that it is *shifted*, not “flipped.”) This is fully consistent with the fact that the winter months in the Southern Hemisphere are June, July, and August, and that the diurnal movement of the solar terminator in the Southern Hemisphere is out of phase by 12 hr with that of the Northern Hemisphere. There have been recent publications of patch detection studies based on electron density measurements along satellite passes, including Noja et al. (2013) and Chartier et al. (2018), in which the conclusion was drawn that the seasonal pattern of patch occurrence in the Southern Hemisphere is correlated directly with that in the Northern Hemisphere, instead of being shifted by half a year. (Interestingly, Chartier et al., 2018 do include, in the left half of their Figure 1, Langmuir probe data which show the same type of seasonal pattern that we observe, but they do not pursue this, and in the conclusion section of their paper no mention is made of it.) When the patch-to-background ratio is computed based on the GPS TEC maps, the half-year shift becomes very readily apparent. In the two above-mentioned papers, the universal time dependence could not be studied due to the nature of the satellite data, so no 12-hr UT shift was found.

It is also apparent from Figure 3 that the patch-to-background ratio is noticeably larger in the Southern Hemisphere. At this time, we do not offer an explanation for this fact. We will note, however, that Coley and Heelis (1998), working with satellite data, found patch occurrence to be twice as high in the Southern Hemisphere.

4. Patch-to-Background Ratios: Model Runs

The Utah State University Time Dependent Ionospheric Model (TDIM) (Schunk, 1988; Sojka et al., 2013) has been run to produce ionospheric simulations on the same grid as the GPS TEC maps, at 2-hourly intervals throughout the year 2018, for both the Northern and the Southern Hemispheres. The same patch-to-background calculations have been carried out on the model outputs as were performed on the GPS TEC maps; the results are shown in Figure 4. The salient features of the wintertime hole and the absence of patches or TOIs during the summer months are readily apparent in both hemispheres. The model produces the same seasonal shift of 6 months and the same 12-hr diurnal shift that were seen in the GPS TEC data. The larger Southern Hemisphere patch-to-background ratio seen so clearly in Figure 3 is not reproduced by the model. The model runs do reflect the slight difference in shape seen between the patch-to-background patterns of the two hemispheres, in that the Southern Hemisphere pattern has a more expanded shape and a wider winter hole than that of the Northern Hemisphere. This happens because the two hemispheres have a different offset between their respective geographic and magnetic poles. In order to make this more evident, in the right-hand panel of the figure we have included an alternative version, showing the Southern Hemisphere with the *y* axis shifted by half a year and the *x* axis offset by 12 hr so that the shape of the patch climatology pattern can be directly compared with that of the Northern Hemisphere.

In the next section of this paper we put forward a very simple mechanism for generating the pattern of seasonal and UT dependence of patch occurrence.

5. A Simple Model to Account for the Patch/TOI Seasonal and UT Pattern in Both Hemispheres

In order that dayside high-density plasma may be transported antisunward into the polar cap, there must exist a certain relationship between the location of the solar terminator and the turn-around point of the convection electric field pattern. By “turn-around point,” we mean the latitude (in the magnetic frame) at which plasma trajectory paths do not continue to corotate as they approach noon in local time, but are diverted antisunward and subsequently transported into and across the polar cap (see Figure S4 in the supporting information). If the terminator is too far equatorward, then the turn-around point itself is in darkness and the plasma transported into the polar cap will be of low density. On the other hand, if the terminator is beyond the pole, as it is throughout the day in summer and during part of the day in equinox, then the whole polar cap will be in a high-density state and there will be no contrast between the plasma transported in to the polar cap and the background density.

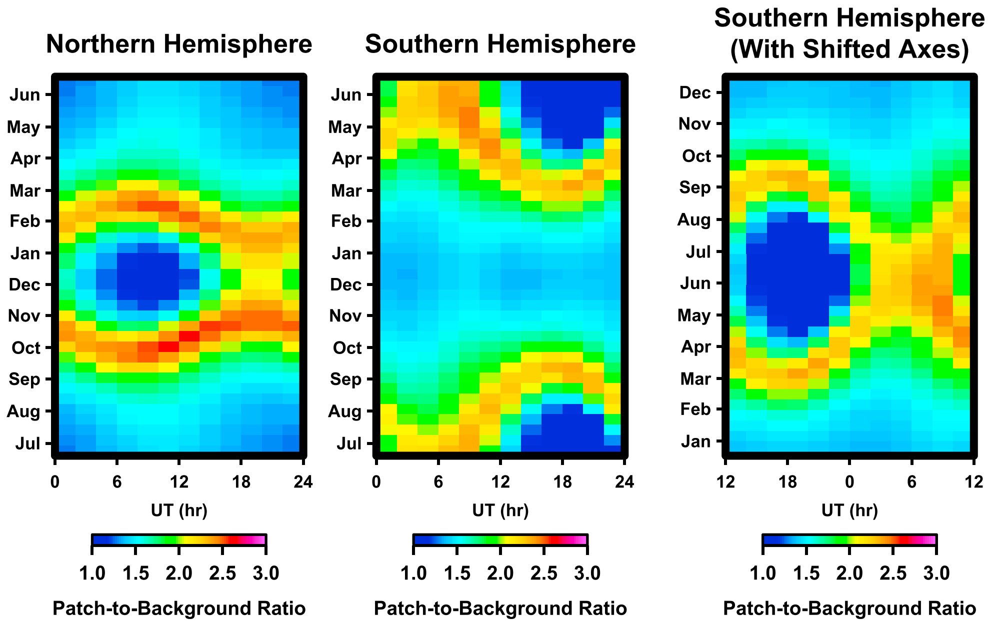

Figure 4. Our calculated patch-to-background ratios from TDIM ionospheric model runs for the year 2018; Northern Hemisphere at left, Southern Hemisphere in the second panel. At right, we have re-plotted the Southern Hemisphere results with the vertical axis shifted by 6 months, and the horizontal axis shifted by 12 hr.

The ideal situation for producing a strong TOI or patches is that the polar cap is in darkness, and the turn-around point will have been sunlit a few hours previously, allowing time for the high-density dayside plasma to be transported into the middle of the polar cap; see Figure S4 in the supporting information.

Based on inspection of the Heppner and Maynard (1987) convection electric field patterns, we choose 70° magnetic latitude at 1200 MLT to represent the turn-around point location for typical geomagnetic conditions. (To represent times of geomagnetic disturbance, a lower latitude would have to be chosen.) Again based on inspection of the aforementioned convection electric field patterns, a time interval of 2 hr has been picked as a round number to represent the transit time for plasma traveling from the turn-around point to reach the center of the polar cap.

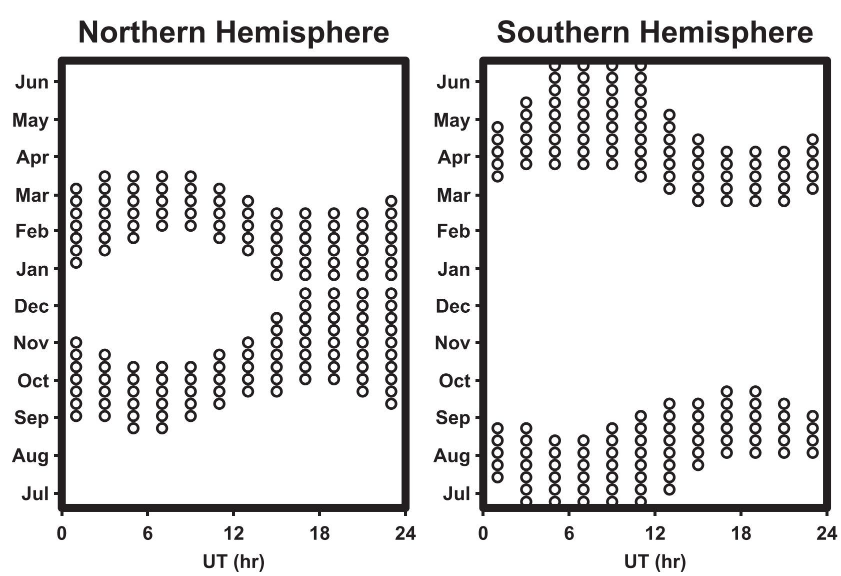

Figure 5. Based on the highly simplified geometrical model discussed in section 5, markers in the plot indicate those times and seasons when tongues of ionization or patches may be expected to appear.

We put this to use by making calculations of the solar zenith angle at the turn-around point and at the magnetic pole, at hourly steps in universal time for every 10th day throughout the year. The ionospheric model is not run, and simulations of the ionosphere are not produced. We generate a 1/0 output based solely on whether the pole is in darkness and the turn-around location was sunlit 2 hr previously. We carried out this test for both the Northern and the Southern Hemispheres, using 83°N, 275°E; and −75°N, 125°E as the locations of the north and south magnetic poles, respectively. Results are drawn in Figure 5, in which a marker is plotted to indicate that the above-mentioned relationship of the terminator and the turn-around point is present and that patches or a TOI may be expected to be present. Where no marker is plotted, the position of the solar terminator is such that TOIs or patches would not be expected to appear. (Unusual or extreme geomagnetic conditions could cause an exception.)

Simple though it is, this little model's output agrees remarkably well with both the 4 years of observations in the GPS TEC maps and the full-scale ionospheric model runs; and again the 6-month seasonal shift and the 12-hr universal time shift are readily apparent.

6. Conclusions

The series of GPS maps of TEC from the Madrigal database provides an excellent platform of observations for studying the seasonal and diurnal climatology of patch and TOI occurrence in both hemispheres, free from many of the drawbacks that beset the effort to study patch occurrence from either ground-based station data or density measurements along satellite tracks.

We find that patch and TOI occurrence in the Southern Hemisphere has a pattern which is seasonally shifted by half a year and diurnally shifted by 12 hr relative to the pattern in the Northern Hemisphere. This is distinctly different from the conclusion reached in other studies based on in situ satellite measurements of electron density, such as Noja et al. (2013) and Chartier et al. (2018).

We have found that this relationship of patch occurrence between the Northern and Southern Hemispheres is supported by simulations carried out with a physics-based ionospheric model. The GPS TEC map analysis shows that the patch-to-background ratio in the Southern Hemisphere consistently reaches higher values than in the Northern Hemisphere; this asymmetry was not reproduced by the ionospheric model, and we do not have an explanation for it at this time.

We devised and tested a very simple geometrical model based solely on the relationship of the solar terminator and the dayside convection turn-around point and found that it can largely account for the patch climatology seen in the two hemispheres.

Data Policy

All GPS TEC data used in the course of this work can be accessed by the public via the Madrigal web server at cedar.openmadrigal.org. Output data from the TDIM ionospheric model can be accessed via the Digital Commons of Utah State University at this site (https://doi.org/10.26078/7rvg-k921).

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References

Buchau, J., Reinisch, B., Weber, E., & Moore, J. (1983). Structure and dynamics of the winter polar cap F region. *Radio Science*, *18*(6), 995–1010. https://doi.org/10.1029/RS018i006p00995

Carlson, H., Oksavik, K., Moen, J., van Eycken, A., & Guio, P. (2002). ESR mapping of polar-cap patches in the dark cusp. *Geophysical Research Letters*, *29*(10), 1386. https://doi.org/10.1029/2001GL014087

Chartier, A. T., Mitchell, C. N., & Miller, E. S. (2018). Annual occurrence rates of ionospheric polar cap patches observed using Swarm. *Journal of Geophysical Research: Space Physics*, *123*, 2327–2335. https://doi.org/10.1002/2017JA024811

Coley, W., & Heelis, R. (1995). Adaptive identification and characterization of polar ionization patches. *Journal of Geophysical Research*, *100*(A12), 23819–23,827. https://doi.org/10.1029/95JA02700

Coley, W., & Heelis, R. (1998). Seasonal and universal time distribution of patches in the northern and southern polar caps. *Journal of Geophysical Research*, *103*(A12), 29229–29237. https://doi.org/10.1029/1998JA900005

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. https://doi.org/10.1002/2016GL068136

Heppner, J. P., & Maynard, N. C. (1987). Empirical high-latitude electric field models. *Journal of Geophysical Research*, *92*(A5), 4467–4489. https://doi.org/10.1029/JA092iA05p04467

Krankowski, A., Shagimuratov, I., Baran, L., Epishov, I., & Tepenitzyna, N. (2006). The occurrence of polar cap patches in TEC fluctuations detected using GPS measurements in Southern Hemisphere. *Advances in Space Research*, *38*(11), 2601–2609. https://doi.org/10.1016/j.asr.2005.12.006

Noja, M., Stolle, C., Park, J., & Lühr, H. (2013). Long-term analysis of ionospheric polar patches based on CHAMP TEC data. *Radio Science*, *48*, 289–301. https://doi.org/10.1002/rds.20033

Pedersen, T., Fejer, B., Doe, R., & Weber, E. (2000). An incoherent scatter radar technique for determining two-dimensional horizontal ionization structure in polar cap F region patches. *Journal of Geophysical Research*, *105*(A5), 10637–10655. https://doi.org/10.1029/1999JA000073

Rideout, W., & Coster, A. (2006). Automated GPS processing for global total electron content data. *GPS Solutions*, *10*(3), 219–228. https://doi.org/10.1007/s10291-006-0029-5

Sato, T. (1959). Morphology of ionospheric F2 disturbances in the polar regions. *Report Ionos. Space Research Japan*, *13*, 91–95.

Schunk, R. W. (1988). A mathematical model of the middle and high-latitude ionosphere. *Pure and Applied Geophysics*, *127*(2-3), 255–303. https://doi.org/10.1007/BF00879813

Sojka, J. J., Bowline, M. D., & Schunk, R. W. (1994). Patches in the polar ionosphere: UT and seasonal dependence. *Journal of Geophysical Research*, *99*(A8), 14959–14,970. https://doi.org/10.1029/93JA03327

Sojka, J. J., Bowline, M. D., Schunk, R. W., Decker, D. T., Valladares, C. E., Sheehan, R., et al. (1993). Modeling polar cap *F*-region patches using time varying convection. *Geophysical Research Letters*, *20*, 1783–1786.

Sojka, J. J., Jensen, J., David, M., Schunk, R. W., Woods, T., & Eparvier, F. (2013). Modeling the ionospheric *E* and *F*1 regions: Using SDO-EVE observations as the solar irradiance driver. *Journal of Geophysical Research: Space Physics*, *118*, 5379–5391. https://doi.org/10.1002/jgra.50480

Spicher, A., Clausen, L. B. N., Miloch, W. J., Lofstad, V., Jin, Y., & Moen, J. I. (2017). Interhemispheric study of polar cap patch occurrence based on Swarm in situ data. *Journal of Geophysical Research: Space Physics*, *122*, 3837–3851. https://doi.org/10.1002/2016JA023750

Vierinen, J., Coster, A. J., Rideout, W. C., Erickson, P. J., & Norberg, J. (2015). Statistical framework for estimating GNSS bias. *Atmospheric Measurement Techniques Discussions*, *8*(9), 9373–9398. https://doi.org/10.5194/atmd-8-1-2015

Weber, E., Klobuchar, J., Buchau, J., Carlson, H. Jr., Livingston, R., de la Beaujardiere, O., et al. (1986). Polar cap *F* layer patches: Structure and dynamics. *Journal of Geophysical Research*, *91*(A11), 12,121–12,129.

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. https://doi.org/10.1029/JA089iA03p01683