RESEARCH ARTICLE

Key Points:
- Polar cap patches occur more frequently around December than around June in both hemispheres
- Patch detection algorithms that use only density doubling tests erroneously show winter maxima in both hemispheres
- The observed annual trend of patch detections is not explained by current formation theories, which rely on local season

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Annual Occurrence Rates of Ionospheric Polar Cap Patches Observed Using Swarm

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Abstract Dense, fast-moving regions of ionization called polar cap patches are known to occur in the high-latitude *F* region ionosphere. Patches are widely believed to be caused by convection of dense, sunlit plasma into a dark and therefore low-density polar cap ionosphere. This leads to the belief that patches are a winter phenomenon. Surprisingly, a long-term analysis of 3 years of ionospheric measurements from the Swarm satellites shows that large density enhancements occur far more frequently in local summer than local winter in the Southern Hemisphere (SH). The reverse is true in the Northern Hemisphere (NH). Previously reported patch detections in the SH are reexamined. Detection algorithms using only a relative doubling test count very small density fluctuations in SH winter due to extremely low ambient densities found there, while much larger enhancements occurring in SH summer are missed due to especially high ambient densities. The same problem does not afflict results in the NH, where ambient densities are more stable year-round due to the ionospheric annual asymmetry. Given this new analysis, the definition of a patch as a doubling of the ambient density is not suitable for the SH. We propose a test for patches linked to long-term averaged solar flux activity, characterized by the 81 day centered mean $F_{10.7}$ index. Importantly, the current patch formation theory is at least incomplete in that it does not predict the observed lack of patches in SH winter, or the many large enhancements seen in SH summer.

Plain Language Summary Dense, fast-moving regions of ionization called patches are known to occur in the high-latitude *F* region ionosphere. Theory and most previous observations indicate that patches are a winter phenomenon (around December in the Northern Hemisphere, around June in the Southern Hemisphere). However, a recent study using a novel patch detection approach showed more patches around December in both hemispheres. We reexamine that approach alongside a well-established approach that produces a winter maximum in each hemisphere. Our new observations and analysis show that the December maximum in both hemispheres is correct. Therefore, the theory of patch formation is incomplete. An explanation is needed for the lack of patches around June solstice in both hemispheres, and for the large number of patches found in Southern Hemisphere summer.

1. Introduction

1.1. Patch Characteristics

Polar cap patches are dense, fast-moving regions of plasma found in the high-latitude *F* region ionosphere. Some of the first observations were made by Hill (1963), Weber and Buchau (1981), Buchau et al. (1983), and Weber et al. (1984). Crowley (1996) defines a convention where patches are regions with electron density at least twice as high as the surrounding area. Tsunoda's (1988) and Carlson's (2012) reviews conclude that large-amplitude (up to 10^6 el/cm^3) and large-scale (~100 to ~1,000 km), high-latitude *F* region enhancements are typically caused by convection of sunlit plasma into the polar caps rather than by precipitation. Regions of less intense ionization can be created by soft particle precipitation at the cusp (Goodwin et al., 2015; Pinnock et al., 1993; Rodger et al., 1994) and in the polar cap (Oksavik et al., 2006).

1.2. Patch Occurrence Rates

Many of the leading theories for patch formation, including the one strongly endorsed by Carlson's (2012) review, are predicated on the belief that patch formation is a winter and equinoctial phenomenon. A strong plasma density gradient in the local noon auroral region is useful for many of the theorized mechanisms, and this gradient is reduced or absent during summer. There have been several observational and theoretical investigations of patch occurrence rates, most of which focus on the Northern Hemisphere (NH). Notable examples include Sojka et al. (1994) using an ionospheric model, Coley and Heelis (1995) using Dynamics

Explorer 2's Retarding Potential Analyzer ion densities, and David et al. (2016) using ground-based total electron content (TEC) maps. All these studies indicate more patches in winter than in summer. Those findings are apparently confirmed for the Southern Hemisphere (SH) by Coley and Heelis (1998) (again using DE2) and by Spicher et al. (2017) (using Swarm's Langmuir probe) who find more patches in winter in both hemispheres. Therefore, the results of Noja et al. (2013, hereafter NOJA) using Challenging Minisatellite Payload's (CHAMP) upward GPS TEC are very surprising in that they show more patches in SH summer—the annual pattern essentially follows the same calendar months in both hemispheres rather than following local season. The aim of this paper is to determine which of these hypotheses is correct:

1. More patches occur in local winter than in local summer.
2. More patches occur in December than in June in both hemispheres.

To test these hypotheses, it is necessary to identify the reasons for the discrepancy between NOJA's results and the other interhemispheric analyses (presented by Coley & Heelis, 1998, and Spicher et al., 2017). It is not clear whether the discrepancy is caused by the use of different types of observation (upward TEC versus in situ F region density), or by the use of different patch detection criteria (NOJA's absolute magnitude enhancement of 4 TEC units (TECU) versus Crowley's, 1996, relative enhancement of 2 times the background density).

It must be noted that all current systematic global patch detection methods rely on time series from single satellites, so there also remains ambiguity as to whether these features constitute "true" patches or islands of plasma, or whether they in fact represent ridges of plasma extended across the path of the satellite. These approaches also rely on measurements of the topside ionosphere, which may complicate comparisons with bottomside observations given the height redistribution of plasma expected during patch formation (Balmforth et al., 1999).

1.3. Previous Satellite-Based Patch Detection Approaches

Polar cap patches are an empirically defined phenomenon. Various heuristic choices have been made in designing detection algorithms suitable for the diverse instruments that observe them. These choices, as well as differences in the characteristics of each instrument, may explain differences between the occurrence rates observed in different studies.

Coley and Heelis (1995) detect patches using in situ ion density observations taken above 70°N magnetic latitude (MLAT) and between 240 and 950 km altitude. For the algorithm to count a patch, the peak density must be at least double the mean density value across a 1,250 km sliding window. Spicher et al. (2017) also use in situ data, this time from Swarm (~460 and 530 km altitudes), and a higher latitude cutoff of 78°. They require that the density enhancement is double the 35th percentile of the values across a 2,000 km window. NOJA's detection algorithm, based on CHAMP data, has two important differences to those two approaches. First, it uses upward looking TEC observations instead of in situ densities. Second, it applies an absolute test for patches, requiring that the peak is greater than 4 TECU above the background.

2. Method

NOJA's detection algorithm produces results that are in apparent conflict with those of Coley and Heelis (1998) and Spicher et al. (2017) in the SH. To determine the reasons for this discrepancy, we reproduce NOJA's detection algorithm and compare it to one that is similar to that first described by Coley and Heelis (1995). To identify the true patch occurrence rate, we then introduce a new detection algorithm that addresses limitations of both approaches.

2.1. Data

Swarm provides an ideal data set with which to detect patches since the satellites carry both upward looking GPS receivers (as used by NOJA's detection algorithm) and Langmuir probes (which produce in situ plasma density observations that are needed for the Coley & Heelis, 1995, detection algorithm). The Swarm mission, which launched in November 2013, is described by Christensen et al. (2006), the Langmuir probes by Knudsen et al. (2017), and the GPS by Buchert et al. (2015). The Langmuir probe provides a measure of in situ electron density, while the upward looking GPS receiver provides observations

of TEC that represent the path-integrated electron density between Swarm (~450–500 km altitude) and the GPS satellites (~20,000 km altitude).

Swarm satellites A and C fly in an 87.4° orbit, while satellite B flies in an 88.0° orbit. Upward looking GPS TEC differential code biases are estimated daily to a reported accuracy of 2 TECU and corrected for by the Swarm team before public release of the TEC observations. Note that the precision of GPS TEC data is typically estimated to be much better than 1 TECU (e.g., Mannucci et al., 1999). The precision is relevant for the observations used in this study, which are the TEC changes during a continuous observation period. The cadence of GPS TEC data is 1 s, and the cadence of the Langmuir probe data is 0.5 s, so the resolution of both data sets is better than 10 km.

2.2. Detection Algorithms

Here we define two patch detection algorithms (D1 and D2) representative of previously published approaches. Following analysis of D1 and D2, a third algorithm D3 is presented in section 3.3 to address the limitations of these two approaches.

Algorithm D1 is intended to detect patches in the Langmuir probe data in a manner similar to that described by Coley and Heelis (1995). The only major difference is that in order to facilitate direct comparison with the work of NOJA, this algorithm also uses a cutoff latitude of 55° MLAT. In keeping with Coley and Heelis (1995), a 100 km median smoothing filter is applied to the data to remove small-scale structures. Following that, a sliding window of 1,250 km is applied. Within that window, there must be a 40% increase within 140 km, followed by a 40% decrease within 140 km (defining the edges of the patch). The mean electron density in the window is defined as the background value. The highest density within the patch edges must be greater than double the mean across the window. There is no "absolute" test of the enhancement in this algorithm.

Algorithm D2 is intended to be exactly as described by NOJA. Upward looking GPS TEC data from satellite locations above 55° MLAT are used. Within a 1,500 km sliding window, the algorithm requires a positive TEC gradient followed by a negative gradient. The peak TEC value in the window (TEC_P) is subjected to three comparative tests (shown in equations (1)–(3)) against the background value (TEC_{BG}), and the start/end values of the enhancement (TEC_{start} and TEC_{end}):

$$\frac{(TEC_P - TEC_{BG})^2}{TEC_{BG}} \geq 1.2 \text{ TECU} \tag{1}$$

$$TEC_P - TEC_{start} \geq 4 \text{ TECU} \tag{2}$$

$$TEC_P - TEC_{end} \geq 4 \text{ TECU} \tag{3}$$

The period of analysis for both methods is selected as August 2014 to July 2017.

3. Results

3.1. Performance of the Established Patch Detection Algorithms D1 and D2

Five day binned patch detection rates by each method are shown in Figure 1. Each subfigure shows the number of patches found above 55° MLAT against the time of year. The figures are separated into Swarm satellites A and B, and into Northern and SH results. The subfigures show the results from the Langmuir probe (Figures 1a–1d) and the GPS (Figures 1e–1h). December and June solstices are indicated by vertical red and blue dashed lines.

D1 produces a seasonal patch detection pattern, with more patches in winter than in summer in each hemisphere. That is, there are more patches around December than around June in the NH, but more patches around June than December in the SH. D2, by contrast, reveals an annual patch detection pattern, with more patches around December than around June in both hemispheres. D2 patch detections are modulated by long-term solar activity, represented in Figure 2 by the centered 81 day arithmetic average of the $F_{10.7}$ index.

3.2. Reasons for the Discrepancies Between D1 and D2

To understand the discrepancy between patch counts arising from D1 and D2, it is necessary to inspect the raw input data in both hemispheres and in both solstices. Representative examples of Swarm (satellite A) Langmuir probe and upward GPS data have been selected from around 18 UT on 21 December 2014 and
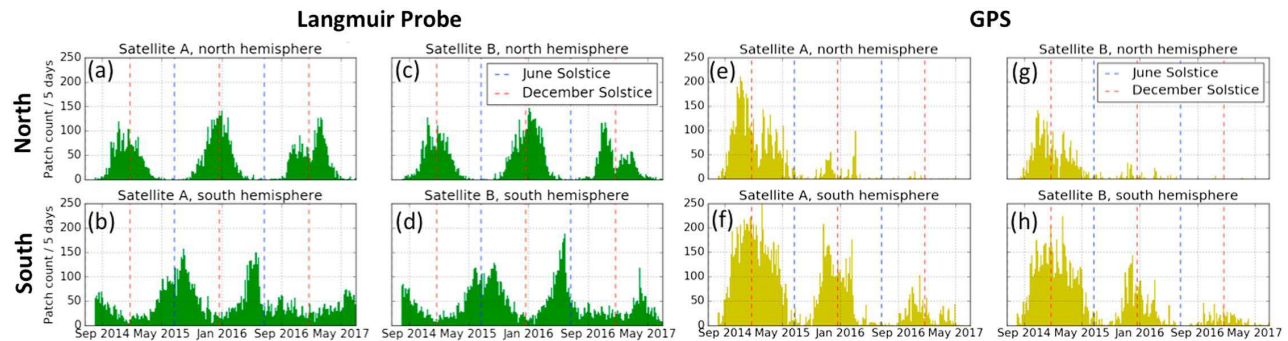
Langmuir Probe **GPS**

Figure 1. Detection algorithm D1 (green) and D2 (yellow) patch detections between August 2014 and July 2017 in each hemisphere. December and June solstices are indicated by vertical red and blue dashed lines.

21 June 2015 and shown in Figure 3. These years are selected because they contain the most D2 patch detections (D1 has about the same number of detections each year). Figure 3a shows NH winter, 3b shows SH summer, 3c shows NH summer, and 3d shows SH winter. The subfigures on the right-hand side (Figures 3e–3h) show the corresponding information from the GPS at the same times.

The raw Langmuir probe and upward GPS measurements show similar behavior in each corresponding example, indicating that large F region ionospheric density enhancements are evident in both techniques and are the major contributor to the TEC observations. However, the two algorithms detect the same "patches" (or lack of patches) only in the NH. Several issues are evident in the performance of filters D1 and D2. These are not "bugs" in the code but in fact are the natural consequence of the two detection algorithms (described in section 2.2). The issues are itemized and explained as follows:

1. D1 does not count the large enhancements seen in Figure 3b (SH summer) as patches. This is because the peak of the enhancement is never greater than double the mean within the 1,250 km sliding window. By contrast, the enhancement in Figure 3a (NH winter) is counted as a patch because the background density is lower.

2. D1 detects several patches in Figure 3d (SH winter) despite the absence of any large enhancements. This is because the background values are so low that even very small fluctuations can surpass double the 1,250 km mean. The same problem does not occur in Figure 3a (NH winter) because background values are not as low (the reason for this is the well-known annual asymmetry, which is explained later).

3. D2 counts the same patches multiple times in Figures 3e and 3f (NH winter and SH summer). This occurs because Swarm receives signals from multiple GPS satellites at any given time. Patches can be up to ~1,000 km in diameter, so the same feature can appear on multiple lines of sight.

Issues 1 and 2 do not afflict algorithm D2 because it uses an absolute test to detect patches. Issue 3 does not affect algorithm D1 because it uses only a single time series of in situ data.

The "phantom" patch detections of Figure 3d (SH winter, identified as Issue 2) are interesting because they might be also expected in NH winter (Figure 3a), but in fact they do not occur there. This is because the
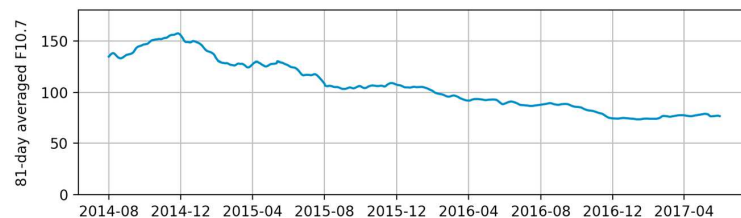

Figure 2. The 81 day (three synodic solar rotations) averaged $F_{10.7}$ from 1 January 2014 to 1 July 2017.
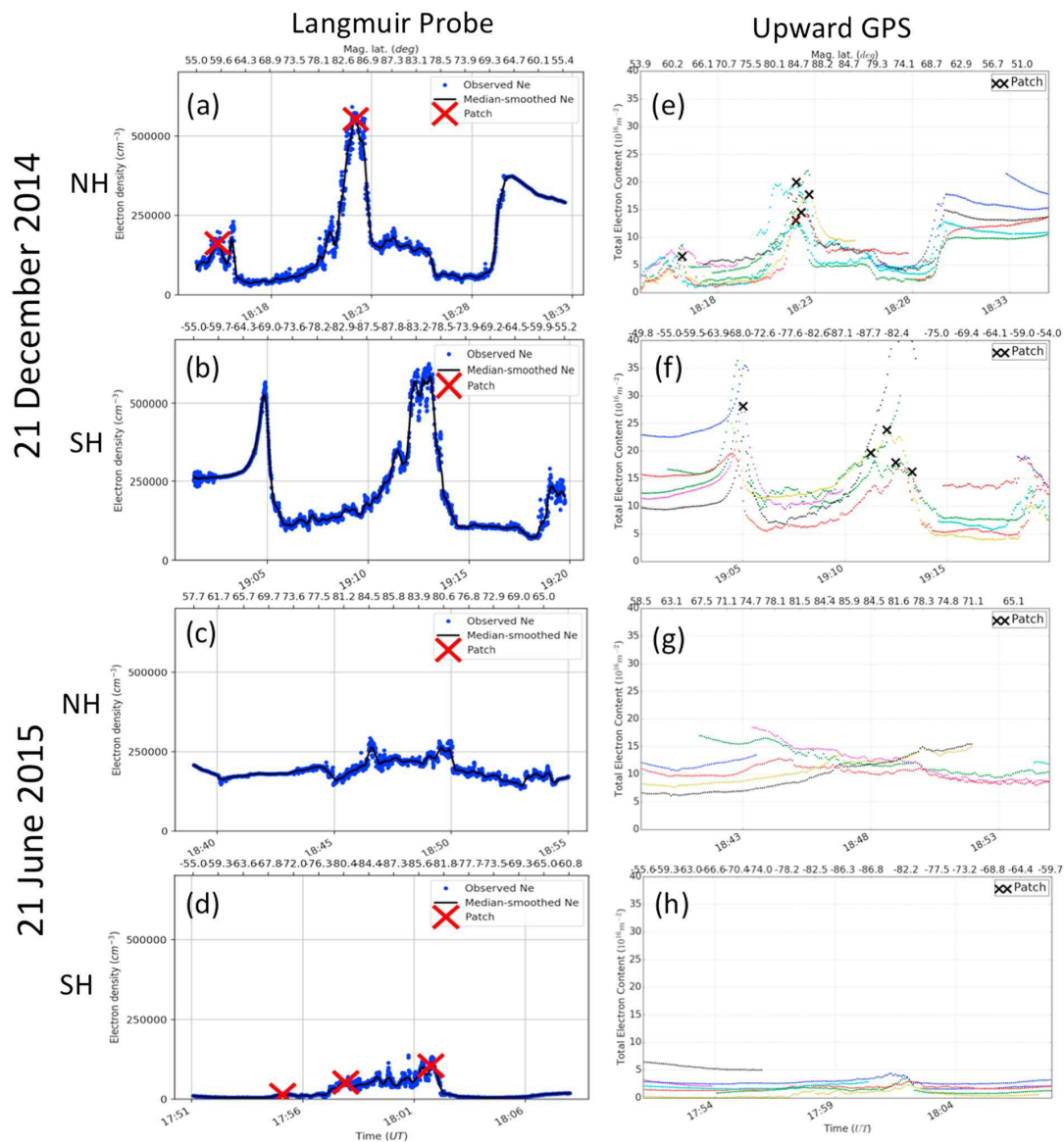
Figure 3. Representative case studies from Swarm A Langmuir probe and upward GPS in both hemispheres during the December 2014 and June 2015 solstices.

background level of ionization is higher in NH winter, as is shown in Figure 4. Five day medians of all electron densities recorded above 55° MLAT throughout the period of study have been plotted. The 5 day period is chosen to match the length of the bins used in Figure 1.

The 5 day median electron densities have the expected seasonal dependence, peaking around the summer solstice in each hemisphere, modulated by declining solar activity over the period of study. There is a notable difference between the two hemispheres, with the SH showing more pronounced seasonal variability. It is this feature (known in the literature as the "annual asymmetry," e.g., Rishbeth & Müller-Wodarg, 2006) which explains the phantom patches reported by D1 in SH winter, where densities are lowest of all.
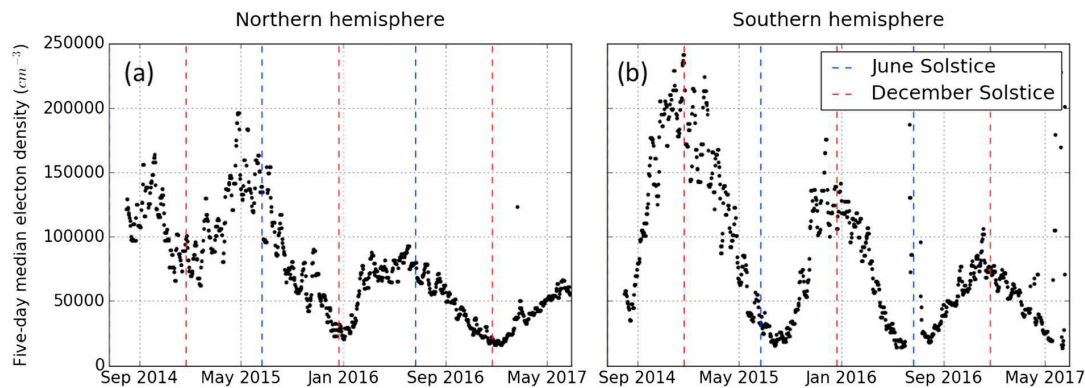
Figure 4. Five day median electron densities detected above 55° magnetic latitude in the (a) Northern and (b) Southern Hemispheres by Swarm satellites A and B between August 2014 and July 2017.

3.3. A New Patch Detection Algorithm

The D1 and D2 algorithms both have serious issues that are described in section 3.2. To provide a better estimate of the true patch occurrence rate, a new patch detection algorithm "D3" is defined that combines the strengths of both approaches. An absolute test for patches is used instead of a relative test so that patches can be detected in higher background density environments, and likewise small fluctuations ignored in low background density environments. Langmuir probe observations are used to prevent the multiple counting of patches that can afflict analysis of upward GPS approaches. To mitigate the impact of solar cycle variations on our results, the minimum magnitude of enhancements is tied to the 81 day averaged $F_{10.7}$ value (shown in Figure 2).

Algorithm D3 is the same as D1, except that the patch peak (in el/cm^3) is defined to be greater than the 1,500 km mean by at least 1,000 times the 81 day (about three solar rotations) centered mean $F_{10.7}$ value. $F_{10.7}$ is used because it provides an indication of the amount of photo-ionized plasma available from which to produce patches through the convective mechanism first proposed by Hill (1963). The 1,000 times factor is chosen based on the specific characteristics of the Swarm electron density data set and should not be applied
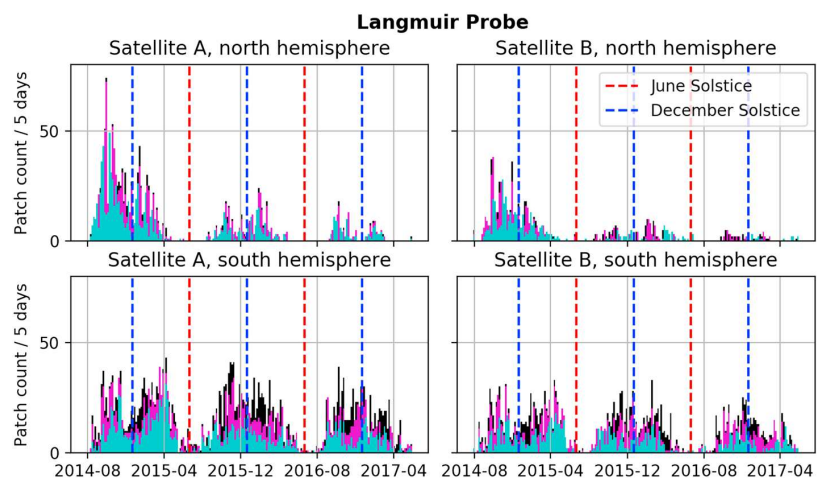

Figure 5. Patch detections between August 2014 and June 2017 using Swarm A and B Langmuir probe data. This algorithm (D3) uses a new absolute test related to 81 day averaged $F_{10.7}$ values to determine the presence of patches. Black indicates patches above 55° magnetic latitude (MLAT), magenta above 70° MLAT and cyan above 78° MLAT.

to data from other altitudes where ionization levels are likely to be quite different. In the chosen period of study the $F_{10.7}$-based test results in minimum enhancement values ranging from 0.7 to 1.6×10^5 el/cm^3. Three latitude cutoffs are tested: 55° MLAT (following NOJA), 70° MLAT (following Coley & Heelis, 1995), and 78° MLAT (following Spicher et al., 2017). Results of the D3 algorithm are shown in Figure 5.

Figure 5 shows the results of the D3 algorithm. The patch occurrence rate follows the same calendar months in both hemispheres, with a pronounced minimum around June. Therefore, the trend is annual rather than following local season, which supports hypothesis (2) from section 1.2. The number of detections is much lower than from D2, which is as expected because D3 does not suffer from the multiple-counting problems of D2. The $F_{10.7}$-dependent threshold reduces the solar cycle effect on the number of patch detections, especially in the SH. A large number of patches are detected in the NH around December 2014, but in subsequent years there are many more detections in the SH. Higher-latitude cutoffs result in fewer patch counts, as expected, but most patches are found above 70° MLAT and the annual variability is similar in all cases. Fewer patches are detected in Swarm B because the satellite is at a higher altitude than Swarm A (so densities are lower), but the trend is otherwise similar in both cases. This indicates that the observed annual variability is not peculiar to a single satellite's orbital or hardware characteristics.

4. Discussion

The results indicate that large enhancements in the F region electron density are often present in December and absent in June in both hemispheres, as is shown in Figures 1, 3, and 5. This result is surprising given that a seasonal pattern is widely expected, with more patches supposed to be detected in local winter. From Hill's (1963) seminal investigation of "sporadic F" onward, the prevailing theory has been that patches constitute photo-ionized midlatitude plasma which, when convected into the polar caps, presents as a large enhancement over ambient levels of ionization. Clearly, the convective theory does not explain the many large density enhancements observed in SH summer, or the absence of such enhancements in SH winter. Likewise, refinements of that theory, such as Lockwood and Carlson's (1992) linking of patches to transient magnetopause reconnection, or Sojka et al.'s (1994) variable convection model, do not predict this variability. Both those models lead to the expectation of more/stronger patches when the terminator is close to the dayside cusp (because the density gradient is strongest then), which typically occurs around equinox and during winter. This does not match what is observed in the SH. Particle precipitation has been advanced as a separate or contribution explanation for patches, for example, by Rodger et al. (1994), but that theory is equally lacking in its ability to explain the annual variability observed in the SH. Given this analysis, it is clear that patch formation theory is, at best, incomplete.

There is no current explanation for the observed annual trend, but there are reasons to expect variations in occurrence rates. For example there is a well-known semiannual variation in magnetic activity that peaks at equinox (e.g., Cortie, 1912; Russell & McPherron, 1973), which will enhance those mechanisms believed to be responsible for patch formation (e.g., magnetospheric convection and possibly particle precipitation). Likewise, the simulations presented by Sojka et al. (1994) predict a minimum of patches at NH winter solstice, because the equatorward boundary of the convection pattern is too far north to capture photo-ionized plasma. The same theory might be applied to predict more patches year-round in the SH, where the magnetic pole is further separated from the geographic pole. These theories, as well as concurring observations (e.g., Rodger & Graham, 1996; Whitteker, 1976) are to some extent substantiated by Figure 5, which does show peaks around the equinoxes and more patches in the SH. However, the central mystery of more patches around December than around June in both hemispheres, which has now been observed in multiple years across two instruments (Langmuir probe and upward GPS) and three satellites in different orbits (Swarm A and B and CHAMP), is not explained by any current theory.

Apparently, contradictory SH results from detection algorithm D1 (shown in Figures 1b and 1d), which match the trends reported by Coley and Heelis (1998) and Spicher et al. (2017), are caused by the reliance on only relative tests for patches (e.g., the peak must be greater than double the background) in those algorithms. This approach misses the large density enhancements present in SH summer, because the background density is too high to count the enhancements, but does count very small fluctuations in SH winter, where densities are very low. The problem of varying background levels of ionization does not afflict the NH because seasonal variations in ambient ionization levels are smaller there due to the ionospheric annual asymmetry

(e.g., Rishbeth & Müller-Wodarg, 2006). This problem can be successfully addressed by adding an absolute test for density enhancements (e.g., 4 TECU in the case of NOJA, or 1,000 times the 81 day averaged $F_{10.7}$ in el/cm^3 in our algorithm D3).

These observations indicate that Crowley's (1996) widely used criterion, which is that a patch is at least double the background density, should be revised in order to appropriately characterize patch occurrence rates in the SH. Algorithm D3 addresses this issue, as well as the problem of multiple counting found in NOJA's approach, which led to approximately a 5 times overestimation in the number of detections in D2 compared to D3. It has to be noted that none of these detection algorithms is capable of distinguishing between true patches (enhanced density islands) and extended ridgelike enhancements across the observational track. Likewise, height redistribution of the plasma could potentially represent a further confounding factor.

5. Conclusions

The results in this paper show that large high-latitude F region density enhancements, or patches, occur more frequently around December than around June in both the NH and SH. Therefore, the occurrence rate of patches does not follow local season, being higher in NH summer and SH winter. The cause of this annual occurrence rate is not known and does not fit with existing formation theory. Patch detection algorithms using only relative magnitude criteria can miss large density structures that are present in SH summer and erroneously count small fluctuations in SH winter. This detection issue is exacerbated by the ionospheric annual asymmetry. For topside data, the widely used definition that a patch constitutes a doubling of the background density needs to be revised. By testing for an absolute density enhancement above a threshold, whose magnitude is linked to solar flux, it is possible to detect the large enhancements seen in the data and avoid counting much smaller fluctuations. A revision of patch formation theory is likely to be required to explain the observed large density enhancements in SH summer, and the absence of such enhancements in winter.

References

Balmforth, H. F., Moffett, R. J., & Rodger, A. S. (1999). Localised structure in the cusp and high latitude ionosphere: A modelling study. *Annales Geophysicae*, *17*(4), 455–462. https://doi.org/10.1007/s00585-999-0455-0

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

Buchert, S., Zangerl, F., Sust, M., André, M., Eriksson, A., Wahlund, J., & Opgenoorth, H. (2015). SWARM observations of equatorial electron densities and topside GPS track losses. *Geophysical Research Letters*, *42*, 2088–2092. https://doi.org/10.1002/2015GL063121

Carlson, H. C. (2012). Sharpening our thinking about polar cap ionospheric patch morphology, research, and mitigation techniques. *Radio Science*, *47*, RS0L21. https://doi.org/10.1029/2011RS004946

Christensen, E. F., Lühr, H., & Hulot, G. (2006). Swarm: A constellation to study the Earth's magnetic field. *Earth, Planets and Space*, *58*(4), 351–358. https://doi.org/10.1186/BF03351933

Coley, W. R., & Heelis, R. A. (1995). Adaptive identification and characterization of polar ionization patches. *Journal of Geophysical Research*, *100*(A12), 23,819–23,827. https://doi.org/10.1029/95JA02700

Coley, W. R., & Heelis, R. A. (1998). Seasonal and universal time distribution of patches in the northern and southern polar caps. *Journal of Geophysical Research*, *103*, 29,229–29,237. https://doi.org/10.1029/1998JA900005

Cortie, A. L. (1912). Sunspots and terrestrial magnetic phenomena, 1898–1911. *Monthly Notices of the Royal Astronomical Society*, *73*(1), 52–60. https://doi.org/10.1093/mnras/73.1.52

Crowley, G. (1996). In W. R. Stone (Ed.), *Critical review of ionospheric patches and blobs, Review of Radio Science*, 1993-1996 (p. 619). New York: Oxford University Press.

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

Goodwin, L. V., Iserhienrhien, B., Miles, D. M., Patra, S., Meeren, C., Buchert, S. C., … Moen, J. (2015). Swarm in situ observations of F region polar cap patches created by cusp precipitation. *Geophysical Research Letters*, *42*, 996–1003. https://doi.org/10.1002/2014GL062610

Hill, G. E. (1963). Sudden enhancements of F-layer ionization in polar regions. *Journal of the Atmospheric Sciences*, *20*(6), 492–497. https://doi.org/10.1175/1520-0469(1963)020%3C0492:SEOLII%3E2.0.CO;2

Knudsen, D. J., Burchill, J. K., Buchert, S. C., Eriksson, A. I., Gill, R., Wahlund, J.-E., … Moffat, B. (2017). Thermal ion imagers and Langmuir probes in the Swarm electric field instruments. *Journal of Geophysical Research: Space Physics*, *122*, 2655–2673. https://doi.org/10.1002/2016JA022571

Lockwood, M., & Carlson, H. C. Jr. (1992). Production of polar cap electron density patches by transient magnetopause reconnection. *Geophysical Research Letters*, *19*(17), 1731–1734. https://doi.org/10.1029/92GL01993

Mannucci, A., Iijima, B., Lindqwister, U., Pi, X., Sparks, L., & Wilson, B. (1999). *GPS and ionosphere*. URSI Reviews of Radio Science, Wiley-IEEE Press.

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

Oksavik, K., Ruohoniemi, J. M., Greenwald, R. A., Baker, J. B. H., Moen, J., Carlson, H. C., … Lester, M. (2006). Observations of isolated polar cap patches by the European Incoherent Scatter (EISCAT) Svalbard and Super Dual Auroral Radar Network (SuperDARN) Finland radars. *Journal of Geophysical Research*, *111*, A05310. https://doi.org/10.1029/2005JA011400

Pinnock, M., Rodger, A. S., Dudeney, J. R., Baker, K. B., Newell, P. T., Greenwald, R. A., & Greenspan, M. E. (1993). Observations of an enhanced convection channel in the cusp ionosphere. *Journal of Geophysical Research*, *98*, 3767–3776. https://doi.org/10.1029/92JA01382

Rishbeth, H., & Müller-Wodarg, I. C. F. (2006). Why is there more ionosphere in January than in July? The annual asymmetry in the *F*2-layer. *Annales Geophysicae*, *24*(12), 3293–3311.

Rodger, A. S., & Graham, A. C. (1996). Diurnal and seasonal occurrence of polar patches. *Annales Geophysicae*, *14*(5), 533–537. https://doi.org/10.1007/s00585-996-0533-5

Rodger, A. S., Pinnock, M., Dudeney, J. R., Baker, K. B., & Greenwald, R. A. (1994). A new mechanism for polar patch formation. *Journal of Geophysical Research*, *99*, 6425–6436. https://doi.org/10.1029/93JA01501

Russell, C. T., & McPherron, R. L. (1973). Semiannual variation of geo-magnetic activity. *Journal of Geophysical Research*, *78*, 92–108. https://doi.org/10.1029/JA078i001p00092

Sojka, J. J., Bowline, M. D., & Schunk, R. W. (1994). Patches in the polar ionosphere: UT and seasonal dependence. *Journal of Geophysical Research*, *99*, 14,959–14,970. https://doi.org/10.1029/93JA03327

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

Tsunoda, R. T. (1988). High-latitude *F* region irregularities: A review and synthesis. *Reviews of Geophysics*, *26*, 719–760. https://doi.org/10.1029/RG026i004p00719

Weber, E. J., & Buchau, J. (1981). Polar cap *F*-layer auroras. *Geophysical Research Letters*, *8*, 125–128. https://doi.org/10.1029/GL008i001p00125

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*, 1683–1694. https://doi.org/10.1029/JA089iA03p01683

Whitteker, J. H. (1976). The magnetospheric clefts ionospheric effects. *Journal of Geophysical Research*, *81*, 1279–1288. https://doi.org/10.1029/JA081i007p01279