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Key Points:

- Small-scale (~1–10 km) plasma structure dissipation in the *F* region ionosphere is inferred from spectral breaks in Swarm density power spectra
- The occurrence rate of spectral breaks and the steepness of the power spectra vary in close accordance with local season
- *E* region conductivity-driven plasma structure diffusion is important for the observed *F* region small-scale irregularity dissipation

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Direct Evidence for the Dissipation of Small-Scale Ionospheric Plasma Structures by a Conductive *E* Region

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Abstract The conductivity of the ionospheric *E* region is known to cause effective dissipation of plasma structures in the *F* region. We use 3.5 years of 16-Hz sampling rate electron density measurements from the Swarm advanced data set to investigate seasonal dependencies of plasma structure dissipation. Using a novel algorithm to infer plasma structure dissipation through detection of spectral breaks in density fluctuation power spectra, we analyze 100,000 spectra based on data from Swarm A in both the northern and southern polar caps. For the first time, we can present long-term development of small-scale (~1–10 km) plasma structure diffusion in the high-latitude ionospheric *F* region. We discuss possible reasons for these variations. This study presents evidence for the *E* region as an important factor in the seasonal variation of *F* region plasma irregularity amplitudes.

1. Introduction

In the high-latitude ionosphere, there exists plasma structures on a wide range of scales, from the decameter-scale gyroradius of thermal ions up to 100-km-sized polar cap patches and auroral blobs (Tsunoda, 1988). Small-scale plasma irregularities are linked to the rapid scintillations in the signal phase and amplitude of satellite communication signals (Kintner et al., 2007; Yeh & Liu, 1982). At the same time, global navigational satellite systems are on track to play a larger role in the operation of global shipping and air traffic, highlighting the importance of understanding ionospheric plasma structuring (Jin et al., 2014; Moen et al., 2013).

The development of high-latitude plasma irregularities is usually realized through variations of ion polarization currents (Keskinen & Huba, 1990; Kintner & Seyler, 1985). Particular irregularity source mechanisms that are of importance to high-latitude ionospheric structuring are gradient drift instability, current-convective instability, and Kelvin-Helmholtz instability (Kintner & Seyler, 1985; Tsunoda, 1988). The gradient drift instability has its origin in steep plasma density gradients often provided by the edges of polar cap patches and plasma blobs (Mounir et al., 1991). A plasma drift velocity parallel and directional to the density gradient causes ion-electron charge separation, leading to polarization electric fields amplifying and growing initial plasma fluctuations in an unstable feedback loop (Tsunoda, 1988). Intimately related to the gradient drift instability, the current-convective instability mechanism also has its origin in polarization electric fields-induced charge separation but requires the presence of an electron current, in addition to a parallel electric field (Kintner & Seyler, 1985). In the high-latitude ionosphere, the current that needed to produce current-convective instability is provided by the magnetic field line-aligned Birkeland currents. The Kelvin-Helmholtz instability, a fluid instability driven by the kinetic energy of the plasma stream, develops when the plasma flow exhibits a spatially varying velocity, or shear, which in turn stems from an inhomogeneous electric field (Horton et al., 1987; Keskinen et al., 1988).

Particle precipitation is important for the production of plasma irregularities and is thought to be an important source for plasma structuring on the dayside (Kelley et al., 1982; Moen et al., 2012). Inside the polar cap, precipitation is less intense, and field-aligned currents are usually absent, meaning that there are fewer plasma irregularity sources. However, large-scale convection patterns transport plasma through the polar cap from the dayside to the nightside (Dungey, 1961; Siscoe & Huang, 1985). This transport of plasma from particle precipitation-driven source regions into the polar cap proper is an important reason for observed polar cap plasma structures (Cowley, 2000; Kelley et al., 1982).

The pressure gradient at the edges of plasma structures causes diffusion into the surrounding plasma. This is an important process in the decay of plasma structures (Vickrey & Kelley, 1982). Diffusion causes structures to dissipate. The presence of a conducting ionospheric *E* region serves to speed up the diffusion of plasma structures in the *F* region (Basu et al., 1988; Danskin et al., 2002; Kane et al., 2012; Kelley et al., 1982; Kivanc & Heelis, 1998; Milan et al., 1999; Vickrey & Kelley, 1982). The electric connection along the magnetic field lines provides a channel for electrons to move between the *F* and *E* regions, allowing *F* region plasma structures to decay significantly faster than they could in the absence of a highly conductive *E* region (Vickrey & Kelley, 1982). The *E* region conductivity is typically provided by photoionization and energetic particle precipitation, and incident sunlight in the high-latitude ionosphere naturally displays a strong seasonal dependence. This causes a much lower *E* region conductivity during local winter—when there is no sunlight in the polar cap—compared to local summer. Using data from the Dynamics Explorer 2 spacecraft, Kivanc and Heelis (1998) find evidence for increased *E* region dissipation of high-latitude *F* region plasma structures during local summer. Considering the slope in the power spectra of ion density and velocity fluctuations, they conclude that during local winter, *E* region dissipation is virtually absent in the polar cap, allowing large-scale convection to inject structures across a range of scales into the polar cap.

Seasonal variations in the high-latitude ionospheric plasma irregularities have been observed in a number of studies, showing evidence for an increase of irregularity amplitude during local winter (Ghezlbash et al., 2014; Heppner et al., 1993). Studies also show an increase in ionospheric scintillations during local winter (Aarons et al., 1981; Basu et al., 1988; Jin et al., 2018; Li et al., 2010; Prikryl et al., 2015). This would indicate an increase in the <1-km irregularities associated with scintillations (Mitchell et al., 2005; Pi et al., 1997; Yeh & Liu, 1982; Skone et al., 2001). Investigating seasonal variations in the characteristics and number of polar cap patches, several studies find that patches are significantly more numerous and long lived during local winter (Coley & Heelis, 1998; Foster, 1984; Schunk & Sojka, 1987; Spicher et al., 2017; Wood & Pryse, 2010). However, conflicting evidence exists for the Southern Hemisphere winter (Chartier et al., 2018; Noja et al., 2013). As the large density gradients found on the edges of polar cap patches are strongly associated with small-scale plasma structures, the seasonal variation in polar cap patch occurrence partially explains the increase in small-scale plasma structuring during local winter (Tsunoda, 1988).

In this study we present results on seasonal variations in plasma structure dissipation, using 3.5 years of high-resolution (16 Hz) plasma density observations from the Swarm advanced data set. The major advantage of the present study lies in a novel method for inferring plasma structure dissipation through an advanced power spectral density (PSD) analysis. This allows us to present a unique insight into the long-term development of structure dissipation in the polar caps. Our results indicate that the role played by the ionospheric *E* region in balancing the proliferation of small-scale (~ km) plasma structures in the polar caps might be greater than hitherto believed.

2. Methodology and Data

The PSD of measured ionospheric quantities such as electron density is a particularly useful tool when considering physics over a range of scales, since the distribution of power across the frequency spectrum reflects the scales in which the measured quantity fluctuates (Stoica & Moses, 2005). The power spectrum of measured high-latitude ionospheric plasma density fluctuations can often be described by a power law (Mounir et al., 1991; Phelps & Sagalyn, 1976; Spicher et al., 2014; Tsunoda, 1988):

$$P(f) \propto f^{-\alpha}, \quad (1)$$

where P is the PSD, f denotes frequency, and α is a real-valued exponent. Many studies that utilize PSD focus on the exponent α , which is the linear slope of the fitted curve in a logarithmic representation. A slope of $\alpha \approx 5/3 = 1.67$ is associated with plasma irregularities such as gradient drift and current convective instabilities (Basu & Coppi, 1988; Kintner & Seyler, 1985). Simulating plasma structuring in the high-latitude ionosphere, Keskinen and Huba (1990) found that plasma structures transition from being mixed between the large-scale inertial regime and the smaller-scale collisional regime to being in the purely collisional regime on a characteristic spatial scale around 2–3 km. They concluded that the collisional regime exhibits a steeper spectral slope than the inertial regime. Using data from the Atmosphere Explorer D mission, Basu et al. (1984) found a steepening in the higher frequencies of plasma density power spectra measured in the high-latitude *F* region auroral zone. They found the spectra to steepen significantly at scales lower than 1 km and interpreted this to be a signature of *E* region dissipation of small-scale plasma structures.

In this study we use the 16-Hz advanced plasma density data set from the Swarm satellite constellation (Friis-Christensen et al., 2006; Knudsen et al., 2017). The data set covers the time period from 1 November 2014 to 28 August 2018, with some small gaps existing in the data coverage. In this study, we present data from Swarm A, though the analysis performed has been applied to data from all three of the Swarm satellites with similar results. To avoid sampling plasma from the auroral regions, where sources of small-scale plasma structuring such as particle precipitation can be high regardless of season, we only use data sampled inside the polar caps, which we conservatively take to be data that was measured poleward of $\pm 77^\circ$ magnetic latitude, with magnetic latitude calculated using the altitude-adjusted corrected geomagnetic coordinates system (Baker & Wing, 1989). We bin the data in time, using 60-s segments, meaning each bin covers approximately 440 km. The particular bin size was chosen after extensive testing: we obtained similar albeit more noisy results using 30-s bins. From each bin we collect the plasma density, and analyze the sampled density fluctuation power spectrum. Additionally, we compute the solar zenith angle at 110-km altitude (directly beneath the location sampled at 460-km altitude), which roughly corresponds to the location of the *E* region.

In analyzing the PSD, we use both the conventional fast Fourier transform (FFT) and a variant of Welch's PSD (Welch, 1967). The latter method consists of averaging modified periodograms over a logarithmically spaced spectral range (Tröbs & Heinzel, 2006). While the conventional FFT provides a low resolution on lower frequencies in a logarithmic representation, the modified Welch's method gives our spectra a fixed-interval logarithmic resolution. Similar albeit more noisy results are obtained when using conventional FFT. To avoid spectral leakage, we center the bin density data around 0 cm^{-3} by subtracting the mean density and apply a Hann window to every bin prior to the power spectral analysis.

To identify steepening in the power spectra akin to such identified by Kivanc and Heelis (1998), we will look for spectral breaks, or knees, in our spectra. Such a break would indicate that the power spectrum is best described by composite power law

$$P(f) \propto \begin{cases} f^{-\alpha_1}, & \text{for } f \leq f_b, \\ f^{-\alpha_2}, & \text{for } f \geq f_b, \end{cases} \quad (2)$$

where f_b is the frequency at which the spectrum starts to steepen and $\alpha_{1,2}$ represents the initial and second slopes, for the low- and high-frequency ranges, respectively. In order to determine whether a power spectrum exhibits a spectral break and consequent steepening, we use a least squares fit, in the shape of a piecewise Hermite function, as documented in D'Errico (2017). This method locates the position of the break between the two linear (in a log-log representation) sections by minimizing the overall root-mean-square error of the fit. Using the logarithmic resolution modified Welch's method for computing power spectra, combined with the piecewise Hermite function fit for locating spectral breaks, we have developed a novel method for PSD analysis. Due to inaccuracies in the low- and high-frequency limits, we constrain the location of the spectral break to [0.21 Hz, 6.7 Hz], values inferred after extensive testing. Neglecting local plasma flow velocity with respect to satellite velocity, this interval corresponds roughly to spatial scales between [36.0 km, 1.1 km]. Whether the identified curve break implies a dual slope spectrum or not is determined by the difference between α_1 and α_2 . In Figure 1, three example spectra are shown, one in which a dual slope is identified, one in which a single slope fits the spectrum, and one where the spectrum hits a characteristic noise floor, which leads to an artificial shallowing of the spectrum. The latter bins are discarded.

After having binned all the density measurements from the polar caps, we are left with 100,000 bins. For each bin, we store the value of the initial (α_1) and the second (α_2) slopes, and the median solar zenith angle. Additionally, we compute the “dual slope index,” which we define as the *proportion* of spectra exhibiting a spectral break during a 24-hr window, a time period that will on average capture 16 polar cap passes in both hemispheres. Interpolating in time through the binned data, we construct time series from the dual slope index, the slope values, and the sampled solar zenith angle, lasting from 1 January 2015 to 1 July 2018. However, the time series are naturally volatile, with large variations resulting from the local conditions of each observation. To capture long-term seasonal variations in the derived quantities, we take a 3-month running average of each time series.

3. Results

In Figure 2 we present the seasonal variations in the dual slope statistics, for the Northern (a and b) and Southern (c and d) Hemispheres, for the 3.5-year time period from January 2015 to July 2018. In Figures 2a

Figure 1. Dual slope classification of power spectral density diagrams and the corresponding plasma density measurements. In the left column, a dual slope spectrum is found in a plasma density measurement bin with a spectral break at 1.4 Hz. α_1 and α_2 correspond to the initial and second slopes, respectively (see equation (2)). In the middle column, a single slope spectrum is identified, and α_0 is the single slope value. The spectrum in the right column hits a noise floor around 2×10^3 P/Hz and is discarded.

and 2c, we show the *E* region-adjusted solar zenith angle on the left axis (blue), and the dual slope index on the right axis (orange), giving the proportion of spectra exhibiting steepening in a 24-hr window. All quantities are smoothed with a 3-month running median window, and colored shaded areas indicate the upper lower quartile distributions in the 3-month running window. The median solar zenith angle takes values from around 70° during local summer when the polar caps are in perpetual sunlight to around 110° during local winter, when the polar caps are not at all exposed to incident sunlight. Looking at the dual slope index, we see that on average around 65% of the analyzed spectra exhibit steepening during local summer, while this proportion is lowered to around 30% during local winter.

In Figures 2b and 2d, we show the value of the initial slope (left axes, blue) and the value of the second slope (right axes, orange), again smoothed with a 3-month running window. Both the initial and the second slopes follow the same trend as the dual slope index. That is, during local summer, when there is a proportional increase in the number of spectra exhibiting a spectral break, both the initial and second slopes steepen. However, the local summer steepening of the *second slope* is substantially more pronounced than that of the initial slope. The second slope steepens from a spectral index of around 2.4 during local winter to around 2.9 during local summer, for both hemispheres, though there is a considerable spread in the slope data during all seasons. Overall, the values of the initial slope data vary around a median of 1.32 ± 0.48 for the Northern Hemisphere and 1.29 ± 0.48 for the Southern Hemisphere, with the uncertainty given by 68% confidence intervals. Likewise, the value of the second slope varies around a median of 2.85 ± 0.61 and 2.80 ± 0.65 for the Northern and Southern Hemispheres, respectively.

We observe a slight solar cycle trend in the data, with the average proportion of spectra exhibiting a spectral break decreasing toward solar cycle minimum. Likewise, the spectral slope steepness undergoes a shallowing toward solar cycle minimum. Note, though, that our data set only covers 3.5 years out of an 11-year solar cycle, and as such, the solar cycle trends we observe should be investigated further using more data.

Collectively, of the 100,000 spectra analyzed from polar cap overpasses made by Swarm A during the time period considered, 49% and 44% exhibit a dual slope for the Northern and Southern Hemispheres, respectively, averaged over all seasons. The spectral location of the break, which does not exhibit clear seasonal variations, corresponds on average to spatial scales of 5.8 km for the Northern and Southern Hemispheres, with 68% confidence intervals varying between 2.7 and 12.5 km for the Northern Hemisphere and between 2.6 and 13.0 km for the Southern Hemisphere. It should be mentioned that, based on in situ measurements in the high-latitude ionosphere, spectral breaks have been found to occur on a large variety of scales: at 800 m (Villain et al., 1986), at 125 m (Basu et al., 1990), at 40 m (Mounir et al., 1991), and at 20 m

Figure 2. (a) Three-month running average of the *E* region-adjusted solar zenith angle (left axes, blue) and the dual slope index (right axes, orange) for the Northern Hemisphere. (b) Three-month running average of the initial slope (left axes, blue) and the second slope (right axes, orange) for the Northern Hemisphere. (c) Equivalent to panel (a) for the Southern Hemisphere. (d) Equivalent to panel (b) for the Southern Hemisphere. In all panels, upper and lower quartile distributions of the raw data are given by the colored shaded areas. Note that for panels (b) and (d), to aid comparison, the left and right y axes span an equal range of values.

Figure 3. (left panels) Second slope 3-month running average data distribution (blue) and a first-order polynomial fit of the latter as a function of E region-adjusted solar zenith angle (orange), for both hemispheres. (right panels) The 3-month running average of the second slope data (blue solid lines) and the linear model (orange dotted lines) for Northern (top) and Southern (bottom) Hemispheres.

(Spicher et al., 2014). The scale of the spectral break found in the present study roughly matches the scale at which Keskinen and Huba (1990) found that irregularities should transition to a fully collisional regime. Note also that the scale of the spectral break found the present study coincides with the ion skin depth. The ion skin depth, or ion inertial scale, is defined as $I_i = c/\Omega_{pi}$, where c is the speed of light and Ω_{pi} is the ion plasma frequency (Stenson et al., 2017). In the data set considered, using Swarm A density measurements and assuming an atomic oxygen ion plasma, the ion skin depth takes on mean values of 2.8 and 2.9 km for the Northern and Southern Hemispheres, respectively, with 68% confidence intervals varying between 2.1 and 5.2 km for the Northern Hemisphere and between 2.0 and 15.1 km for the Southern Hemisphere.

4. Discussion

Inspecting the running average curves in Figure 2, we see clear seasonal variations in both the dual slope occurrence rate and the steepness of the dual slope spectra. An explanation for these variations is diffusion of plasma structures caused by a highly conducting E region, as first modeled by Vickrey and Kelley (1982). During local summer, photoionization increases the E region conductivity, meaning electrons can neutralize the space charge associated with ion diffusion. The absence of photoionization during local winter retards the ion diffusion by constricting the E region conductivity, resulting in F region plasma structures diffusing at a slower electron diffusion rate (Vickrey & Kelley, 1982). The plasma structure dissipation observed in the abundance of local summer dual slope spectra serves to remove plasma structures on scales smaller than the spectral break and thus lowering the small-scale plasma irregularity amplitude. This explains the observed low occurrence of scintillations during local summer (Basu et al., 1988; Jin et al., 2018; Li et al., 2010; Prikryl et al., 2015) and conversely the reported increase in winter irregularities (Ghezlbash et al., 2014; Heppner et al., 1993). The general decline in extreme ultraviolet radiation from the Sun as the solar cycle approaches minimum would then cause a lowering of E region conductivity and a lowering of the dual slope index. This may explain the long-term trends we tentatively observe in the data.

To illustrate the seasonal dependency of the second slope data, we can fit the second slope data as a first-order polynomial function of solar zenith angle. In Figure 3 left, we show the data distributions and the resulting linear fit, where we use data from both the Northern and Southern Hemispheres, since the zenith angle dependency is similar for both hemispheres. The linear model is given by

$$\alpha_2 = 3.846 - 0.013 \cdot Z, \quad (3)$$

where Z is the solar zenith angle in degrees, at an altitude of 110 km. In the right panels of Figure 3, we show the 3-month running average of the second slope data in solid blue lines and equation (3) in dotted orange lines. Here due to the clear seasonal variations in the occurrence and steepness of dual slope spectra, we see an excellent agreement between the first-order polynomial model and the observations. Thus, we conclude that E region conductivity due to high summer photoionization rates cause a substantial dissipation of small-scale (~ 1 -10 km) F region plasma structures in the polar caps. Furthermore, the local summer increase in dual slope occurrence and steepness then serves as direct evidence for the E region as an important factor in controlling observed plasma structure dissipation in the F region polar caps.

5. Conclusion

E region magnetic field-aligned conductivity causes F region plasma structures to diffuse effectively. By using a new algorithm for detecting dual slope power spectra in high-latitude density measurements, coupled with solar zenith angle, we can infer structure dissipation and thus the presence of plasma diffusion from the 16-Hz Swarm plasma density data set. Having analyzed 3.5 years of density measurements, we present the first long-term seasonal overview of the changes in small-scale plasma structure dissipation due to E region-induced plasma diffusion. During local summer, small-scale ionospheric plasma structures in the polar caps are effectively and frequently being dissipated, as opposed to during local winter.

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