1 Introduction

Space weather refers to a variety of phenomena that originate from the sun and affect the Earth's magnetosphere, thermosphere, and ionosphere. Space weather can have adverse effects on human technology, such as power grid failure, radiation, damage of near-earth satellites, and disturbances of communication and satellite positioning and navigation systems. Modern technology relies increasingly upon satellite communication, used for example in positioning and navigation systems. Thus, for satellite communication and navigation systems, space weather is an important field of study. Understanding the underlying drivers for space weather effects, and ultimately predicting space weather events, is an important step forward.

Disturbances on signals propagating through the ionosphere manifest as rapid fluctuations in phase and amplitude, called scintillations (Kintner et al., 2007; Yeh & Liu, 1982). Scintillations are associated with irregularities in electron density, which are found in events like storm-enhanced density, auroral precipitation, and polar cap patches (Alfonsi et al., 2011; De Franceschi et al., 2008; Jin et al., 2014, 2015, 2016; Mitchell et al., 2005; Moen et al., 2013; Prikryl et al., 2010, 2015; Spogli et al., 2009). Scintillations degrade position accuracy and can cause loss of lock (Aarons, 1982; Garner et al., 2011; Jacobsen & Andalsvik, 2016; Mitchell et al., 2005; Moen et al., 2013; Prikryl et al., 2010, 2015; Spogli et al., 2009). Scintillations degrade position accuracy and can cause loss of lock (Aarons, 1982; Garner et al., 2011; Jacobsen & Andalsvik, 2016; Mitchell et al., 2005; Moen et al., 2013; Prikryl et al., 2010, 2015; Spogli et al., 2009).

A statistical study (Jin et al., 2016) found that in the Scandinavian sector, the most prevalent space weather effect on the Global Positioning System (GPS) were phase scintillations and that the most severe scintillations occurred at nighttime. They found that the scintillations are caused by patches of high-density plasma (polar cap patches) exiting the polar cap and being pulled into the auroral oval during tail reconnection. In this study, we focus our interest on such scintillations caused by polar cap patches on GPS signals in the Scandinavian Arctic region.

Polar cap patches are clouds of high-density plasma, usually defined as at least two times the density of the surrounding plasma (Crowley, 1996). Patches have been found to cause scintillations of GPS satellite signals (e.g., Basu et al., 2002; Buchau et al., 1985; Clausen et al., 2016; Jin et al., 2014, 2016; Meeren et al., 2015; Prikryl et al., 2010; Spogli et al., 2009; Weber et al., 1986). Polar cap patches are created on the dayside, by one of several possible mechanisms behind polar cap patch creation (Moen et al., 2006; Zhang et al., 2011, provides a summary). When the interplanetary magnetic field (IMF) is directed southward, the twin-cell convection system carries the patches across the polar cap with velocities up to 1,000 m/s (Moen et al., 2015;
When the patch enters the auroral oval, the patch reconfigures into a blob (Crowley et al., 2000) and causes scintillations.

A space weather forecast that could predict the arrival of polar cap patches into the nightside auroral boundary would be highly beneficial. Industries that rely on satellite communication systems, like aviation, agriculture, civil engineering, and the maritime sector can save time, fuel, and money if they have access to a space weather forecast. This paper outlines a method to predict severe space weather events caused by polar cap patches in the European Arctic sector.

2. Methodology

We will first explain our prediction model in section 2.1, which consists of two parts. First, a reference table that provides an approximation to the total electron content at any given day and any given location in the polar region. We use GPS total electron content (TEC) data from MIT Haystack's Madrigal CEDAR database to establish our reference TEC table. Furthermore, we have included a decay rate that allows us to calculate the expected evolution of TEC magnitude for every time step throughout the simulation. Second, the expanding/contracting polar cap paradigm (ECPC) (Cowley & Lockwood, 1992; Lockwood & Cowley, 1992) provides a convection model that transports the plasma patch from the dayside reservoir to the nightside by means of dayside and nightside reconnection. The convection model takes Super Dual Auroral radar network (SuperDARN) cross polar cap potentials as input and calculates propagation velocity at each point in the polar cap, for each time step.

The instruments used to verify our method is presented in section 2.2. We consider a geomagnetically disturbed event on 26 September 2011. The event was caused by a coronal mass ejection, which led to a significant increase in high-density plasma in the polar cap ionosphere and the formation of a polar cap patch. The patch drifted across the polar cap and, as will be shown later, caused scintillations in GPS receivers in Svalbard.

2.1. Forecasting Model

2.1.1. Convection Model

The ECPC paradigm is a model that explains the high-latitude ionosphere's response to changes in magnetospheric driving. The idea of an inflating/deflating polar cap was first introduced by Siscoe and Huang (1985). Cowley and Lockwood (1992) and Lockwood and Cowley (1992) elaborated on the different convection patterns that are established under different solar wind conditions, substorms, and changes in reconnection rates on the nightside and dayside (Lockwood et al., 1993; Moen et al., 1995). This paper uses the ECPC model as presented by Freeman (2003), modified to include a nightside merging gap (Milan, 2013; Walach et al., 2017). Below is a summary of the salient features.

The model assumes that the magnetic field in the high-latitude ionosphere is stationary, which is reasonable for the time scales considered in patch transportation, which is hours. Accepting stationarity, the relationship between the irrotational electrostatic potential $\Phi$ and the associated electric field $E$ is given by

$$E = -\nabla \Phi.$$  \hspace{1cm} (1)

We consider the current in the polar cap region perpendicular to the magnetic field, $J_\perp$. The relationship to the electric field is given by

$$J_\perp = \Sigma_p E + \Sigma_H \hat{B} \times E,$$  \hspace{1cm} (2)

where $\hat{B}$ is the unit vector of the magnetic field and $\Sigma_p$ and $\Sigma_H$ are the height-integrated Pedersen and Hall conductivities, respectively. We assume uniform conductivity in the polar cap and return flow region, implying that the field-aligned currents are restricted to the boundaries between regions. There are no field-aligned currents into or out of the ionosphere polar cap, so the divergence of the perpendicular current is zero, $\nabla \cdot J_\perp = 0$. Taking the divergence on both sides of equation (2) and substituting for $E$ by equation (1) reduces the current problem to that of solving Laplace's equation in the polar cap and on the polar cap boundary:

$$\nabla^2 \Phi = 0.$$  \hspace{1cm} (3)

Again, we assume that there are no spatial gradient in the Pedersen and Hall conductivities. Next, we assume that the ionosphere is a thin, spherical shell, such that equation (3) has two variables, colatitude $\lambda$ and local
time \( \theta \). The coordinate system is oriented such that \( \theta = 0 \) at local midnight, \( \theta = \pi / 2 \) at 06 magnetic local time (MLT) and \( \theta = \pi \) at magnetic local noon. Laplace’s equation (3) can then be written as

\[
\nabla^2 \Phi = \frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial \theta^2} = 0, \quad (4)
\]

where we have used the substitution \( x = \ln \left\{ \tan \left( \frac{\theta}{2} \right) \right\} \). The convection model assumes that the polar cap boundary coincides with the open/closed field line boundary and that it is circular and centered on the Earth’s geomagnetic pole.

We assume that all magnetic reconnection takes place in merging gaps of half-width \( \Theta = \pi / 6 \), that is, \( \Theta_N = \Theta_D = \pi / 6 \). The corresponding lengths are \( L_D = 2\Theta_N R_E \sin(\lambda_1) \) and \( L_N = 2\Theta_D R_E \sin(\lambda_1) \), where \( R_E \) is the earth’s radius, and \( \lambda_1 \) is the colatitude of the polar cap boundary. The gaps are centered at \( \theta = 0 \) for the nightside gap and \( \theta = \pi \) for the dayside gap. The remainder of the polar cap boundary is adiabatic, that is, there is no plasma flow across the boundary (Siscoe & Huang, 1985).

We define three regions separated by boundaries located at \( x_1 \) and \( x_2 \). Latitudes \( x < x_1 \) are defined as the polar cap, and the \( x_1 \) is the open/closed field line boundary. Latitudes \( x_1 < x < x_2 \) make up the return flow region, such that \( x_2 \) is the equatorward limit of the convection pattern, also known as the Heppner-Maynard boundary after the works of (Heppner & Maynard, 1987). Latitude equatorward of \( x_2 \) have zero current in this model.

The amount of open magnetic flux in the polar cap, \( F_{PC} \), varies with the amount of dayside \( \Phi_D \) and nightside \( \Phi_N \) reconnection (Siscoe & Huang, 1985):

\[
\frac{dF_{PC}}{dt} = \Phi_D - \Phi_N. \quad (5)
\]

Assuming a dipolar magnetic field with strength \( B \) and a given polar cap flux, the polar cap boundary radius \( \lambda_1 \) is can be found from

\[
F_{PC} = 2\pi BR_E^2 \sin^2(\lambda_1). \quad (6)
\]

Equations (5) and (6) allow us to find the location of the open/closed field line boundary for a given flux, and by its derivative, the speed at which the boundary moves, \( v_{x_1} \):

\[
v_{x_1} = \frac{\Phi_D - \Phi_N}{2\pi R_E^2 B \sin(2\lambda_1)}. \quad (7)
\]

The electric field along the adiabatic portions of the boundary is given by \( \mathbf{E} = -\mathbf{V} \times \mathbf{B} \). Now we may find the electric field component parallel to the polar cap boundary around the circumference:

\[
E_p(\lambda_1, \theta) = \begin{cases} 
-v_{x_1} B_r & \text{if } \Theta_N < |\theta| < \pi - \Theta_D \\
v_{x_1} B_r + \frac{\Phi_N}{2\Theta_N} & \text{if } |\theta| > \pi - \Theta_D \\
-v_{x_1} B_r - \frac{\Phi_D}{2\Theta_D} & \text{if } |\theta| < \pi - \Theta_N.
\end{cases} \quad (8)
\]

Where \( B_r \) is the radial component of the earth’s magnetic field, such that \( B_r = 2B \cos \lambda \).

We find the potential at the polar cap boundary \( x_1 \) by integrating the electric field around the boundary, \( E_p \), as shown by Milan (2013; equation 14):

\[
\Phi_{x_1} = -R \sin \lambda_1 \int_0^\pi E_p(\lambda_1, \theta) d\theta. \quad (9)
\]

Knowing the potential at the polar cap boundary, we can find the solution for the rest of the polar region by equation (10).

\[
\Phi(x, \theta) = \begin{cases} 
\sum_{m=1}^{x_1} c_m \exp m(x - x_1) \sin(m\theta) & \text{if } x \leq x_1 \\
\sum_{m=1}^{x_2} c_m \sinh m(x - x_2) \sinh m(x - x_1) \sin(m\theta) & \text{if } x_1 < x \leq x_2 \\
0 & \text{if } x > x_2.
\end{cases} \quad (10)
\]
Figure 1. Reference TEC values for the northern polar cap, 21 March 2011. The unit is TEC units (TECu), where 1 TECu = \(10^{-16}\) electrons. Latitude is indicated at \(10^\circ\) intervals and magnetic local time is shown around the circumference, with 12 (noon) toward the top of the page. Each bin contains the median value for that bin over a period of 31 days, that is, 21 March 2011 ± 15 days. TEC = total electron content.

where \(c_m\) are the coefficients of a Fourier expansion of the potential at the polar cap boundary:

\[
c_m = \frac{1}{\pi} \int_0^{2\pi} \Phi(x_1(\theta)) \sin(m\theta) d\theta.
\]

For ease of computation, we use \(m = 1.20\).

Solving equation (10) for each time step allows us to calculate the flow speed using

\[
V = \frac{E \times B}{B^2}
\]

such that

\[
v_\lambda = -\frac{E \theta}{B r},
\]

\[
v_\theta = \frac{E_\lambda}{B r}.
\]

2.1.2. Plasma Density

Current observation techniques of the ionosphere provide good coverage of the TEC in the northern polar cap, but there is a significant time lag of several days before data are available. In a space weather forecast, we need data in real time, which is currently unavailable. Substantial work has been done to establish an empirical model of the ionospheric TEC at midlatitudes and low latitudes, (see for example Chen et al., 2015). We wish to obtain a similar model for the polar cap using a simple method to provide an estimate for the expected TEC distribution, which will be explained in the following paragraphs.

We use data from MIT’s Haystack observatory, which provides TEC from the global GPS receiver network in 1° by 1° bins every 5 min. To obtain a reference TEC distribution for the northern polar cap, we have considered TEC data for 11 years, 2007–2017, the duration of one solar cycle. The long-term variations between different solar cycles are not taken into account. We consider magnetic latitudes from 60° and northward and divide the polar cap into 30 bins in the latitudinal direction and 60 bins in the longitudinal direction. For each bin, we take the median over 1 month for each day of the solar cycle. For example, for 15 March 2014, we take the median TEC value from 28 February to 30 March 2014. Similarly, for 16 March 2014, we take the median TEC value from 1 March to 31 March 2014. The number of data points varies with latitude, with fewer observations at the highest latitudes. The average number of data points per bin is 6,258. The result is a TEC distribution map for each day, exemplified in Figure 1 showing the TEC contents in the northern polar cap at spring equinox 2011.

The rolling median smoothes out daily variations, while retaining the monthly, seasonal, and yearly variations, as shown in Figure 2. The top panel graph shows the evolution of the TEC content in a bin located at 12 MLT and latitude 60° (annoted “dayside” in the figure) and another at 24 MLT at the same latitude (“nightside”) over the course of 11 years. We see clearly the monthly and yearly variations, which concur with Chen et al. (2015). Observe that in each year, TEC peaks in around summer solstice, and there is a minimum around winter solstice. The second and third panel of Figure 2 shows the daily average Kp and f10.7 index, obtained from Nasa’s OMNIWeb service. Kp is a measure of the disturbance of the earth’s magnetic field and while the f10.7 is the amount of solar flux at 10.7 cm wavelength, an indicator of solar activity. The long-term variation of our TEC estimation agrees with the solar activity of the 24th solar cycle, which is which reached a maximum in 2014. Furthermore, the TEC concentration is always higher on the dayside, while simultaneously also varying more. The TEC variation pattern shown in Figure 2 agrees with our current understanding of TEC content in the polar cap. Diurnal variations are not available in our reference table. It is known (Jin et al., 2016) that patches are more severe at certain times, for example, at local nighttime in the Scandinavian sector, and hourly variations should thus be included for best results. However, the data coverage is not good enough to ensure statistical significance, so we are satisfied with daily TEC values.

2.1.3. Decay of Polar Cap Patch

In their study, Hosokawa et al. (2011) quantified the loss rate of a patch traversing the polar cap. They analysed altitudes between 150 and 450 km and found that the particle loss rate falls exponentially with
increasing altitude. A patch at the highest altitudes (around 450 km) has a loss rate of the order $10^{-7}$ s$^{-1}$, while a patch at low altitude (around 150 km) has a loss rate of the order $10^{-1}$ s$^{-1}$. We assume that the electron density is equal to the O$^+$ density in the F region and a thin ionosphere at 350 km altitude, as was done in the GPS TEC calculations. From the findings of Hosokawa et al. (2011) we estimate a loss rate of $\beta = 10^{-5}$ s$^{-1}$ for altitude 350 km. The electron density of a patch is then given by

$$n(t) = n_0 \exp(-\beta t),$$

(13)

where $n(t)$ is the electron density, $\beta$ is the loss rate in s$^{-1}$, $t$ is time in seconds since patch generation, and $n_0$ is the electron density at $t = 0$ s. In the forecasting model, the polar cap patch density $n(t)$ is calculated by using TEC at $t = 0$ s, estimated from the TEC reference maps explained in section 2.1.2 as $n_0$ and loss rate $\beta$ as explained above. Equation (13) thus gives the polar cap patch density at every timestep.

2.1.4. Implementing the Convection Model

The essential input for the ECPC model is an initial polar cap flux to define the boundary locations of the different flow regimes described in section 2.1.1 and a time series of both the dayside and nightside reconnection rates. The polar cap flux is set to 0.5 GWb. For our case study, we find the cross polar cap potentials from SuperDARN measurements, retrieved from the SuperDARN website. We estimate reconnection rates on dayside and nightside by assuming that the cross polar cap potential is the average of the dayside and nightside reconnection rates (Lockwood, 1991; Lockwood & Cowley, 1992):

$$\Phi_{PC} = \frac{1}{2}(\Phi_D + \Phi_N).$$

(14)

We assume that the dayside reconnection is 10 kV higher in the growth phase of the storm, while nightside reconnection dominates in the expansion phase, to simulate an expanding and contracting polar cap. The result is shown in Figure 3, where dayside reconnection rate is drawn in red, nightside reconnection is drawn in blue, and the cross polar cap potential as measured by SuperDARN is in black.

The distribution of dayside/nightside reconnection is chosen somewhat arbitrarily, but as we shall see, the total amount of reconnection is more important than the distribution between nightside and dayside. To show that our estimates are reasonable, we have conducted a sensitivity study, including two limiting cases. In case one, all magnetic reconnection is on
either dayside or nightside. In the first half of the event, all reconnection is on the dayside. In the second half, all reconnection happens at the nightside. The result was that the patch convected somewhat slower and spent 10 min longer in the polar cap before entering the auroral oval compared to our chosen reconnection rates. In case two, reconnection rates are the same at the dayside and the nightside, throughout the whole event. The result was that the patch impacted with the auroral oval at the same time as with our chosen reconnection rates.

To track the temporal and spatial evolution of a polar cap patch, we add tracer particles that represent the patch to the convection model. At the start of the simulation, we assume a position of the open-closed field line boundary (OCB) based on the amount of open flux in the polar cap. We place 10 tracer particles on the OCB, at 0.125 MLT hour intervals. Ten additional tracers are added every minute, on the minute, for the next 7 min, that is, the average duration of a flux transfer event (Lockwood & Cowley, 1992). We now have 70 tracer particles in total, allowing us to predict the transportation and evolution of a patch throughout its journey across the polar cap.

2.2. Instrumentation

Our prediction model will be verified by studying an event. We run our model with the input parameters for that event and compare our results with observations from an event. The following paragraphs provide the different observation techniques we have used.

2.2.1. Total Electron Content

From MIT Haystack’s Madrical CEDAR database, we obtain the TEC measured by the world-wide GPS receiver network. The data are processed using the minimum scallop technique, presented in detail by Rideout and Coster (2006); Vierinen et al. (2016). In the polar cap, the TEC is provided at 5-minute intervals, binned in 1° latitude and 1° longitude. We apply median filtering, a technique that eliminates noise by taking the median over a window of data.

2.2.2. Super Dual Auroral radar network

The SuperDARN is a network of high-frequency radars that monitors the Earth’s ionosphere at midlatitudes and polar latitudes (Greenwald et al., 1995). We apply the technique described by Ruohoniemi and Baker (1998) to find the electric potential. We overlay the convection maps on GPS TEC maps from the Madrigal CEDAR database. Thomas et al. (2013) provides an example of the use of SuperDARN convection in combination with GPS TEC to study a storm event.

The high-resolution real-life data obtained with SuperDARN allow us to assess to which extent the ECPC convection model is appropriate for predicting evolution of polar cap patches. In the next section, we compare step by step the observations from SuperDARN/GPS with the ECPC model results.

2.2.3. GPS Scintillations

The University of Oslo operates a GPS scintillation receiver located at Ny-Ålesund, Svalbard. The position of the receiver is 75.8° magnetic latitude and 110.19° magnetic longitude. The scintillations are described by the parameter $\sigma_\phi$, which is the standard deviation of the detrended carrier phase. Additionally, the receiver calculates vertical total electronic content. A more elaborate explanation of the receiver and the scintillation parameter can be found in, for example, Jin and Oksavik (2018).

3. Observations

3.1. Overview

We choose an event in the evening of 26 September 2011, from 18:00 UT to 22:00 UT. The event was caused by a coronal mass ejection on 24 September 2011, which impacted with the magnetosphere 2 days later and caused auroral activity, patches in the polar cap and scintillations on GPS signals. In terms of geomagnetic indices, the storm resulted in Kp = 6 from about 18–21 UT, corresponding to a geomagnetic storm level G2 in the National Oceanic and Atmospheric Administration classification system.

Figure 4 shows the solar wind conditions throughout the event. The data are from the ACE and Wind spacecrafts, obtained from NASA's OMNIweb service. The data are automatically time shifted to the bowshock nose.

The event is characterized by a sudden and intense southward turning of the IMF, in which the IMF $z$-component $B_z$ reversed from $+15$ nT (northward) to $-25$ nT (southward) in a matter of minutes around
17:35 UT. $B_Z$ remained negative for 1.5 hr, enabling masses of plasma to be stored in the magnetotail. At approximately 19:10 UT, the IMF $B_Z$ reversed before fluctuating around zero and eventually returning to a regular, calm state at approximately 20:00 UT. The IMF is directed southward throughout the event, resulting in a strong and persistent convection system that transports significant amounts of plasma across the polar cap. The Auroral Electrojet (AE) index is relatively stable but high ($\approx 1000$ nT) at the beginning of our event. The AE index is high because the magnetosphere is still in recovery from a previous substorm earlier in the day. The AE index remains stable until 19:00 UT, before it grows steeply and maximizes at 19:25 UT with ($AE \approx 2600$ nT). Thereafter, auroral activity recovers slowly to a calm state at around 21:30 UT.

In terms of the polar cap plasma, a tongue of ionization forms and grows before it is pinched off around 19:40 UT and becomes a patch, which is transported across the polar cap and transformed into an auroral blob as it impacts with the auroral oval. The event has previously been considered by Zhang et al. (2013), who describes patch formation and transport in terms of direct observations.

3.2. Snapshots From Observations and Model

Figures 5 and 6 each show snapshots at three time steps from SuperDARN/TEC and the prediction model, together with selected properties of the solar wind and GPS scintillations. The top panel in each figure recaps the solar wind properties, with vertical lines indicating the time of the snapshots to follow. The second panel shows SuperDARN/TEC observations. The image shows the polar cap TEC as observed by the GPS network and convection pattern as observed by SuperDARN. MLT is indicated on the horizontal axis, and the gray lines denote magnetic latitude. The colorbar to the right is common for all three time steps.

The third panel shows the ECPC model. The picture is centered on the magnetic pole, showing magnetic latitudes from 60° to 90°. The electrostatic potential is shown as equipotential contours, as indicated by the colorbar on the right hand side. Magnetic local noon is toward the top of the page, with midnight toward the bottom, dawn on the right hand side, and dusk on the left hand side. Tracer particles are colored turquoise. The colorbar on the right hand side is common for the three time steps.

The fourth panel shows the prediction model, where we have combined the ECPC convection pattern with our reference TEC map. The axes are the same as for the ECPC model. As before, the colorbar on the right hand side is common for the three time steps. The fifth and last panel shows the GPS scintillations (colored lines) at Ny-Ålesund, quantified by the parameter $60 \, s \, \sigma_\phi$. The dotted black line is the vertical total electron content (VTEC) calculated by the Ny-Ålesund GPS receiver, reported in terms of TEC units (TECu).

The first time step, denoted a in Figure 5, is at 18:40 UT. The cross polar cap potential is 68 kV. SuperDARN/GPS (panel 2) shows an increased plasma density in the cusp forming around magnetic noon and extending poleward, up to around 75–80°, highlighted in the figure by a circle. We observe a patch centered at 75° latitude, 13-hr MLT. The GPS observations give a TEC value in the patch of about 18 TECu. Our TEC lookup table (described in section 2.1.2) gives an estimated patch density of 15.2 TECu.
Figure 5. Prediction model snapshots at 18:40, 19:30, and 19:40 UT. Top panel: IMF $B_z$ (Blue), AE Index (red), second panel: SuperDARN/GPS TEC, third panel: convection model, fourth panel: tec model, fifth panel: GPS scintillation (colors) and VTEC (black) at Ny-Ålesund, Svalbard.
Figure 6. Prediction model snapshots at 20:30, 21:20, and 21:40 UT. Top panel: IMF $B_z$ (Blue), AE Index (red), second panel: SuperDARN/GPS TEC, third panel: convection model, fourth panel: tec model, fifth panel: GPS scintillation (colors) and VTEC (black) at Ny-Ålesund, Svalbard.
At 18:40 UT, just over an hour has passed after the southward turning of the IMF and the twin-cell convection pattern is well established (see second panel of Figure 5a). There is significant auroral activity (AE ≈ 800), due to the previous substorm as already mentioned. The prediction model (panels 3 and 4) have all tracers in place and they have started to convect with velocity v ≈ 570 m/s at magnetic latitude (MLAT) 77–78°.

Figure 5b shows snapshots at 19:30 UT. SuperDARN/GPS TEC (panel 2) shows that a large tongue of ionization has formed, stretching from the prenoon cusp, poleward and across 90° MLAT, indicated by a circle. The dense plasma convects along the convection streamlines, which show a clear twin-cell pattern. The IMF is dominated by \( B_Y \approx 18 \) nT, while the north/south component has reduced to \( B_z \approx -5 \) nT. The AE index shows significant auroral activity, with the maximum peak \( AE \approx 2,600 \) nT appearing in time interval 19:25–19:30 UT. The prediction model describes a strong twin-cell convection pattern, with cross polar cap potential of 94 kV. The tracer particles (the patch) is traveling at \( v \approx 480 \) m/s and is traversing the very upper MLATs in around 19:30 UT.

Figure 5c shows snapshots at 19:40 UT. The TEC enhancement we termed a tongue of ionization in the previous section has now been cut off from the dayside reservoir. A region of low-density plasma is convected into the cusp and thus effectively cutting off the plasma patch from the reservoir and creating a polar cap patch. The patch extends from 70° MLAT in the prenoon sector, across the 90° MLAT point, and toward 80° in the premidnight region. The cross polar cap potential reaches its peak around 95 kV, and we observe significant auroral activity at the same time. IMF is dominated by a strong negative \( B_z \). In the prediction model, the tracer particles have crossed the 90° MLAT point and are convecting toward magnetic local midnight at \( v \approx 510 \) m/s.

Figure 6d shows snapshots at 20:30 UT. SuperDARN/GPS observations show that the patch has crossed the polar cap and is located at around 75° MLAT and 21 MLT. The patch density is somewhat lower than it was in the first snapshot. The cross polar cap potential has reduced to 60 kV but the twin-cell convection pattern is still in place. Auroral activity has declined somewhat but is still high, with \( AE \approx 1000 \) nT. The prediction model, the tracer particles crossed the polar cap boundary located at 75° MLAT at 20:25 UT. The density at the crossing of the boundary is 14.2 TECu, 1 TECu less that at the start of the simulation. Scintillations at Ny-Ålesund reach a peak of almost 0.8 radians at 20:30 UT, shown in the fifth panel of Figure 6. There is a peak in VTEC just before 20:30 UT.

As an exercise, we calculate the expected velocity of the polar cap patch from our observations. We assume that the polar cap boundary is stationary at 75°, such that one crossing of the polar cap means traversing 30 MLATs. A duration of 1 hr and 50 min (18:40 to 20:30 UT) gives a patch convection velocity \( v \approx 500 \) m/s, which is similar to the values produced by the prediction model and as expected from current knowledge of patch propagation.

Figure 6e shows snapshots at 21:20. The patch has crossed the open/closed field line boundary and stretched out over the return flow region of the dusk convection cell. The patch has now been transformed into a blob, as shown by, for example, Robinson et al. (1985). It is located at approximately 65–70° MLAT. The prediction model is now dominated by nightside reconnection. The tracer particles are stretched out, similar to a so-called blob. The drift velocity has decreased significantly, averaging at 378 m/s in the snapshot. There is a slight increase in observed TEC at Ny-Ålesund. The IMF has returned to a calmer, non-storm event state, with both \( B_z \) and \( B_Y \) fluctuating around zero. The AE index is reduced to \( \approx 300 \) nT.

Figure 6f shows snapshots at 21:40 UT. The patch/blob has almost ceased to exist, with only some traces left at 16 MLT. The IMF is in a calm state, with both \( B_z \) and \( B_Y \) fluctuating around zero. The AE index is further reduced to \( \approx 250 \) nT and in recovery phase. The prediction model shows a blob that is even more stretched out and a decelerating drift velocity.

4. Discussion

We have presented results from the ECPC prediction model and SuperDARN/GPS observations for a polar cap patch crossing the polar cap during a geomagnetically disturbed event.

Our case study showed that the polar cap patch is formed from convection of high-density plasma from lower latitudes into the polar cap. As the IMF turns southward, the convection cells expand to lower latitudes. Here, the convection pattern “bites” into the large reservoir of high-density plasma and brings it poleward.
toward the polar cap. Next, continuous dayside reconnection allows the patch to convect on open field lines into the polar cap and across.

There is good agreement between predicted and observed events in terms of patch drift velocity and duration of the polar cap crossing. SuperDARN/GPS shows that the leading edge of the patch observed at 18:40 UT crossed the open/closed field line boundary at 20:30 UT, 1 hr and 50 min later. The prediction model gives a duration of 1 hr and 55 min. The result is somewhat sensitive to interpretation of where the open/closed field line boundary is located. For example, if the OCB was located 2° further equatorward, the duration would be 7 min longer, a relatively small error.

We observed significant scintillations at Ny-Ålesund at 20:30 UT, which agrees well with our prediction. The VTEC observations show a significant drop at 20:30 UT, consistent with a peak in the scintillation parameter (Jin & Oksavik, 2018). However, a patch does not have to be exactly above the receiver to cause scintillations, because GPS satellites are seen in different directions and elevations, and so the patch can be observed at a different time. The same pattern was seen by Jin and Oksavik (2018). Additionally, there are some data gaps in the GPS TEC observations in the first panel of Figures 5 and 6 (white areas). There may be additional, unobserved, regions of increased plasma density that contributed to the recorded VTEC values at Ny-Ålesund.

Moreover, the ECPC cap paradigm explains the evolution of the patch into a boundary blob well. When the patch enters the return flow region, it is structured and stretched out and slowly convects back into the dayside region. The restructuring of the patch into a blob is confirmed by SuperDARN and GPS observations.

The patch density is somewhat underestimated by the prediction model, which predicts 15.2 TECu at the start of the simulation, while the observations show a patch density of 18 TECu. At the patch's crossing of the open/closed field line boundary, the prediction model estimates a TECu of 14.2, showing a small decay of the patch due to recombination. GPS observations show that the patch density is somewhat lower at its arrival on the nightside (see Figure 6d). We must conclude that our loss rate $\beta$ is correct, at least to the degree of accuracy we are considering here. As Hosokawa et al. (2011) explains, a patch at a lower altitude (higher loss rate $\beta$) would have decayed so rapidly that it would not have reached the nightside. A higher assumed altitude would mean a lower loss rate, which would result in a higher predicted patch density on the nightside. Moreover, in terms of predicting GPS scintillations, the estimate is sufficiently accurate. This is because the main factor influencing the amount of scintillations on GPS signals is the instabilities and structuring observed at steep density gradients along the edges of the patch, not the absolute density of the patch itself.

The model predicts patch trajectory in an idealized manner. The model uses a perfect twin-cell convection system, and the patch trajectory is determined by the starting position in local time. Since there is no asymmetry about the noon-midnight axis, a tracer particle placed at 12 MLT will drift in a straight line and exit the polar cap at midnight. A tracer particle placed in the postnoon sector will exit in the premidnight sector. SuperDARN/GPS observations shows that reality is more complex. Firstly, the convection pattern and drift velocities are not steady state but dynamic and pulsed (Oksavik et al., 2010). Secondly, the convection pattern is asymmetrical about both the midnight-noon and dawn-dusk axes and is heavily dependent on IMF direction, as shown for example by Pettigrew et al. (2010). It is possible to change the location of the merging gaps (and their size) in the ECPC model.

In a trial run, we have used IMF-dependent merging gap location and size and compared with our results. Pettigrew et al. (2010, Figures 4, 5, and 6) provide visual representations of the convection pattern as a function of dipole tilt, transverse IMF field strength, and IMF clock angle. Pettigrew et al. (2010)'s results were obtained by fitting velocity vector observations from SuperDARN to a spherical harmonic function of 8th order, as proposed by Ruohoniemi and Greenwald (2005). We estimated the merging gap location and size visually from Pettigrew et al. (2010)'s convection patterns. This analysis resulted in a relative error of patch arrival time of $\pm 10$ min. Determining the merging gap locations accurately, for example, by detecting flow reversal boundaries, would increase accuracy. This task is left for future work.

Keeping in mind that our goal is to predict the arrival of patches on the nightside auroral oval, these factors do not hinder us. As we will explain shortly, these imperfections do not influence the drift velocity significantly. For instance, the perfectly symmetrical convection pattern limits the spatial variance of the patch trajectory. However, the difference in flow time to cross the polar cap between a tracer particle starting at MLT = 12
and one starting at MLT = 13.25 is only 15 min. Assuming an average drift velocity of 500 m/s, the difference corresponds to distance of 450 km or 4° latitude. As shown in Figure 5c, the patch stretches over more than 20° MLAT. The relative error is therefore not very large. Furthermore, the patch MLT location does not have to be predicted exactly in order to forecast scintillations. As long as the patch is in the field of view of the GPS receiver, such that signals from GPS satellites have to pass through the patch, scintillations may occur. From a space weather forecasting point of view, we conclude that the ECPC model gives sufficiently accurate predictions, even without considering B⊥-dependent convection pattern.

The ECPC prediction model only includes the large-scale twin-cell convection pattern. It neglects the presence of flow channels, which are mesoscale regions (100–200 km wide) where particle drift velocities exceeds 4,000 m/s (Nishimura et al., 2014). These flow channels are associated with poleward moving auroral forms and, by association, localized magnetic reconnection (Nishimura et al., 2014). These local regions will give the patch a burst of speed and reduce propagation time. This factor is not included in the model and indicates that the ECPC underestimates propagation speed.

The model does not take into account any transformation in shape that the patch goes through, other than that imposed by the idealized twin-cell convection system. As shown by Crowley et al. (2000), a patch propagating across the polar cap will change shape due to the varying convection system. The patch may become distorted, move between the dusk/dawn cell, and spread out. In terms of scintillations, this means that there is an uncertainty in the MLT distribution on the nightside of where the patch enters the auroral oval.

The ECPC prediction model does not capture the inner dynamics of a patch. In their case study, Oksavik et al. (2010) describes the trajectory of two patch events in the polar cap. They found that a patch can undergo substantial rotation in the polar cap, such that the trailing edge overtakes the leading edge. This is important because the gradient drift instability is known to be most severe on the trailing edge of patches and is a significant contributor to GPS scintillations. A limitation of the ECPC model is that is does not include possible rotation of a patch inside the polar cap. However, previous studies (e.g., Moen et al., 2013; Jin et al., 2016) have shown that the most severe disturbances occur where patches impact with the auroral oval. Thus, in terms of predicting GNSS scintillations, we are mainly concerned with predicting the arrival of polar cap patches at the auroral oval.

An alternative and contrast to the ECPC derived convection pattern is to use the SuperDARN convection map (Greenwald et al., 1995). The network of SuperDARN radars measure plasma drift in the ionosphere and fit the velocities to spherical harmonical functions to create global convection maps (Ruohoniemi & Baker, 1998). The patterns are further constrained by statistical convection patterns based on upstream IMF conditions (Thomas & Shepherd, 2018). SuperDARN convection maps therefore inherently show patterns of steady-state processes. The ECPC paradigm, on the other hand, decouples dayside and nightside reconnection and thus mimics the evolution of a typical substorm by first exhibiting an enhanced dayside reconnection rate (growth phase), followed by a period of enhanced nightside reconnection rate (expansion phase) (Lockwood & Cowley, 1992). This behavior makes the ECPC paradigm a unique candidate to form the basis of a space weather forecasting algorithm.

5. Conclusion and Future Work

We have shown how the ECPC model can be used to describe the motion of a polar cap patch across the polar cap. The model describes the motion well, predicting the time of arrival with an accuracy of 5 min. Additionally, the model provides a reasonable estimate for the TEC intensity in the patch. This conclusion is found by comparing our prediction model with SuperDARN/GPS data, as well as observed scintillation levels on a receiver at Svalbard. It should be noted that detailed dynamics such as patch rotation, patch transformation, and flow channels are not captured by the model but for the application of predicting arrival times at the auroral boundary, the model is applicable. The model can be developed further by including real-time data of the potential distribution across the polar cap, which would provide a more accurate convection pattern and reveal possible flow channel events.

Real-time data on the position of the auroral oval can be obtained using magnometer data and will increase the accuracy of the prediction model. Furthermore, a space weather forecast system must include a patch detection system. This can be acheived using for example satellites with Langmuir Probes (Spicher et al., 2017) and/or GPS receivers (Noja et al., 2013) or ground-based observation techniques like all-sky imagers,
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