An Improved Estimation of SuperDARN Heppner-Maynard Boundaries Using AMPERE Data

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Abstract Super Dual Auroral Radar Network (SuperDARN) ionospheric convection maps are a powerful tool for the study of solar wind-magnetosphere-ionosphere interactions. SuperDARN data have high temporal (approximately minutes) and spatial (~45 km) resolution, meaning that the convection can be mapped on fine time scales that show more detail than the large-scale changes in the pattern. The Heppner-Maynard boundary (HMB) defines the low-latitude limit of the convection region, and its identification is an essential component of the standard SuperDARN convection mapping technique.

However, the estimation of the latitude of this boundary is dependent on ionospheric scatter availability. Consequently it is susceptible to nonphysical variations as areas of scatter in different latitude and local time regions appear and disappear, often due to changing propagation conditions. In this paper, the HMB is compared to an independent field-aligned current data set from the Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE). A linear trend is found between the HMB and the boundary between the AMPERE Region 1 and Region 2 field-aligned currents in the Northern Hemisphere, at both solar minimum and solar maximum. The use of this trend and the AMPERE current data set to predict the latitude position of the HMB is found to improve the interpretation of the SuperDARN measurements in convection mapping.

1. Introduction

The circulation of the polar ionosphere as a result of the solar wind-magnetosphere-ionosphere interaction is known as ionospheric convection. The Dungey cycle (Dungey, 1961) drives antisunward flow across the polar cap and sunward flow at lower latitudes, under interplanetary magnetic field (IMF) $B_Z < 0$ conditions. This cycle results in a twin-cell convection pattern (Cowley, 2000). If dayside reconnection dominates over nightside reconnection, the creation of open flux at the magnetopause causes an expansion of the polar cap area, according to the expanding-contracting polar cap (ECPC) model (Cowley & Lockwood, 1992; Lockwood & Cowley, 1992; Milan et al., 2003, 2013, 2007). If the nightside reconnection rate exceeds that at the magnetopause, the amount of open flux is reduced, and the polar cap area shrinks. The size of the polar cap will change as the balance between dayside and nightside reconnection varies. The ionospheric convection cells wrap around the polar cap boundary, such that as the polar cap expands and contracts, so does the size of the convection pattern.

The divergence of horizontal currents in the ionosphere, driven by convection, leads to field-aligned currents (FACs) flowing vertically into and out of the polar ionosphere. The overall morphology of the FACs was originally presented by Iijima and Potemra (1976a, 1976b, 1976b, 1978) as two continuous rings of current, the Region 1 (R1) currents at the boundary between sunward and antisunward flow, and the Region 2 (R2) currents at the equatorward edge of the convection pattern (e.g., Milan et al., 1976a). The Region 0 (R0) currents exist in the noon sector poleward of the R1 currents and are associated with flows caused by magnetic tension forces on newly reconnected field lines (e.g., Milan et al., 2017). Both the convection and FAC patterns are a barometer for the state of the coupled magnetosphere-ionosphere system. Like the convection pattern, the FAC pattern will expand and contract in response to
variations in the position of open and closed magnetic field lines (Burrell et al., 2019). Therefore, comparison of the latitudinal extent of the two systems could reasonably be expected to produce a linear trend, as both patterns will expand and contract as the polar cap size varies.

The Super Dual Auroral Radar Network (SuperDARN) (Chisham et al., 2007; Greenwald et al., 1995; Nishitani et al., 2019) consists of a long-standing global network of, currently, over 30 ground-based high-frequency coherent scatter radars. SuperDARN radars provide high spatial (~45 km) and temporal (1 or 2 min) resolution data, and the network has achieved near-global coverage in the polar regions. The radars measure movements of ionospheric plasma irregularities and were originally conceived to study ionospheric convection (Greenwald et al., 1995), the topic of this paper.

The average morphology of the convection pattern under differing IMF conditions has been studied at length with SuperDARN radars (Cousins & Shepherd, 2010; Pettigrew et al., 2010; Ruohoniemi & Greenwald, 1996, 2005; Thomas & Shepherd, 2018), creating multiple convection models. The convection pattern is seen to expand to lower latitudes during periods of prolonged $B_z < 0$, agreeing with the ECPC model, and the relative shape and size of the dawn and dusk cells has an IMF $B_y$ dependence. Changes in the morphology of the pattern due to geomagnetic activity such as substorms has also been studied (Bristow & Jensen, 2007; Grocott et al., 2009; Lester et al., 1993; Milan et al., 2003; Provan et al., 2004). An example SuperDARN convection map is presented in Figure 1a, showing a twin-cell pattern under $B_z < 0$, $B_y > 0$ conditions. This map was created by assimilating SuperDARN data using the map potential technique (Ruohoniemi & Baker, 1998); see section 2.1 for further description. In this example, and all following convection maps, the convection streamlines (electrostatic equipotentials) are shown in black, with numbers indicating electrostatic potential associated with that streamline. The difference in the peak potentials of each cell (cross-polar cap potential) is recorded in the bottom right. The velocity vectors from SuperDARN observations are plotted with color and vector length indicating speed and the flagpole pointing in the direction of flow; the number of vectors is recorded in the bottom center of the panel. The IMF clock angle vector is plotted in the top right hand corner of the panel.

Heppner and Maynard (1987) defined the low-latitude boundary of the convection pattern and used it as an essential component of modeling ionospheric convection. They used spacecraft passes to identify a departure in the gradient of the electric field from low-latitude to midlatitude values. By grouping measurements by $K_p$ and smoothing the data they created the shape of the Heppner-Maynard boundary (HMB), which varies in latitude as a function of magnetic local time (MLT) and expands to lower latitudes with increasing geomagnetic activity. Shepherd and Ruohoniemi (2000) used the HMB to define the edge of the SuperDARN convection region. They found that SuperDARN data showed the convection region extended to higher latitudes on the dayside, leading to a solution similar to that of Heppner and Maynard (1987). Shepherd and Ruohoniemi (2000) created a functional form of the boundary that is almost circular on the nightside but flattens at higher latitudes on the dayside, reaching the highest latitude around 1100 MLT. Below this boundary, the convection electric field is assumed to be 0. In Figure 1a and all further maps the HMB is plotted in green, and the minimum latitude of the HMB is recorded in the bottom left-hand corner.

Data from SuperDARN radars were first assimilated into convection maps by Ruohoniemi and Baker (1998). In this technique, the HMB is used to define the equatorward boundary of the Dungey-driven convection region, poleward of which a spherical harmonic fitting to the data is performed. As described by Shepherd and Ruohoniemi (2000), the latitude of the HMB is selected by ensuring that the boundary encloses all “significant” convection observations. In the standard estimation of the HMB latitude, this is 1° below the lowest latitude at which three or more vectors of at least 100 m s$^{-1}$ or more lie on the noncircular HMB shape. This method of calculating the latitude of the HMB, therefore, is heavily dependent on scatter availability. Changes in irregularity detection by individual radars can be caused by changes in radar operations (operational mode, operating frequency, or radar downtime) and propagation conditions, as well as changing geophysical conditions. This can lead to areas of scatter in convection maps appearing and disappearing in different latitude and MLT regions. Such variations affect the determination of the HMB latitude and can lead to unphysical temporal changes in the HMB. It is these unphysical variations that the new method presented in this paper is designed to remove.

The Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE) (Anderson et al., 2000, 2014; Coxon et al., 2018; Waters et al., 2001) utilizes data from engineering magnetometers on the
Figure 1. (a) Northern Hemisphere SuperDARN convection map plotted onto a magnetic latitude-magnetic local time grid, with noon at the top and dusk on the left (the grid is the same for all panels). Electrostatic equipotentials/convection streamlines are plotted in black (numbers indicate electrostatic potential); vectors are colored indicating the magnitude of velocity according to the color scale, and flagpoles point in the direction of flow. Length of flagpole also indicates speed according to key at bottom left. The HMB is plotted in green; its minimum latitude is recorded in the bottom left corner of the panel. Cross-polar cap potential is recorded in the bottom right corner of the panel; beneath it is the $\chi^2$ fit statistic from the map potential technique. The number of vectors in the map ($n$) is recorded in the bottom center of the plot. (b) AMPERE current density map. Current density is shaded according to the color scale on the right. Upward (red) FACs saturate at 0.5 $\mu$A m$^{-2}$; downward (blue) FACs saturate at $-0.5$ $\mu$A m$^{-2}$. (c) SuperDARN convection map overplotted onto AMPERE field-aligned current data, as in (a) and (b) (HMB is thicker in this instance so it can be seen clearly on top of AMPERE data); (d) AMPERE current density map with R1/R2 boundary overplotted in purple. All data from 0024–0026 UT, 4 December 2011.
Iridium constellation to provide continuous measurements of the FACs in both hemispheres. Iridium magnetometer data were first used for science by Anderson et al. (2000), leading ultimately to the AMPERE data set. The 66 telecommunications satellites forming the Iridium constellation measure three components of the magnetic field. The radial current density is then calculated using a spherical harmonic fit and Ampère's law (Coxon et al., 2018). These measurements are normally calculated at a 10 min cadence, but a 2 min average current map is also provided (Milan et al., 2015), to enable an easy comparison with 2 min resolution SuperDARN data. An example current density map is presented in Figure 1b, showing the R1/R2 current system. Figure 1c shows the AMPERE and SuperDARN data plotted together, in an interval where the data sets agree well. Clausen, Baker, et al. (2013) showed a statistical similarity in the position of the R1 current oval, as identified by Clausen et al. (2012), and the open/closed field line boundary (OCB). Since the OCB position moves according to the ECPC paradigm, it is expected that the R1/R2 current pattern will expand and contract similarly, fitting with work by Clausen, Baker, et al. (2013) and Clausen, Milan, et al. (2013).

This paper presents a trend between the scale sizes of the HMB and the FAC pattern. Section 2 describes how the data have been assimilated and processed to produce time-varying scale sizes for comparison, and the selection criteria that have been applied to the data. Section 3 outlines the results of the study, and section 4 discusses the results.
2. Data

2.1. SuperDARN Data

For this paper all SuperDARN data available in 2011 and 2015 from the high-latitude and polar radars were used and were processed using the newest FitACF version (3.0) in RST 4.2 (SuperDARN Data Analysis Working Group. Participating members et al., 2018). The spatial coverage of these radars is shown in Figure 2; radars which are only available in 2015 are indicated with dashed lines. The use of FitACF 3.0 to process SuperDARN RawACF data results in more scatter per radar, when compared with previous versions. The major difference that contributes to this increased amount of scatter is the change to data selection criteria for autocorrelation function (ACF) lags (Bland et al., 2018; Ponomarenko et al., 2018). Other contributing factors are changes to ACF selection criteria and fitting (Bland et al., 2018; Ponomarenko et al., 2018). This results in an increased number of map potential convection vectors contributed per radar when compared with previous versions, occasionally creating maps with the order of up to 2,000 vectors or more. While the use of FitACF 3.0 for SuperDARN data processing produces reliable data at all latitudes, the usage of midlatitude radar data within the current convection model requires further study (Bland et al., 2018; Ponomarenko et al., 2018). In the high-latitude regions, FitACF 3.0 data provides greater vector coverage of the polar cap and hence a more detailed description of ionospheric flows. At midlatitudes, more low-velocity and sparsely distributed vectors are observed, which can confuse the estimation of the HMB minimum latitude. This can result in long plateaus in the HMB, which are unlikely to be representative of physical changes in the size of the convection pattern. In order to counter this, midlatitude radar data were excluded from this study.

In the most recently published climatological ionospheric convection model, Thomas and Shepherd (2018) utilize greater latitudinal coverage by including midlatitude radar data. Their work shows that for weakly driven intervals, even with a purely \( B_Z < 0 \) interplanetary magnetic field (IMF), the climatological pattern does not expand beyond 60° latitude. Midlatitude radars uniquely provide observations between 50° and 60° latitude, so it is only in active periods that these radars observe Dungey-driven flows. In this study, the years of 2011 and 2015 are selected for analysis, as they are within the lifetime of both the SuperDARN and AMPERE data sets and represent years around solar minimum and maximum, respectively. The distribution of IMF conditions from the years 2011 and 2015 are displayed in Figures 3a and 3b, respectively. The IMF data are sorted into equal width clock angle bins, and IMF \( B_T \) magnitude increases with radius \( (B_T = (B^2_x + B^2_y + B^2_z)^{1/2}) \). As expected when comparing data at opposing stages in the solar cycle, there are more instances of greater IMF \( B_T \) in 2015 than 2011, as can be seen from Figure 3. However, in 2011, the value of IMF \( B_T \) is more negative than 5 nT for only 7% of the time, and in 2015 only 16% of the time. Hence in 2011, according to the work by Thomas and Shepherd (2018) described previously, a negligible number
of instances would benefit from midlatitude data. Although a more significant fraction of periods in 2015 are driven by a strong IMF $B_Z < 0$, it is not the majority.

SuperDARN radar data have been assimilated using the map potential technique (Ruohoniemi & Baker, 1998), and the convection has been mapped using all available data from the selected years, at 2 min resolution. In this technique, a temporal and spatial boxcar filter is applied to line-of-sight velocity data from individual stations, which is then combined into a global grid. All observations are used to constrain the convection solution. In the convection maps presented in this paper, such as those in Figure 1a, fitted vectors are drawn in every grid cell location which contains a line-of-sight velocity observation and are representative of the electric potential pattern. The RG96 (Ruohoniemi & Greenwald, 1996) model is used to predict the shape of the convection contours and the electrostatic potential pattern, which is scaled over a circular region defined by the HMB minimum latitude. Using IMF data from the OMNI data set and the radar observations, the set of coefficients for the model which best recreate the observations are determined by minimizing the $\chi^2$ fit statistic. The map potential technique has been implemented using the freely available software package Radar Software Toolkit (RST) version 4.2 (SuperDARN Data Analysis Working Group. Participating members et al., 2018), and the standard HMB latitude condition (see above) has been used. For a full description of the map potential technique, the reader is directed to Ruohoniemi and Baker (1998).

In this study the latitude at which the HMB crosses the midnight meridian, $\Lambda_0$, is found (midnight meridian values of the HMB are available online; see Fogg, 2020). The functional form of the HMB is near semicircular on the nightside, so it is expected to have the most successful comparison with a circular measure of the FAC in this region.

2.2. AMPERE Data

AMPERE data were used to determine the latitudinal extent of the FAC pattern, since the data set can be used to automatically determine scale sizes for the FAC regions (e.g., Clausen et al., 2012; Milan et al., 2015). In this study, the boundary between the R1/R2 currents is calculated using a method similar to that of Milan et al. (2015) (R1/R2 boundaries are available online; see Milan, 2019). The current strength is integrated around circles of different radii, at various circle center locations. Currents in the dusk sector are multiplied by $-1$, so that a positive value will be measured when a circle intersects the R1 currents and a negative value for the R2 currents. Hence, a bipolar signature is seen in the integrated current with respect to radius. The position of the circle center and the circle radii are varied, and the combination that presents the largest peak-to-peak bipolar signature is selected as the boundary between the R1 and R2 currents. This boundary was chosen for the scale size of the FAC pattern as it is easier to locate the intersection between upward and downward currents than the equatorward edge of the FAC pattern, as the latter would require the user to define what fraction of the peak current density constitutes the “edge” of the current region. Additionally, the R1/R2 boundary expands and contracts according to the ECPC model, while the equatorward edge of the FAC pattern may expand further on the nightside due to auroral precipitation.

From this technique the radius of the boundary between the R1/R2 currents is taken, and the boundary is assumed to be a circle centered 4° antisunward of the geomagnetic pole (see Milan et al., 2015, and references therein). This boundary can be seen in purple in Figure 1d. To compare with $\Lambda_0$, $R_F$ is selected as the latitude at which the R1/R2 boundary crosses the midnight meridian.

2.3. Data Selection

A 24 hr time series of $\Lambda_0$ from 4 December 2011 is shown in Figure 4b. Around 1200 UT there is lower data coverage, that is, a low number of vectors (see Figure 4e), which leads to sharp jumps to higher latitude, as can be seen in Figure 4b. Intervals with less than 400 vectors can be susceptible to this kind of error; a threshold level of 400 vectors is plotted onto Figure 4e as a dashed line. Additionally, sharp jumps of the HMB to lower latitude can be caused by the switching on and off of areas of scatter. These have the greatest effect near 1100 MLT where the HMB is at its highest latitude; some examples of this can be seen toward the end of the time series in Figure 4b. Figure 4b also illustrates that a gradual decrease in $\Lambda_0$ to lower latitudes is followed by a sharp jump to higher latitudes between 0700 UT and 0900 UT. This is an example of a patch of scatter moving around the polar cap into the morning sector, where the HMB is at its highest latitude. Although the latitude of the scatter does not change, as it moves into the 1100 MLT region the HMB gradually moves to lower latitudes, in order to include this scatter in the convection region. As the area of scatter slows down and switches off, the HMB jumps back poleward over 4 min (two time intervals). Values
An example of a 24 hr times series of $R_F$ from 4 December 2011 is seen in Figure 4a and plotted together with $\Lambda_0$ in Figure 4d. $R_F$ varies much more smoothly than $\Lambda_0$ and generally lies at higher latitudes. It can be difficult to identify the R1/R2 boundary when the current density of the FAC pattern is weak, as there are smaller departures in current between the R1 and R2 currents. Such occasions where the currents are too weak to fit successfully are considered to be unreliable and are also excluded from further analysis (and from Figures 4a and 4d, explaining the gaps in the time series). Figure 4c will be discussed later in the paper.

The data selection criteria described above are applied to both data sets, and only time intervals which meet the conditions for both $\Lambda_0$ and $R_F$ are selected for further analysis. For 2011, 25% of time intervals pass both criteria, and 17% of intervals pass both selection criteria for 2015. Figure 5 shows the latitude distribution of the two data sets before and after the data selection criteria have been applied, for 2011 data. Figures 5a and 5b show the distributions of $\Lambda_0$ and $R_F$, respectively, before the application of any selection criteria, while Figures 5c and 5d show the distributions of $\Lambda_0$ and $R_F$, respectively, following the application of both criteria.

Figure 5a shows the latitude distribution of $\Lambda_0$ before data selection is roughly symmetrical between 55° and 75°, centered on a peak at 65°. Outside this range the distribution extends to 50° latitude, with a small peak at 50°. The enhancement of the distribution at 50° is likely due to instances in which a few low-velocity vectors cause an incorrect estimation of the HMB latitude (for which the minimum value is $\Lambda_0 = 50°$); an example of this is discussed in section 3. In addition, the distribution tails off at greater numbers on the high-latitude side and has a peak at 68°. The latitude distribution of $\Lambda_0$ after the data selection steps described (Figure 5c) demonstrates that the enhanced numbers at the higher latitudes have been removed by data selection, and the peak at 68° has been reduced. The local peak at 50° in Figure 5a has also been reduced from ~4,000 to ~150 in Figure 5c, although it retains a similar relative size to the main peak in both distributions. Figure 5b shows that the latitude distribution of $R_F$ before any data selection criteria have been applied is symmetrical, with slightly larger occurrence at high latitudes (74°–76°) than at low latitudes. The latitude distribution of $R_F$ following the application of all data selection criteria (Figure 5d) demonstrates a similar symmetrical distribution, with slightly more values at high latitudes than at low latitudes. Finally, the $R_F$ distribution
Figure 5. Latitude distribution for 2011 data only, binned in 1° latitude bins for (a) $\Lambda_0$ and (b) $R_F$ before data selection criteria are applied and from intervals that pass data selection criteria for both data sets, (c) $\Lambda_0$ and (d) $R_F$.

in Figure 5d peaks at 68°, several degrees higher than the peak of the $\Lambda_0$ distribution in Figure 5c, which peaks at 65°. This fits with the theoretical expectation, that the boundary between the R1 and R2 currents will generally be at a higher latitude than the HMB.

For brevity, only the distributions for 2011 are presented, as the shape of all four distributions are similar for 2011 and 2015. The significant difference between the latitude distributions of the data from 2011 and 2015 is a shift in latitude of the peaks of the distributions. For $\Lambda_0$ in 2015, the distributions (equivalent to Figures 5a and 5c) peak between 63° and 64°, 1–2° lower than for 2011. For $R_F$, the 2015 distributions (equivalent to Figures 5b and 5d) peak around 67°, 1° lower than the 2011 data. This suggests that both the FAC and convection patterns are more likely to be at lower latitudes in 2015 than in 2011; this confirms previous findings of HMB solar cycle variations (e.g., Imber et al., 2013).

3. Results

First, the data from 2011 will be examined. The occurrence of $R_F$ as a function of $\Lambda_0$ for the year 2011 has been sorted into 1° by 1° bins in Figure 6a. A clear linear trend can be seen in the main cluster of data.
Figure 6. (a) Occurrence of $R_F$ as a function of $\Lambda_0$ for 2011 data binned in 1° by 1° latitude bins, plotted according to the color scale on the right. Linear trend plotted onto the data as a solid line (1), according to the equation above the plot. Resulting correlation coefficient ($r_1$) recorded at the top right; number of contributing time intervals ($N_1$) is recorded at the top left. RMS error ($RMS_1$) is recorded in the bottom right, and the percentage of data points above and below the trend line ($a_1$ and $b_1$, respectively) are recorded in the bottom left. Linear trend calculated following the removal of data at $\Lambda_0 = 50°$ and $R_F = 76°$ is plotted as a dashed line (2), according to the equation above the plot. Resulting correlation coefficient ($r_2$) recorded at the top right; number of contributing time intervals ($N_2$) is recorded at the top left. RMS error ($RMS_2$) is recorded in the bottom right, and the percentage of data points above and below the trend line ($a_2$ and $b_2$, respectively) are recorded in the bottom left. (b) As for (a) but with 2015 data; Trend 3 includes all data passing selection criteria; Trend 4 was calculated following the removal of data at $\Lambda_0 = 50°$ and $R_F = 76°$. (c) The four linear trends shown in (a) and (b), plotted together, on a different scale than (a) and (b).

Using linear regression analysis, a linear fit to the data was calculated. This resulted in the trend given by equation (1) and plotted onto Figure 6a as the solid line (marked as 1 in Figures 6a and 6c).

$$\Lambda_{cor} = 0.966R_F - 2.60°$$

Despite data selection criteria, two notable areas of outliers exist; one grouping along $\Lambda_0 = 50°$ and one along $R_F = 76°$. These outliers account for 2.9% of the data that pass the selection criteria. The linear trend analysis was repeated without these outliers, resulting in the dashed line trend labeled 2 which is recorded
in equation (2) and will be discussed in the next section.

\[ \Lambda_{\text{cor}} = 0.953R_F - 1.45^\circ \]  

(2)

Trend 1 has a correlation coefficient \((r)\) greater than 0.5, but not close to 1. The Pearson correlation coefficient, \(r\), is a measure of the strength and direction of the linear trend within a data set. This coefficient varies from \(-1\) to \(1\); values close to \(1\) indicate strong correlation between \(R_F\) and \(\Lambda_{\text{cor}}\) \((\Lambda_{\text{cor}}\) values increase with increasing \(R_F\)) while values close to \(-1\) indicate strong anticorrelation \((\Lambda_{\text{cor}}\) values decrease with increasing \(R_F\)). In this instance, \(r\) suggests a moderately correlated linear relationship.

The number of data points above \((a)\) and below \((b)\), the line of best fit, is recorded at the bottom left of the plot, indicating that there are about 10% more data points above the line of best fit than below. The line is pulled down away from the \(y = x\) line (see Figure 6c) by the asymmetry of the distribution of data either side of the main cluster of occurrence. Simply put, the distribution extends further away from the main occurrence cluster in the high \(R_F\) side of the main cluster of occurrence. Similarly to Figure 6a, the linear trend analysis was repeated without the outliers along these clusters of data will be discussed further in the following section. Finally, the RMS error for Trend 3 is 2.71, which again suggests a moderately correlated positive linear relationship.

For 2011, the occurrence of \(R_F\) as a function of \(\Lambda_0\) has been sorted into \(1^\circ\) by \(1^\circ\) bins in Figure 6b. Similarly to 2011 data, there is a clear linear trend in the main cluster of data. Using linear regression, a line of best fit for the data set was retrieved and plotted onto Figure 6b as a solid line (Trend 3). The trend is recorded below in equation (3).

\[ \Lambda_{\text{cor}} = 0.803R_F + 8.82^\circ \]  

(3)

The linear trend, correlation coefficient, number of points above and below the line of best fit, and RMS error for Trend 3 are recorded on the panel, as for Figure 6a. The correlation coefficient for Trend 3 has a similar value to that from Trend 1, \(r_3 = 0.577\), which again suggests a moderately correlated positive linear relationship. Similarly to Figure 6a, the linear trend analysis was repeated without the outliers along \(\Lambda_0 = 50^\circ\) and \(R_F = 76^\circ\), and this trend is overplotted onto Figure 6b as a dashed line (Trend 4). Trend 4 is presented below in equation (4) and, along with Trend 2, will be discussed in the next section.

\[ \Lambda_{\text{cor}} = 0.827R_F + 7.35^\circ \]  

(4)

The number of data points above \((a)\) and below \((b)\), the line for Trend 3, suggests that about 13% more of the data lie above the line than below it. A similar argument to that from 2011 data can be made regarding the asymmetric spread of the data, the resolution of the data set, and the position of the line of best fit with respect to the occurrence of the data points. In contrast to Figure 6a, in Figure 6b the distribution of the data either side of the main linear cluster widens as \(R_F\) and \(\Lambda_0\) increase. For example, there are clusters of data where \(R_F\) is substantially higher than \(\Lambda_0\) or vice versa, which will affect the trend. Potential sources of these clusters of data will be discussed further in the following section. Finally, the RMS error for Trend 3 is 2.71, which for values ranging between \(50^\circ\) and \(76^\circ\) constitutes percentage error of between 5.42% and 3.57%, similar to the RMS error for Trend 1.

The trends for 2011 and 2015 (Trends 1 and 3) are plotted together in Figure 6c as purple and red lines, respectively. Either equation could be used to estimate a “corrected” value for the HMB at the midnight meridian based on \(R_F\). The analysis was completed on both 2011 and 2015 resulting in two trends describing the linear relationship between \(R_F\) and \(\Lambda_0\) near solar minimum and maximum, respectively. Therefore, in order to make an estimation of a “corrected” value for the HMB, it is wise to utilize the trend from 2011 for instances near solar minimum, and for instances near solar maximum the trend from 2015. For succinctness, examples of the effectiveness of Trend 1 on intervals from 2011 only will be presented below.

The trend in equation (1) was used to estimate a “corrected” value for the HMB at the midnight meridian based on \(R_F\), referred to from now on as \(\Lambda_{\text{cor}}\). A 24 hr time series of this can be seen in Figure 4c.
estimated value has the smoothly varying form of $R_F$ (Figure 4a), without the unphysical variations that $\Lambda_0$ (Figure 4b) has. $\Lambda_{cor}$ follows the lower-latitude values of $\Lambda_0$. Intervals without a high quality R1/R2 boundary fit are omitted from Figure 4a, in which case the value of $\Lambda_{cor}$ is the same as the last estimated $\Lambda_{cor}$. This results in small plateaus in $\Lambda_{cor}$, and for short intervals of the order of minutes, this is unlikely to cause problems. Since an estimation of $R_F$ is only unavailable for intervals with very weak currents, it is also unlikely that there would be a significant change in the latitude of $R_F$ and hence $\Lambda_{cor}$, even over a long interval without $R_F$ estimates.

Figure 7a shows an example in which the traditionally calculated HMB has been dragged down to a lower latitude than would be expected by the latitudinal extent of the scatter at all local times, as well as the prevailing IMF. This results in a region of equatorward flow near noon, which is not likely to be a physical mapping of the data, given that IMF $B_Z$ is weakly negative. This area of slowly moving scatter is in the morning sector (between 0930 and 1100 MLT), where the HMB is at its highest latitude, which results in a low value for $\Lambda_0$ at midnight. Furthermore, the form of the convection cells does not conform to a reasonable twin-cell pattern, as would be expected. Around 0200 MLT, a small patch of scatter causes an elongation of the dusk convection cell across the midnight meridian. This is similar to the extension of the convection reversal expected to precede substorm onset (Bristow & Jensen, 2007; Bristow et al., 2001, 2003) and be accompanied by shear flow in the midnight region. Scatter coverage at 0000 MLT is poor in this interval, so although there is a shear in the equipotentials in this region, it is not confirmed by vector coverage. A substorm signature was observed in IMAGE magnetometer data (Tanskanen, 2009), with the substorm onset occurring around 2330 UT, 3 December 2011 and the peak of substorm activity at 2350 UT. This puts the interval in Figure 7 during the recovery phase of the substorm, well after substorm onset. At the point of substorm onset, shear flows relax into equatorward meridional flows at 0000 MLT, and the extension of the dusk cell disappears (Bristow & Jensen, 2007; Bristow et al., 2001, 2003). Hence, this elongated feature is not expected to be a physical feature in this interval. In Figure 7c SuperDARN data are overplotted onto the AMPERE current density map, showing that the latitude of the HMB (as normally estimated from SuperDARN data) in this interval falls far outside the latitudinal extent of the R1/R2 FACs.

A value for $\Lambda_{cor}$ is estimated using equation (1), and this is used as the minimum latitude for the HMB (i.e., the value at the midnight meridian). This allows the entire HMB to be predicted using the standard functional form described earlier. The resulting map is shown in Figure 7b, where $\Lambda_{cor}$ is 63°, more similar to that which would be expected from the scatter alone, and is 13° above the traditionally calculated $\Lambda_0$. This results in a more physical interpretation of the scatter, with the scatter around 1100 MLT being excluded from the convection pattern. Although there are still three convection cells shown, the majority of the pattern conforms to expectations in a twin-cell setup. The third cell sits just after 1200 MLT and partially outside the convection region. It has a much lower peak electrostatic potential than the other cells and is not a dominant feature. The elongated dusk cell feature has been removed (Bristow & Jensen, 2007; Bristow et al., 2001, 2003). Figure 7d shows the SuperDARN data from Figure 7b overplotted onto AMPERE current density measurements. Using the new method, the latitudinal extent of the convection and the R1/R2 FAC pattern agree well, in particular in the dawn and dusk sectors. The cross-polar cap potential is reduced by 3 kV in Figures 7b and 7d by the use of $\Lambda_{cor}$ to predict the HMB latitude. A lower potential suggests a weaker convection pattern, but in this case it is perhaps due to the reduction of the size of the convection region.

Figure 8 shows the same time interval as Figure 1, with Figures 8a and 8c using a traditionally calculated HMB and Figures 8b and 8d using a HMB predicted using $\Lambda_{cor}$. The predicted HMB is 1° higher than the traditionally calculated HMB, and the cross-polar cap potential is 2 kV less than with the traditionally calculated HMB. However, the convection streamlines are very similar in the two cases. Figures 8c and 8d show the data overplotted onto AMPERE current density maps; both maps agree well with the AMPERE data, the main difference being a small area of current that is excluded from the $\Lambda_{cor}$ predicted HMB in the premidnight R2 current. Overall, the maps agree well, showing that the use of $\Lambda_{cor}$ to predict the HMB works well in cases where the traditional HMB had been a realistic interpretation of scatter.

4. Discussion

The trends presented in this paper can be used, along with AMPERE-derived $R_F$ values, as a method to determine the HMB latitude. SuperDARN vectors can occur across all MLT and latitude locations that are
Figure 7. Northern Hemisphere magnetic latitude-magnetic local time plots of (a) SuperDARN convection map with a traditionally determined HMB, (b) SuperDARN convection map with HMB predicted using $\Lambda_{cor}$, (c) SuperDARN convection map with traditionally determined HMB overplotted onto AMPERE current density map, and (d) SuperDARN convection map with HMB predicted using $\Lambda_{cor}$ overplotted onto AMPERE current density map. Taken from 0006–0008 UT, 4 December 2011.

covered by the network or occur at a subset of these locations. Estimating the HMB latitude using the traditional method is inherently dependent on this varying scatter availability. The new method presented in this paper uses an independent data set to determine the latitude position of the HMB and in the examples provided improves the interpretation of scatter in convection mapping by removing the dependence on scatter availability and smoothing out sharp temporal changes in the HMB. However, there are limitations to the method, such as the problem of comparing different shaped boundaries and the development of the method without midlatitude radar data. This new method provides two trends, created using 2011 and 2015 data, which can be used to estimate the latitude position of the HMB for periods near solar minimum and solar maximum, respectively.
Figure 8. Northern Hemisphere magnetic latitude-magnetic local time plots of (a) SuperDARN convection map with a traditionally calculated HMB, (b) SuperDARN convection map with HMB predicted using Λ_{cor}, (c) SuperDARN convection map with traditionally calculated HMB overplotted onto AMPERE current density map, and (d) SuperDARN convection map with HMB predicted using Λ_{cor} overplotted onto AMPERE current density map. Taken from 0024–0026 UT, 4 December 2011.

As shown in Figure 3, the solar wind-magnetosphere-ionosphere system is less strongly driven in 2011 than 2015; these two years were selected to allow solar cycle comparisons. The resulting linear trends from 2011 and 2015 are presented in equations (1) and (3), respectively. Trend 3 has a gradient about 0.15 less than that of Trend 1 and an offset that is about 10° more positive. Although the offsets of the trends are very different, both trends remain below the y = x line (see Figure 6c, fitting with expectations of the HMB being a few degrees below the R1/R2 boundary. The majority of R_{f} data fall between 60° and 75° (see Figures 6a and 6b), and between these values, the predicted Λ_{cor} values in Figure 6c are similar. Neither SuperDARN HMB data or AMPERE data extend down below 50° in either of the data intervals, so it is important to note the trends are not constrained by data at these low latitudes.
Although there is a clear linear trend in the main cluster of data for both Figures 6a and 6b, in Figure 6b, the distribution of the data widens at higher values of $\Lambda_0$ and $R_F$. These regions of data are either anomalously high $\Lambda_0$ or $R_F$, likely to be caused by low quality fitting of the boundaries which has not been removed by the data selection criteria applied. In strongly driven periods the FAC pattern can depart from the R1/R2 pattern, for example, the presence of strong R0 currents, making it difficult to fit a boundary automatically; this is a possible explanation for anomalously high values of $R_F$. If there are enough vectors to pass the data selection criteria but these vectors are contributed by only the polar radars, an anomalously high $\Lambda_0$ may be calculated. This is an important, practical issue, as an additional polar radar began operations after 2011, which is included in the 2015 data set (shown by the dashed field of view in Figure 2). Although it was initially thought that the addition of extra scatter in the polar region would not affect the HMB position estimation, it is possible that the scatter from this radar contributes to this issue, as without sufficient scatter the HMB position defaults to 62°.

The seasonal variation in ionospheric conductance affects the two data sets differently, and this contributes to a large amount of intervals being excluded due to the data quality criteria. Based on the quality factors discussed in section 2, 75% of available intervals in 2011 and 83% of available intervals in 2015 are excluded from the study. In the summer months SuperDARN radars receive less backscatter (Milan et al., 1997), which frequently places the number of vectors below the threshold level of 400. Milan et al. (1997) attribute this to the seasonal variation in the conductance of the ionosphere. In summer months, longer periods of illumination lead to more photoionization, increasing ionospheric conductivity. This leads to a higher proportion of $E$ region echoes from near ranges. Ionospheric convection occurs in the $F$ region, echoes from which are more often received in winter months. This seasonal variation in the ionospheric conductance has the opposite effect on the FACs; they are strongest in the summer and weakest in winter (Coxon et al., 2016), in contrast to SuperDARN backscatter returns. This means that in winter months the R1/R2 boundary fits are less likely to satisfy the data selection criteria discussed earlier. This could result in better quality HMB calculation during periods of poor fitting R1/R2 boundaries, and vice versa.

The functional form of the HMB is noncircular and, in this paper, is compared with the circular R1/R2 boundary (see Figures 1c and 1d). Since the HMB is near semicircular on the nightside the best location to compare the boundaries is the midnight meridian, with the R1/R2 boundary centered 4° antisunward of the geomagnetic pole. Comparison of the entirety of the noncircular form of the HMB with the circular R1/R2 boundary would result in a trend with an MLT dependence. Instead, it was decided to consider only the relationship between the two boundaries at the midnight meridian, as this would suffice to show a trend between the scale size of the two patterns. However, the problem of comparing a circular boundary with a noncircular one cannot be ignored and is countered in this study by comparing the boundaries at the midnight meridian. Additionally, the availability of scatter in the SuperDARN convection maps affected the reliability of $\Lambda_0$ values used for the study. SuperDARN vectors can be observed at all MLT and latitude locations covered by the network or at a subset of these locations. A threshold value on the number of vectors contributing to the HMB latitude determination was applied to the data set to eliminate intervals with reduced coverage.

The traditional estimation of the HMB minimum latitude is limited to a minimum $\Lambda_0$ of 50°. The cluster of outliers in Figures 6a and 6b at $\Lambda_0 = 50°$ is due to this limit. These instances can be caused by a number of nonphysical scatter changes. An example is the gradual decrease followed by sharp high-latitude shift around 0700–0830 UT in Figure 4b. The initial gradual change is caused by an area of scatter moving around the polar cap into, for example, the 1100 MLT region, as described previously. This gradual change leads to an HMB position that causes an unlikely interpretation of vectors, and a very low value of $\Lambda_0$, which does not appear physical in the midnight sector (see Figure 7c). However, as it is a gradual change, it is not filtered out by the data selection criteria. At the end of the gradual decrease, the scatter slows down leading to a sharp shift to higher latitudes, greater than the limit of 7°, but as this change happens over two time intervals, it is also not removed by the data selection. Instances such as these contribute to the anomalous cluster at $\Lambda_0 = 50°$ in Figures 6a and 6b, in particular those at higher values of $R_F$.

The Milan et al. (2015) method used to determine $R_F$ has a hard-wired limit at 76° latitude. During weakly driven intervals the FAC pattern can be very weak and depart from the standard R1/R2 pattern, which can cause the boundary estimation to default to the hard-wired limit. The existence of an anomalous cluster at $R_F = 76°$ in Figures 6a and 6b are due to this limit.
Table 1

Results From Linear Regression as Presented in Figure 6

| Trend | Year | Gradient | Offset \( \Lambda RF \) | \( N \) | \( r \) | RMS error \( RF \) | \( a \) | \( b \) |
|-------|------|----------|-----------------|-----|-----|----------------|-----|-----|
| 1     | 2011 | 0.966    | \(-2.60^\circ\)  | 66803 | 0.559 | 3.26^\circ       | 55.0% | 45.0% |
| 2     | 2011 | 0.953    | \(-1.45^\circ\)  | 64895 | 0.598 | 2.75^\circ       | 54.8% | 45.2% |
| 3     | 2015 | 0.803    | \(8.82^\circ\)   | 45617 | 0.577 | 2.71^\circ       | 56.8% | 45.2% |
| 4     | 2015 | 0.827    | \(7.35^\circ\)   | 44891 | 0.564 | 2.61^\circ       | 57.1% | 42.9% |

The effect of the clusters of outliers at \( \Lambda_0 = 50^\circ \) and \( RF = 76^\circ \) will be discussed here. For both 2011 and 2015 data, the distributions at \( \Lambda_0 = 50^\circ \) and \( RF = 76^\circ \) were removed from the data set, and linear regression was performed again. The resulting trends are overplotted onto Figures 6a and 6b as dashed lines, marked as 2 and 4 for 2011 and 2015, respectively. The trends marked as 1 and 3 refer to the fit from the data before the removal of these anomalous distributions. The linear trend resulting from the fit from Trend 2 is recorded in equation (2) and at the top of Figure 6a, as are the correlation coefficient \( r \) and the number of contributing time intervals \( (N_2) \). In Table 1 and at the bottom of Figure 6a the number of points above and below the line of best fit \((a_2\) and \(b_2)\) and the RMS error \((RMS_2)\) are recorded.

The gradient of the line in Trend 2 (equation (2)) is the same as one decimal place of that in Trend 1 (equation (1)), but the intercept is 1.15^\circ less negative. The correlation coefficient in both cases is the same as one decimal place, although improved by 0.039 by the removal of outliers, and the difference in the number of points above and below the line is reduced by 0.2%. The RMS error for Trend 2 is 2.75^\circ, which for values ranging from 50^\circ to 75^\circ represents a percentage error of between 5.50% and 3.67%. Trend 1 is overplotted as a solid line in Figure 6. Overall, the two trends are very similar, showing that the data at \( \Lambda_0 = 50^\circ \) and \( RF = 76^\circ \) do not have a great effect on the resulting trend. The main effect seen from the inclusion of the values at \( \Lambda_0 = 50^\circ \) and \( RF = 76^\circ \) is to change the offset value.

For 2015 data, the line of best fit resulting from the removal of data clusters along \( \Lambda_0 = 50^\circ \) and \( RF = 76^\circ \) is labeled Trend 4 and is recorded in equation (4). At the top of Figure 6b the correlation coefficient \( r \) and number of contributing time intervals \( (N_4) \) are recorded, along with the trend presented in equation (4). Compared with Trend 3, Trend 4 is similar, the gradient is the same as one decimal place, but the offset is about one sixth smaller. The correlation coefficient is similar to that in Trend 3, although decreased by 0.013 by the removal of data along \( \Lambda_0 = 50^\circ \) and \( RF = 76^\circ \). The difference between the number of points above and below the line of best fit for Trend 4 is 0.3% greater than in Trend 3, although the RMS error is 0.1^\circ smaller \((RMS_4) = 2.61)\). For values in between 50^\circ and 75^\circ, \( RMS_4 \) creates a percentage error of between 5.22% and 3.48%, respectively. As with 2011 data, data along \( \Lambda_0 = 50^\circ \) and \( RF = 76^\circ \) for 2015 accounts for a small amount of the data set which passed selection criteria, only 1.6%, so it was not expected that it would have a drastic effect on the trend.

All four trends are presented together in Figure 6c and Table 1 along with other relevant statistics. Although data from near solar minimum and maximum gave different equations of linear fit, the resulting \( \Lambda_{cor} \) values are similar in the latitude regions with highest data occurrence. Hence, in this region, the use of either trend would create a similar \( \Lambda_{cor} \). Outside of this region, at the extremes of the data set, the differences in predicted \( \Lambda_{cor} \) from the solar minimum and maximum data sets are greater, particularly at low values of \( RF \). The removal of outliers along \( \Lambda_0 = 50^\circ \) and \( RF = 76^\circ \) had a negligible effect on the trends from both data sets; therefore, Trends 1 and 3 are presented as solutions for near solar minimum and maximum, respectively. Neither Trend 1 or Trend 3 goes through the center of the dense cluster of occurrence for the data sets, and although this can be explained by the spread of the data, this could have an effect on estimated values of \( \Lambda_{cor} \). The resulting trends have correlation coefficients of greater than 0.5, suggesting that the data are more likely to fit the trend than not. Unfortunately, the correlation coefficients are reduced by the spread of the data away from the main cluster of occurrence in both instances.

Some examples of the use of this trend to estimate the HMB latitude have been presented in this paper. In these examples, the use of the trend to estimate the HMB latitude presents a much more smoothly varying boundary to the convection region, without the sharp jumps in latitude the traditional calculation of the HMB can suffer from (see Figure 4). Successfully estimated HMB values resulting from the new method fit the general latitude coverage of the vectors, as well as encircling the R1/R2 current system.
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Implementation of this method of estimating HMB latitudes can improve the interpretation of SuperDARN data in ionospheric convection maps, as shown in Figure 7, and creates convection maps on a similar processing time scale to that of the traditional method for determining the HMB. However, the method is dependent on the user having access to a secondary data set (AMPERE) or a data set of $A_{cor}$ values. Finally, when using this method, the user must select the trend from either solar minimum or maximum, based on the conditions in the period.

5. Conclusion

The traditionally calculated SuperDARN Hepper-Maynard boundaries are known to experience unphysical variations including step changes due to scatter availability. These unphysical variations will continue while SuperDARN HMB latitudes are determined by vector coverage. Scale sizes for the convection and field-aligned current regions were calculated using SuperDARN and AMPERE, respectively. This paper establishes a linear relationship between the scale size of the convection region and the field-aligned current region. Use of an independent data set eliminates the dependency of the HMB on scatter availability. Two trends have been developed, for use near solar minimum and maximum, showing a solar cycle dependence. However, the resulting estimated $A_{cor}$ values are almost indistinguishable where most of the data are. A full functional dependence of the trend throughout the entire solar cycle is left as a topic for future research, since only 6 years of R1/R2 boundaries are available. The use of these trends can improve upon the determination of the position of the HMB and hence the interpretation of line-of-sight velocities in SuperDARN convection maps.

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