Steady Magnetospheric Convection Selection Criteria: Implications of Global SuperDARN Convection Measurements

K. A. McWilliams and J. B. Pfeifer

Institute of Space and Atmospheric Studies, University of Saskatchewan,
Saskatoon, Saskatchewan, Canada

R. L. McPherron

Institute of Geophysics and Planetary Physics, University of California, Los Angeles, California, USA

K. A. McWilliams, Department of Physics and Engineering Physics, University of Saskatchewan, 116 Science Place, Saskatoon, SK S7N 5E2, Canada.
kathryn.mcwilliams@usask.ca
Quantitative definitions have been developed to detect intervals of steady magnetospheric convection (SMC), but these methods are based only on proxies of convection, such as the Auroral Electrojet (AE) indices. For the first time, observations of convection on a global scale are studied during intervals identified as steady magnetospheric convection events. The SMC occurrence and SuperDARN transpolar voltage exhibit a strong seasonal bias, which is believed to be due to the seasonal variation of ionospheric conductivity. Equivalent AE values in winter and summer correspond to similar electrojet current strengths but to different levels of convection. Convection events selected using a constant AE threshold are shown to be enhanced but above a variable threshold. This SuperDARN study is the first step in improving the reliability of SMC event selection by using convection observations. We present a new variable AE cutoff function to to reduce the seasonal dependence of SMC selection on ionospheric conductivity.
1. Introduction

The stability of any physical system is of fundamental importance to understanding its behaviour. The Earth’s magnetosphere is an open system that is driven by its interaction with the solar wind, and the dynamic state of the magnetosphere incorporates a recent time history of its interaction with the solar wind. The solar wind is neither steady nor continuous, so the magnetosphere finds itself in a highly variable space plasma environment, and this fluctuating driver results in variability of the magnetosphere. The situation is further complicated by internal processes intrinsic to the magnetosphere, which also affect its dynamics. The result is a complex interaction between internal and external processes. Steady magnetospheric convection (SMC) events [Pytte et al., 1978] are intervals of enhanced convection without any classical substorm signatures (e.g., see Sergeev et al. [1996] and references therein). When the magnetosphere is driven to this relatively steady state there is, effectively, a balance between the creation of open flux on the dayside and the closure of flux on the nightside.

1.1. Quantitative Definitions of SMC

While attempts have been made to develop a quantitative definition of SMC, all studies have used only proxies for convection. SMC selection criteria primarily involve the magnetometer response to the auroral electrojet currents. Sergeev et al. [1996] defined SMC intervals as having enhanced convection satisfying Auroral Electrojet (AE) index criteria, stable and continuously southward averaged interplanetary magnetic field (IMF) for 4-6 hours, no typical substorm signatures observed on the ground, and, if spacecraft data were available, no evidence of current sheet disruptions or plasmoid releases in the tail.
Other studies have relied only on magnetosphere and ionosphere data sets, in an attempt to eliminate presumptions about the upstream driver of SMC, such as the southward IMF condition of Sergeev et al. [1996]. O’Brien et al. [2002] developed a quantitative SMC identification method based solely on the AE indices, and therefore solely on ionospheric currents that are driven by magnetospheric convection. Convection was considered to be enhanced when AE exceeded 200 nT. A minimum rate of change of AL was applied to eliminate substorms (i.e., to ensure steadiness of convection), since AL tends to drop quickly when there is a substorm. The AL derivative was required to be positive or dropping no faster than 25 nT/min. These criteria were required to hold for at least 90 min. DeJong and Clauer [2005] presented a SMC selection method employing global images of the ultraviolet auroral oval from Polar UVI. The polar cap area, which is not expected to change during balanced dayside and nightside reconnection, was estimated from the poleward boundary of the ultraviolet aurora. If the area of the polar cap changed by less than 10% for a minimum of 3 hours, the event was deemed to be SMC. The 200-nT AE cutoff was applied as a secondary criterion, in cases when the UVI polar cap area was not available for the entire interval.

1.2. SuperDARN Convection and SMC

The plasma drift in the ionosphere, which is the field-aligned footprint of magnetospheric convection, can be measured on a global scale by the Super Dual Auroral Radar Network (SuperDARN) [Greenwald et al., 1995], [Chisham et al., 2007]. SuperDARN coverage is continuing to expand, with the installation of more radars in the northern and southern auroral zones, as well as some subauroral and polar cap radars. By the end of
2007 there were twenty SuperDARN radars in operation, and further expansion of the network continues. The expansion of SuperDARN allows for ever more accurate global ionospheric convection maps, created by assimilating data from all operational radars. These convection maps are an excellent tool to quantify convection in the magnetosphere, but their accuracy is highly dependent on several factors, including a variable data rate (depending critically on changing radio wave propagation in the ionosphere) and the use of a priori convection models to produce the global convection maps. All SuperDARN convection maps are constructed from the spherical harmonic functions that best fit the measured SuperDARN velocity components [Ruohoniemi and Baker, 1998]. These fits are constrained by a statistical convection pattern parameterized by the orientation of the upstream IMF [Ruohoniemi and Greenwald, 2005]. It is the use of this inherently steady convection pattern that could lead to problems when using SuperDARN to study SMC. It is critical to differentiate whether the steadiness of SuperDARN convection maps is due to the steady nature of the convection itself or due to the statistical model constraining the fit. The present study is not an attempt to produce a SuperDARN definition of SMC; rather it is an evaluation of current SMC selection methods, using observations of global convection by SuperDARN. In particular, the SuperDARN convection maps will be used to test the AE index threshold as an indicator of enhanced convection above a consistent level throughout the year.
2. Data Analysis

2.1. Initial SMC Selection

We initially adopted a slightly modified version of the SMC definition of O’Brien et al. [2002]. The criteria $\text{AE} \geq 200 \text{ nT}$ and $\frac{d\text{AL}}{dt} \geq -25 \text{ nT min}^{-1}$ were required to hold for at least of 3 h. The 3 h minimum duration was chosen as a compromise between the 1.5 h of O’Brien et al. [2002] and the 4-6 h of Sergeev et al. [1996], since it would eliminate most substorm recovery phases. These selection criteria were applied to the AE indices from 1966 to 2001, inclusive. In total 1126 SMCs were found.

2.2. Solar Cycle and Seasonal Dependencies of SMC

On average, about two SMCs occurred every three weeks, but the SMC events did not occur at regular intervals. More SMCs were found near solar maximum. The solar cycle dependence can be demonstrated by comparint the yearly SMC total to the F10.7 cm solar flux (Fig. 1). Interestingly, the number of SMC events is not directly proportional to the intensity of the F10.7 cm flux. The solar cycle peak may be related to the increased occurrence of magnetic clouds associated with coronal mass ejections, inside of which the IMF is unusually steady. This behaviour warrants further investigation but is out of the scope of the present study.

The number of SMC events also exhibits a seasonal dependence. The cumulative monthly count of all SMC events is the dark grey histogram in Fig. 2. Very few SMCs were found during the northern winter months using the constant AE cutoff, and this trend is preserved in the distributions for individual years (not shown). The AE indices, which are derived from the magnetometer responses to the northern auroral electrojets,
are expected to experience a seasonal bias, because they depend on both magnetospheric
convection and ionospheric conductivity [McPherron et al., 2005]. Both seasonal and so-
lar cycle effects on the AE indices have been reported [Ahn, 2000]. Due to the increased
photoionization, when convection is equivalent stronger currents will flow in the sunlit
ionosphere than in the dark ionosphere. Alternately, stronger convection is required dur-
ing the dark winter months to achieve the same auroral electrojet currents that occur
during the sunlit summer months. A 200-nT cutoff therefore is expected to eliminate all
but the strongest convection events during the winter.

2.3. SuperDARN Convection During SMC

To investigate if the $\text{AE} \geq 200$ nT criterion quantifies different levels of convection
throughout the year, the SuperDARN convection maps for years 1998-2001 were examined.
For the duration of each SMC interval, sequential 2-min northern hemisphere convection
maps were produced, using a fixed delay of 60 min to the ACE Magnetic Field Instrument
[Smith et al., 1998]. The mean voltage for each SMC interval is presented in Figure 3(a).
The SuperDARN polar cap voltage is the difference between voltage extrema of the con-
vection pattern, and the mean interval voltage is the average of all 2-min voltages within
an interval.

Fig. 3(c) contains the mean voltages for randomly selected intervals, as a reference for
“typical” SuperDARN observations. These events are selected by changing the dates of
properly identified SMC events using a random number generator and ensuring that all
months have about the same number of events. The mean voltages during the random
intervals are predominantly between 20 and 60 KV, and the average of the 2-min map
voltages is 45 kV. Only 7 SMC events of the 153 selected using the constant AE cutoff have a mean interval voltage below 45 kV. In addition, 90% of the 18379 individual 2-min map voltages for the SMC intervals in panel (a) exceed 45 kV. The constant AE cutoff of 200 nT is therefore selecting intervals that are clearly a subset of SuperDARN data with enhanced convection.

A running mean (2-month average and 1-month shift) has been included in Fig. 3. It appears that the northern summer SMC voltages in panel (a) are generally lower than the voltages in the winter months. The randomly selected events in panel (c) do not seem to exhibit such a seasonal variation. We do acknowledge that the uncertainty in the SuperDARN voltages is large, and more work must be done to investigate if this is a significant trend in the data.

As an extra check of the 200 nT enhanced convection threshold, events were selected for which \( \text{AE} < 200 \text{ nT} \) and \( \frac{d\text{AL}}{dt} \geq -25 \text{ nT min}^{-1} \) were satisfied for at least 3 h. These events are presented in Fig. 3(d). 84% of the 1967 events had an average voltage below 45 kV. These events therefore comprise a subset of SuperDARN data with weak convection. One should also note that the SuperDARN voltage is always positive, so northward IMF convection will have a voltage that is positive and possibly large.

### 2.4. Modified SMC Selection Criteria

Because the minimum AE threshold quantifies enhanced currents rather than enhanced convection, a variable AE threshold is required to reduce the seasonal conductivity bias. A simple AE cutoff function was developed that would increase the number of SMC events in the northern winter months and produce a “flat” distribution. The 200-nT AE cutoff
was preserved at mid-summer, and the winter AE cutoff was lowered. The new variable AE cutoff function is of the form:

\[ AE \,[\text{nT}] \geq (200 - A) + A \cos^n \left( \frac{(x - 173)}{365} \pi \right). \tag{1} \]

Integer values of \( n \) and \( A \) were varied until the winter events were as numerous as the summer events. The “flatness” of the resulting events distribution was quantified by two methods: (1) the difference between the largest and smallest monthly event totals and (2) the variance of the monthly event totals. Both of these “flatness” tests, presented in Fig. 4, minimized at nearly identical values of \( n \) and \( A \). This cosine dependence is not understood, but it is expected to be related to the dependence of the ionospheric conductivity on the square root of the cosine of the solar zenith angle, as well as to the combined probabilities of AE magnetometer stations contributing to AE during the several hours over which a SMC event is measured. Other functions were tried, but no significant advantage was gained by using a different or more complicated function.

The improved enhanced convection criterion is given by:

\[ AE \,[\text{nT}] \geq 90 + 110 \cos^5 \left( \frac{(x - 173)}{365} \pi \right), \tag{2} \]

where \( x \) is the day of the year. The function was designed so that throughout the year the argument of the cosine function would vary between \( \pm \pi/2 \), so the AE threshold minimizes at 90 nT at the northern winter solstice.

When the new variable AE cutoff function was applied, the number of SMC events increased to 2767. The AE indices for the SMC events found using Equation 2 were all visually examined. The AE indices are normalized monthly by subtracting the average of the five international quietest days from the month’s magnetic components. There were
several months for which only provisional data were available when the normalization appears not to have been sufficient, and the AU index was elevated but constant for many hours. Qualitatively, these intervals are quite unlike SMC intervals, in that there is no accompanying enhancement in AL, which is expected when the electrojets are enhanced. These events were removed from the voltage comparison. The SuperDARN voltages for these rejected intervals were found to be extremely low (∼20 kV), which is near the lower limit of the SuperDARN voltages, in practice.

The new cumulative monthly distribution is the white histogram in Figure 2. The number of winter events is nearly equal to the number of summer events, and the trend for a “flatter” distribution is preserved in the individual years (not shown). The distribution maximizes near equinox, but this is not unexpected, as the Russell-McPherron effect predicts increased geomagnetic activity near equinox [Russell and McPherron, 1973]. Ahn [2000] noted that AU maximizes during the northern summer and that AL, which is more closely related to substorm and therefore to geomagnetic activity, maximizes near equinox.

The mean SuperDARN voltages for the SMC events selected using the new optimized AE function are presented in Fig. 3(b). The extra events that occur during the northern winter months have mean voltages very similar to the summer values, which supports the constant minimum convection threshold condition arising from the variable AE selection criterion. The variable-AE SMC voltages are also in the higher range of the “random” events, with 86% of the 439 variable-AE SMC events having a mean voltage above 45 kV, and likewise for 80% of the 55105 2-min map voltages. The variable AE cutoff therefore preserves the enhanced convection condition throughout the year.
The one-month running mean, which is the solid line in Fig. 3(b), suggests that the SMC events selected using the variable AE cutoff have, on average, higher voltages near equinox. This also supports the hypothesis that there is more effective coupling (and therefore more opportunity for increased convection) near equinox. Again, due to the uncertainty in the SuperDARN voltages, investigation of this phenomenon is necessary. Interestingly, the variable-AE SuperDARN SMC maps contained 10% more data points (>200 points per map, on average) than all other sets of events studied. Further investigation is required to determine if the SuperDARN data rate responds to the steadiness of the magnetosphere system during SMC.

3. Discussion and Conclusions

The AE indices are commonly used to quantify SMC, but AE is not a direct measurement of convection. Because the electrojet currents depend on the ionospheric conductivity, a constant minimum AE threshold does not quantify a constant convection threshold throughout the year. The SuperDARN convection maps reveal: (1) that the majority of SMC events with AE>200 nT were indeed enhanced convection intervals, and (2) that weaker convection events were detected during the northern summer.

We developed an improved variable-AE SMC criterion, designed to detect as many SMC events in the winter as in the summer. The new SMC distribution maximized near equinox, which agreed with the increased coupling with the IMF described by the Russell-McPherron effect. The SuperDARN voltages of the additional SMC events were preponderantly above the typical average, so this new variable AE cutoff is successfully identifying enhanced convection intervals.
The seasonal variations of ionospheric conductivity are also expected to impact the “steadiness” criterion ($dA/dt \geq -25 \text{ nT min}^{-1}$). This criterion is already problematic, since all it takes is one noisy data spike to cut short a SMC interval or even to preclude the selection of an interval. Modification of the $A_L$ criterion may also change the occurrence distribution that was used to develop the variable-AE cutoff function in Equation 2. Further refinement of the SMC criteria is essential.

Ideally, SMC events would be defined using observations of global convection. Because SuperDARN the convection mapping technique employs statistical convection patterns to constrain the fitting algorithms, one must be extremely cautious when attempting to quantify the steadiness of these convection patterns. It is this inherently steady model that may cause problems identifying SMC using SuperDARN. Before a SuperDARN definition of SMC is produced, work is required to deduce the properties of SMC seen by SuperDARN using maps where data, not models, dominate the convection maps.

**Acknowledgments.** Funding for this research was provided by an NSERC Discovery Grant to Dr. K.A. McWilliams and by NSERC CRO fund for the Canadian SuperDARN Program. The solar radio flux data are provided as a service jointly by the National Research Council of Canada and the Canadian Space Agency. The authors thank the WDC-C2 Kyoto AE index service for providing AE index data.

**References**


Ruohoniemi, J.M., and R.A. Greenwald, (2005), Dependencies of high-latitude plasma convection: Consideration of interplanetary magnetic field, seasonal, and


Figure 1. Average annual F10.7 cm flux and annual total SMC events found using the constant minimum AE 200 nT threshold.

Figure 2. Cumulative number of SMC events per month for years 1966-2001, inclusive, selected using two methods with different enhanced convection criteria: (1) constant minimum AE threshold (dark grey histogram) and (2) variable minimum AE threshold (white histogram).
Figure 3. The average SuperDARN polar cap voltage for (a) SMC events found using AE > 200 nT, (b) SMC events found using the AE cutoff function, (c) randomly selected intervals for reference, and (d) intervals selected when AE < 200 nT for reference.
Figure 4. (a) The difference between the maximum and minimum monthly number of SMC events, and (b) the variance of the monthly number of SMC events for a variety of amplitudes $A$ and exponents $n$ for Equation 2.