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1 Observations of the relationship between ionospheric
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4 Abstract.

5 Convection observations from the southern hemisphere SuperDARN net-
6 work are presented and examined for their relationship to solar wind and in-
7 terplanetary magnetic field (IMF) conditions, restricted to periods of steady
8 IMF. Analysis is concentrated on two specific regions, the central polar cap
9 and the dayside throat region. An example time series is discussed in detail
10 with specific examples of apparent direct control of the convection velocity
11 by the solar wind driver. Closer examination however shows that there is vari-
12 ability in the flows that can not be explained by the driving. Scatter plots
13 and histograms of observations from all periods in the year 2013 that met
14 the selection criteria are given and their dependence on solar wind driving
15 is examined. It is found that on average the flow velocity depends on the square
16 root of the rate of flux entry to the polar cap. It is also found that there is
17 a large level of variability that is not strongly related to the solar wind driv-
18 ing.

1. Introduction

19 The Super Dual Auroral Radar Network (SuperDARN) observes plasma convection in
20 the ionosphere in both the northern and southern hemispheres. In the southern hemi-
21 sphere, the radar located at McMurdo Station, Antarctica, observes directly over the
22 magnetic pole, which lies at a distance of about 1000 km from the radar; an optimal
23 range for HF radar observations of convection [*Bristow et al.*, 2011]. A new pair of radars
24 was added to the southern SuperDARN network in the Antarctic summer of 2012/2013
25 with radars at the US base South Pole Station, and the French-Italian base at Dome
26 Concordia (Dome-C). This new pair of radars observes the region just equatorward of
27 McMurdo station. Figure 1 shows the fields-of-view of the McMurdo, South Pole, and
28 Dome-C radars. This observing geometry enables observations of the central polar cap
29 plasma flow while simultaneously observing the auroral zone, which is ideal for studies
30 of (for example) the day-side inflow region or the night-side outflow region. The dayside
31 observations are particularly interesting since the cusp region is the main location where
32 solar-wind energy is deposited in the Earth's magnetosphere, driving convection in the
33 entire system. As Figure 1 shows, the South Pole and Dome-C fields-of-view cover the re-
34 gion just to the east of the 180° longitude line, which means that the dayside observations
35 occur during the time interval between about 1700 UT and 2100 UT.

36 Development of plasma flow in the polar caps is a central topic of magnetospheric
37 dynamics. Ever since *Dungey* [1961] described an open magnetosphere, we have had the
38 concept of the solar wind electric field mapping along magnetic field lines into the polar
39 cap. In that seminal paper, a twin-cell convection pattern was described resulting from

40 this mapping along equipotentials from the solar wind into the ionosphere generating
41 anti-sunward flow in the polar cap and sunward return flow within the region of closed
42 magnetic field lines. The concept has developed over time into sophisticated models of
43 the Earth's magnetosphere that include the distortion of the field by gas-dynamic forces
44 and the expected modifications to the magnetic field configuration for different merging
45 geometries [*Toffoletto and Hill, 1989*]. The concept of convection being driven by direct
46 mapping of the solar wind electric field into the polar-cap ionosphere, however, leads to
47 the unphysical conclusion that the flow velocity in a particular region of the ionosphere
48 would correspond directly to the electric field of the specific region of the solar wind
49 lying along the same magnetic field line. Such correspondence would at times lead to
50 regions of compression and rarefaction of the ionospheric magnetic flux, which is not
51 possible for physically realizable flow velocities. This understanding led *Siscoe and Huang*
52 [1985] to describe patterns of convection in the ionosphere that differed from that due
53 to direct mapping. The model for convection described in that paper and subsequent
54 refinements [*Moses et al., 1987; Moses et al., 1989; Moses and Reiff, 1991; Lockwood*
55 *et al., 1990; Cowley and Lockwood, 1992*] has convection being the result of two somewhat
56 independent reconnection processes. The first being dayside merging of the interplanetary
57 magnetic field (IMF) with the Earth's magnetic field. The second being in the magnetotail,
58 which closes flux previously opened by the dayside merging. In this scenario, the electric
59 field along the dayside merging line maps into the ionosphere along the magnetic field
60 and drives ionospheric convection. In magnetotail reconnection, it is not the solar wind
61 electric field that drives convection (directly). Rather, it is the release of energy that
62 has been accumulated in the lobes through convecting magnetic flux from the dayside.

63 Since the cusp driven ionospheric flow is excited by a mapping of the electric field in
64 the reconnection region along the cusp magnetic field lines, the ionospheric speed should
65 correlate best to metrics of the solar wind that attempt to characterize that process such
66 as the Akasofu epsilon parameter [Akasofu, 1979] rather than the solar wind electric field
67 itself.

68 In a recent paper *Newell et al.* [2007] examined the correlation between various measures
69 of magnetospheric activity and a number of solar wind-magnetosphere coupling functions.
70 They demonstrated that nearly every magnetospheric measure could be predicted with
71 fairly high correlation by functions of solar wind parameters related to the dayside merging
72 rate, with some of the correlations exceeding 0.8. While the paper did identify a “best”
73 function, the differences in performance among the top few candidates were small. The
74 main conclusion from that study was that the dayside merging rate was “the single largest
75 correlate for most magnetospheric activity”. In the work presented here, the Newell et al.
76 *best* function was adopted for characterizing solar wind driving and is referred to as E_{MP}
77 to signify the merging electric field at the magnetopause.

78 While there may be strong correlation between global measures of activity and solar
79 wind driving parameters, the variability in those measures for a given driving level is large
80 [e.g. *Bristow et al.*, 2004; *Lockwood et al.*, 2009]. To some extent the variability can be
81 explained by accounting for the history of the magnetospheric state prior to an interval.
82 *Lockwood et al.* [2009] examined the cross-polar-cap-potential, Φ_{PC} , as a function of the
83 driving but separated intervals based on substorm phase. Figure 7 of that paper showed
84 a significantly reduced level of variability in Φ_{PC} during intervals classified as “Quiet &

85 Growth” versus the variability in intervals described as “Disturbed AL”. Even in the quiet
86 intervals however, the spread in values about the trend lines was still large.

87 Simultaneous observations of flows localized in the cusp and central polar cap provide
88 additional information on the degree to which dayside reconnection exerts control over
89 convection in the system. It might be expected that since the dayside merging drives
90 convection in the cusp region, flow in that region would correspond more closely to the
91 solar wind driving than would flow in other regions. The expectation is that dayside
92 reconnection excites high-speed flow in the cusp region that influences the flows at all
93 latitudes and local times. However, the magnitude of influence should decrease with
94 distance from the cusp but the correlation should remain high. The cusp flows appear
95 in the *dayside throat* region, which is an identifiable feature of the convection patterns
96 measured in the ionosphere.

97 In this study, observations from the full southern hemisphere SuperDARN network
98 obtained during selected periods of the first year of operation of the South Pole and Dome-
99 C radars, calendar year 2013, were used to form convection patterns using the standard
100 SuperDARN potential mapping algorithm [*Ruohoniemi and Baker, 1998*]. The magnitude
101 of these vectors was averaged within areas identified as the dayside throat and the central
102 polar cap for each two minute period, producing time series of average convection in the
103 two regions. In addition to producing time series, the data were accumulated in scatter
104 plots and histograms and examined for various dependencies on IMF, solar wind, and
105 each other.

106 Periods included in the study were chosen based upon the ACE IMF observations.
107 Data were included from intervals in which the observed IMF components had only small

108 fluctuations ($\sigma_B < 1$ nT) for periods of at least an hour. Choosing such intervals has
109 two results. First, it helps to overcome the uncertainty in the propagation delay from the
110 observing satellite to the point at which the observed IMF becomes effective at driving
111 flow in the ionosphere. Second, it allows examination of flow evolution under steady
112 driving, which may differ from flows under variable driving [Lockwood *et al.*, 2009].

2. Data presentation

113 Figure 2 shows the line-of-sight (LOS) velocity observations from McMurdo and the IMF
114 observations from the ACE spacecraft during one of the intervals selected for study. The
115 satellite observations were delayed by an amount calculated using an algorithm similar to
116 that used to create the OMNI database [*e.g.* Weimer and King, 2008]. The algorithm es-
117 timates the position where a flux tube intersected the earth-sun line and uses the observed
118 solar wind velocity to propagate from that point to the magnetopause. The figure shows
119 ten hours of observations from 1200 UT (0455 MLT) to 2200 UT (1435 MLT) including
120 the interval from about 1535 UT to about 2041 UT, which met the criteria for this study.
121 The ACE observations show relatively steady southward IMF during most of the interval.
122 Prior to 1535 UT the y-component varied between about -5 nT and +5 nT, and there was
123 a positive excursion of the z-component between about 1500 and 1530, which was more
124 variation than was acceptable. If the central cap velocity is determined solely by the
125 IMF, based upon these observations the expected flow would be primarily antisunward
126 with a fairly steady velocity for most of the period. In the interval, the McMurdo position
127 rotated from near dawn through magnetic local noon, which occurs around 1930 UT. The
128 look direction of the radar beam plotted in the figure rotates from perpendicular to the
129 earth-sun line to parallel to it. If the central cap velocity were steadily antisunward, the

130 observed LOS velocity would show a cosine dependence starting with zero velocity around
131 1330 UT, peaking around 1930 UT and dropping off after that time. The B_y component
132 observed during the interval would modify this expectation somewhat, with the negative
133 B_y observed in the early part of the interval adding a dawn-to-dusk velocity component,
134 and the positive B_y observed in the latter portion yielding a dusk-to-dawn component.
135 The actual pattern observed by McMurdo was similar to the expected, with a value near
136 0 at the beginning, increasing through the first half of the period, then decreasing toward
137 the end. The observations through the interval show moderately variable flows of 0 m/s
138 to about -900 m/s, where negative indicates velocity away from the radar. The peak ob-
139 served value occurred just prior to 1800, which was about an hour and a half before the
140 expected time of the peak at magnetic noon. For a 30 minute interval before about 1530
141 the line-of-sight velocity decreased and even briefly reversed from negative to positive.

142 A few features of the interval are typical of McMurdo observations. First, at times there
143 is a clear response in the flows that can be associated with a specific observation in the
144 IMF. For example, the IMF fluctuation observed around 1500 to 1530 UT clearly relates to
145 the decreased LOS velocity observed in that time period. The brief sign change of the LOS
146 velocity even appears to reflect the bi-polar fluctuation in the IMF B_y and B_z components
147 observed at the time. It should be noted that the decrease in LOS velocity begins some
148 20 minutes or so after the change in the IMF begins, however the brief sign change of the
149 LOS velocity is simultaneous with the brief bi-polar IMF fluctuation. This discrepancy
150 illustrates that while the delay between the IMF observation and the time at which it
151 reached the magnetopause was estimated algorithmically accounting for tilts of the IMF
152 planes, there is still uncertainty both in that delay, and in the time at which the IMF

153 becomes effective in influencing convection after reaching the magnetopause. This should
154 be kept in mind in when evaluating some of the later results presented in this manuscript.
155 A second typical feature of the McMurdo observations is illustrated in the interval from
156 about 1600 UT to about 2000 UT. The scatter in this interval was not continuous over
157 area, rather it was characterized by distinct regions of irregularities receding from the
158 radar. These regions are the signature that would be expected from polar-cap patches
159 propagating across the central polar cap. Further, while the radar backscatter appears
160 patchy, the magnitude of the velocity within the patches and over time remains relatively
161 steady, corresponding to the roughly steady value of the IMF.

162 Convection patterns were formed for this interval using all available southern hemisphere
163 SuperDARN observations. The patterns were generated using the potential mapping tech-
164 nique of *Ruohoniemi and Baker [1998]*, which estimates global maps of the electrostatic
165 potential that minimize inconsistency with the available observations. The technique ex-
166 presses the potential as a summation of spherical harmonic functions with coefficients
167 determined by a fit constrained by observed LOS velocities. In regions where there are no
168 observations, the fit is constrained by a sampling from model convection patterns keyed
169 to the IMF. Figure 3 shows the pattern for one two-minute interval with the fields of view
170 of the McMurdo, South Pole, and Dome-C radars highlighted. The figure displays the
171 region between -55° and the south magnetic pole, with noon at the top, midnight at the
172 bottom, and dawn and dusk on the left and right respectively. The small clock-dial in the
173 upper right corner shows the observed IMF $B_y - B_z$ components that were observed at
174 ACE at the calculated delay time, about 70 minutes prior to the interval. The convection
175 arrows shown on the figure illustrate the areas where there were observations from at least

176 one radar during the interval. The vectors were determined from the fitted convection
 177 pattern rather than directly from the measurements. This method tends to smooth the
 178 results but ensures that the vectors are divergence free. It likely reduces the peak velocity
 179 values from those truly present. The figure shows good data coverage of both the dayside
 180 throat and the central cap, which persisted throughout the period of interest. The red
 181 circle of 5° radius centered on the magnetic pole represents the area over which vectors
 182 were averaged to get the central-polar cap velocity. The box centered at 75.5° magnetic
 183 latitude and 1100 magnetic local time (MLT) represents the approximate averaging area
 184 identified as the throat. The location of the box was determined by inspecting the maps
 185 for each two-minute period in the interval. While there was evolution of the pattern over
 186 time and some motion of the throat, the 3° latitude width and 1-hour MLT width of the
 187 averaging area captured the motion. The convection pattern was somewhat complex but
 188 was two-celled as would be expected from the IMF. The estimated cross-cap potential was
 189 about 50 kV. The observed flows show antisunward convection in the central cap with a
 190 speed of around 500 m/s. The day side throat velocity was somewhat higher speed and
 191 was directed into the cap but across noon from dawn to dusk. Flow observed near 0300
 192 MLT and 0600 MLT show the return flow was for the most part contained above 65° .

193 Figure 4 shows the time series of spatially averaged velocity magnitude for the two
 194 regions, with the blue line indicating a calculation of the solar wind driving, $E_{MP} =$
 195 $v_x^{4/3} B_t^{2/3} \sin^{8/3}(\theta/2)$, where B_t is the magnitude of the component of the IMF transverse
 196 to the magnetopause, and θ is the IMF clock angle ($\theta = \arctan(B_y/B_z)$). The units
 197 of this function are discussed in *Cai and Clauer* [2013], where the authors empirically
 198 determined that a normalization factor of 100 makes the unit Wb/s. As discussed in the

199 introducton, this product characterizes the dayside merging rate and has been shown to
200 correlate well with measures of magnetospheric activity [*Newell et al.*, 2007]. The black
201 lines indicate the dayside throat flow speed and the red lines indicate the central polar cap
202 flow speed. The dashed lines show 16-minute averages of the 2-minute values, which are
203 shown by the solid lines. The dotted lines adjacent to the solid lines show the statistical
204 uncertainty. E_{MP} remained steady up until about 1930 UT when it began a gradual
205 decrease until the end of the interval. While the driver remained relatively steady or was
206 slowly decreasing, the flow velocities in both regions showed substantial variations during
207 the interval. The dayside flow ranged between 500 m/s and 1700 m/s, and exceeded 1500
208 m/s for an extended time. Additionally, the dayside flow showed higher variability in
209 both short term excursions of a few minutes and in the longer term averages shown by
210 the dashed lines. At times the short term excursions exceeded 500 m/s amplitude above
211 or below the average over tens of minutes. The longer term average value increased from
212 500 m/s to 1700 m/s over the time from the beginning of the interval and 1800 UT, then
213 decreased from 1800 UT to 1910 UT to about 1000 m/s and rose again over the remaining
214 time in the interval. The central cap average value ranged between about 350 m/s and
215 700 m/s; exceeding 700 m/s only briefly at around 1740 UT. It shows a gradual increase
216 from the beginning of the period up until about 1740 UT, followed by a gradual decrease
217 until the end of the period. There was short term variability in the central cap flow,
218 but it was a substantially lower amplitude than that in the dayside flow. Some of the
219 fluctuations observed in the central cap appear to correlate to the dayside fluctuations,
220 but the correlation coefficient calculated for the overall interval was only 0.475. The
221 correlation coefficient peaked for a zero time lag between the two time series.

222 The central cap flow, while less variable than the dayside flow, still varied by over a
223 factor of two. The dayside flows varied by more than a factor of three. Such variations
224 without an obvious solar wind driver are likely related to internal magnetospheric pro-
225 cesses. The concepts of the expanding-contracting polar cap model for convection [*Milan*
226 *et al.*, 2007] could potentially explain the some of the observations, though only partially.
227 Examination of magnetometer observations from the IMAGE chain in northern Europe
228 (<http://space.fmi.fi/image/index.html>) during the interval indicate that there was sub-
229 storm activity. It appears that there was a growth phase that started around 1500 UT
230 or earlier, followed by an expansion phase onset around 1700 UT, and a recovery phase
231 that began around 1715 UT and lasted until at least 1900 UT. The timing of these mag-
232 netometer signatures don't directly align with the changes in the observed flow velocities,
233 however arguments could be made to associate them. For example, the increase in the
234 dayside throat flow velocity could be understood from the increasing polar cap diame-
235 ter during period prior to expansion onset. If the low-latitude convection boundary did
236 not move equatorward at the same rate as the polar cap boundary, the flow would have
237 become constricted and if the reconnection rate remained unchanged, the velocity would
238 have had to increase to supply the same amount of flux. At some point after expansion
239 onset, reconnection in the tail would begin to close open flux and the polar cap diameter
240 would begin to decrease, which would eventually decrease the constriction of the dayside
241 convection. In addition to the increase due to geometrical changes, the doubling of the
242 polar cap velocity over the period up until about 1730 UT could have been due to the
243 potential associated with magnetotail substorm processes. It should be noted, however,
244 that the influence of the night-side reconnection processes is expected to decrease with

245 distance, so should be reflected more strongly in the central cap flow than in the dayside
246 flows [Cowley and Lockwood, 1992].

247 To further investigate the relationship between solar wind forcing and convection speeds,
248 a large database of similar intervals was examined. The level-2 ACE magnetic field data
249 from 2013 were searched for periods in excess of an hour within which the standard
250 deviations of the y- and z-components did not exceed 1 nT. Figure 5 shows the resulting
251 occurrence histograms of one-minute intervals for each component of the IMF and their
252 absolute deviations. The deviations were calculated for each interval by subtracting the
253 average value for the period from the observed value at each instant. The histograms
254 show that the x-,and y-components were fairly uniformly distributed between +5 nT and
255 -5 nT, while the z-components appear normally distributed and concentrated around 0
256 nT, but with significant density in the distribution out to about ± 5 nT. The deviations
257 for all three components were small. The plasma data observations from ACE were also
258 examined for the intervals but are not shown in a figure. The average radial velocity was
259 415 km/s with a standard deviation of 80 km/s. The average number density was 3.5/cc
260 with a standard deviation of 2.6/cc. The absolute deviations of both the velocity and
261 density were small, the full width at half maximum of the velocity deviation distribution
262 was about 20 km/s, while the density deviation full width was 0.5/cc. In all about 4504
263 hours of observations met the criteria.

264 Southern-hemisphere convection patterns were formed every two minutes of the steady-
265 IMF intervals. For each pattern, the velocity magnitudes were spatially averaged in the
266 throat and cap as described above. To determine the location of the throat, an average
267 convection pattern was formed for the each steady IMF interval and the region between

268 75° and 80° magnetic latitude, and between 1000 MLT and 1400 MLT was searched to
269 find the location with the maximum time average poleward velocity. That location was
270 identified as the average throat for the entire steady-IMF interval and all points within
271 the area $\pm 1.5^\circ$ magnetic latitude and ± 0.5 hours of MLT from that point were averaged to
272 determine the throat velocity for each two-minute interval. The averages were included in
273 this study only if a minimum of five vectors fell within the throat region and a minimum
274 of ten vectors fell within the central-polar cap region. With these restrictions, 3443 hours
275 met the criteria for the central polar cap, 538 hours met the criteria for the throat, and
276 just 435 hours met the criteria for both the throat and the central cap simultaneously.

277 Figure 6 shows histograms of the observed velocity magnitudes for the whole database
278 for both the central polar cap (a) and the throat (b). The two distributions show some
279 similarities and some differences. Speeds in both regions are concentrated below about
280 1000 m/s, and show more velocities below the mean than above the mean. The central-
281 cap distribution peaks at a velocity of around 200 m/s, an average velocity of 233 m/s, a
282 standard deviation of 139 m/s, and shows very few velocities below 50 m/s. The throat
283 distribution extends to higher velocities, with an average of 561 m/s and a standard
284 deviation of 311 m/s. The smooth curves superposed on the histograms are Rayleigh
285 distributions calculated using the means and deviations of the histograms and scaled by
286 the peak number of observations. Both smooth curves appear to represent the respective
287 distributions fairly well. In addition, it is interesting to note that the central-cap distribu-
288 tion shows no recorded velocities over 900 m/s. Examples of velocities in the central cap
289 region of over 1000 m/s can be found in a broader database, however none were observed

290 in the set used here. This may indicate a difference between steadily driven intervals and
291 general intervals.

292 The observations for both regions were examined versus a number of parameters char-
293 acterizing the solar wind and IMF driving of the magnetosphere. All of the comparisons
294 gave similar results in the sense that higher driving led to higher average velocities but in
295 each case there was a large spread about the average, with the standard deviations being
296 about the same magnitude. Two sets of figures illustrating the different driving functions
297 are presented here. First, Figure 7 shows a scatter plot of observed velocity magnitude
298 versus the product of the solar wind velocity x-component, v_x , and the IMF z-component,
299 B_z , which gives the y-component of the solar wind electric field. Each point in the scatter
300 plot represents the average velocity observed in the central polar cap from a two-minute
301 interval. The points are color coded by the IMF y-component. IMF B_y could influence
302 the velocities in two ways. First, it could increase the dayside reconnection rate leading to
303 higher observed velocities. Second, distortion of the convection pattern caused by a finite
304 B_y could concentrate the flow into a channel and lead to either higher or lower velocities
305 for the same applied potential depending on the location of the channel for a given value of
306 B_y . The figure does not show any clear evidence of a B_y dependence. The green diamonds
307 show the mean calculated for bins of 0.5 mV/m of solar wind electric field. Vertical bars
308 are plotted at each diamond indicating the uncertainty in the means determined from the
309 standard deviation divided by the square root of the number of observations. While the
310 spread of the points is large, the number of points is also large, which yields a small un-
311 certainty as is illustrated by the short length of the bars. The standard deviations ranged
312 from 103 m/s up to about 140 m/s, while the number of points ranged from about 400

313 up to over 16,500, resulting in uncertainties ranging from less than a meter per second up
 314 to about 7 m/s. For positive values of $v_x B_z$ (southward IMF), there is a clear trend of
 315 increasing cap velocity with increasing solar wind electric field. Between about -1 mV/m
 316 and 3 mV/m solar wind electric field, the increase is relatively linear with a value of about
 317 80 (m/s)/(mV/m). Other than the point at $v_x B_z = 2.5 \text{ mV/m}$ lying below the trend line,
 318 there is no evidence for saturation of average cap velocity for higher driving in these data.
 319 For negative values of $v_x B_z$ \approx -2 mV/m (northward IMF) there is also a trend of increasing
 320 average velocity magnitude with increasing $v_x B_z$ magnitude.

321 Figure 8 shows the same data plotted versus E_{MP} . The trend of the data shows a
 322 similar pattern to that illustrated in Figure 7. The average cap velocity increases with
 323 increasing E_{MP} , though there is a large spread of points around the average. In addition
 324 to the colored points corresponding to 2-minute intervals, there are black diamonds rep-
 325 resenting the average values over 15-minute intervals. The distribution of the 15-minute
 326 average points is essentially the same as the distribution of the 2-minute points. This
 327 lack of reduction in spread illustrates that during an individual interval of steady driving
 328 parameter the cap velocity does not show large point-to-point variability. Rather it shows
 329 secular increases and decreases of longer duration, as was seen in Figure 4. The spread
 330 of values indicates that the polar cap velocity during different intervals with similar solar
 331 wind conditions can have significantly different values. That is, similar driving can lead
 332 to very different responses. As in Figure 7, the green diamonds and connecting line rep-
 333 resent the average values for the 10 bins of E_{MP} . In this figure the superposed blue line
 334 is a linear fit of the velocity vs the square root of E_{MP} . At E_{MP} values between about
 335 5×10^5 Wb/s and 1×10^6 Wb/s, the diamonds could be fit equally well with either a

336 linear dependence on E_{MP} itself or its square root. At low values however, below about
337 2×10^5 Wb/s, the rapid increase of average velocity with increasing E_{MP} is clearly better
338 represented by the square root dependence than by a linear dependence.

339 To further examine the dependence of polar cap plasma velocity on solar wind driving,
340 Figure 9 shows histograms of observed velocity for increasing values of E_{MP} . The panels
341 are organized with the lowest range of E_{MP} in the lower left, increasing to the right and
342 upward. On each histogram a skew-normal distribution is superposed scaled to match the
343 total number of observations in the histogram. The average and standard deviation of the
344 distribution are printed in the upper right corner of each frame. The average value is seen
345 to increase systematically with increasing E_{MP} range, which simply illustrates the trend
346 shown in the scatter plot. The standard deviation however, remains relatively constant
347 from range to range, with the value between 107 m/s and 148 m/s for all frames. With
348 the exception of the lowest frame and the highest four frames, the value was around 120
349 m/s. For the lowest values of driving, the histograms show significant skew toward low
350 velocity.

351 Figure 10 and Figure 11 show the throat velocity observations in the same formats as
352 those given for the cap velocity in Figures 8 and 9. As was illustrated in Figure 6, the range
353 of velocities observed in the throat extends to higher values than those in the central cap,
354 with significant numbers of observations up to 1500 m/s and beyond. There is a trend of
355 velocity increase with increasing E_{MP} over the range where there were significant numbers
356 of observations. As was the case with the central cap velocity observations, the trend is
357 not linear and for low values of E_{MP} the slope is steeper than it is for values above about
358 2.5×10^5 Wb/s. The blue line superposed on the figure is a linear fit of the velocity vs the

359 square root of E_{MP} . The histograms of throat velocity show similar behavior to those in
360 the central cap, though also with higher parameter values. The average velocities for each
361 bin are about twice those in the cap. The standard deviations also remain fairly constant
362 from bin-to-bin, but have a range from about 250 m/s up to about 300 m/s.

363 As a final examination of the data, Figure 12 displays a scatter plot of observed cen-
364 tral cap velocity vs the observed throat velocity when simultaneous determinations were
365 available. As would be expected from the previous figures, the cap velocity increases with
366 increasing throat velocity, but there is a broad spread about the trend. The trend ap-
367 pears to be linear with a slope of about 0.18 (m/s)/(m/s). At the lowest values of throat
368 velocity, the average velocities is about the same in the two regions. At the highest values
369 of throat velocity, the cap velocity is less than half the throat velocity. The standard
370 deviation of the cap velocities about the trend line is fairly constant around 100-120 m/s
371 over the full range of throat velocities. This is a lower deviation than the value obtained
372 when binning the cap velocities versus the solar wind driving, but not significantly lower.
373 This variability indicates that there are factors influencing the two regions that were not
374 considered here. A time delay between the two regions in response to solar wind driving
375 is one possibility. Another is the relative sizes of the polar cap and the throat region.
376 A certain potential value applied across a narrow throat gives a higher velocity than the
377 same potential applied across a broad throat. The convection velocity in a region depends
378 on the length over which a potential is applied. A common driver acting simultaneously
379 in both regions would lead to very different comparisons for the case of a narrow throat
380 and broad polar cap versus a broad throat and small polar cap.

3. Discussion

381 The observations presented here examine the relationship between solar wind driving
382 and the plasma flow velocities observed in the ionosphere, focusing on two specific regions:
383 the dayside throat and the central polar cap. The goals of the study were to examine
384 the characteristics of the flow, to examine their dependence on solar wind driving, and to
385 examine the interrelationship between the flows in the two regions. While many studies
386 have examined the relationship between solar wind quantities and global measures of the
387 magnetospheric state [*e.g. Reiff et al., 1986; Newell et al., 2007; Bristow et al., 2004;*
388 *Lockwood et al., 2009; Bristow and Spaleta, 2013*], there is value in looking at specific
389 regions in the same context. There may be reasons why one would expect a more direct
390 relationship between local quantities in these regions and the driving functions than might
391 be expected for global quantities and the same functions. For example, if reconnection
392 at the dayside magnetopause is the primary driver of convection, one might expect the
393 relationship between the flow in the dayside throat and E_{MP} to be closer there than in
394 other regions of the convection pattern. Likewise, if the mapping of the solar wind electric
395 field along magnetic field lines were responsible for driving convection, the central cap
396 flow should be closely related to that quantity. Further, in a space weather context, local
397 quantities often are the thing of interest. For example, when estimating the probability
398 of scintillation causing irregularities developing in a specific region, it is the plasma flow
399 over that region that is important, rather than something like the value of the cross-cap
400 potential.

401 As was illustrated in Figure 2, the flows often show a nearly direct relationship to solar
402 wind driving. The IMF transition that occurred in the interval around 1500 UT to 1530

403 UT was coincident with the observed slowing of the flow. There is even a small bipolar
404 signature where the LOS velocity changed sign for a few minutes that corresponded to a
405 similar signature in the IMF B_z and B_y components. After that brief interval, the IMF
406 returned to being steadily southward, and the flows returned to being fairly steady and
407 higher speed. A similar IMF change occurred at the end of the interval, about 2030 UT,
408 when the z-component turned positive and there was a coincident decrease in the observed
409 LOS velocity.

410 While such coincidences in the observations indicate direct control, looking at the total
411 time interval shows that there is more to the picture. Figure 4 shows that, while the
412 central cap flows were less variable than the dayside throat flows, they still varied by a
413 factor of two when the solar wind driving was essentially unchanged. The driving was
414 equally steady whether it is calculated from E_{MP} or from the solar wind electric field. The
415 variability can be explained at least in part by considering additional driving of convection
416 coming from the observed substorm and the associated magnetotail reconnection.

417 Short term variability of magnetospheric activity driven by dayside merging would be
418 expected if merging was not a continuous processes. The nature of dayside merging is a
419 long-standing debate in the space physics community with evidence supporting both quasi-
420 steady [*e.g. Newell and Meng, 1995*] and strongly-pulsed merging [*e.g. Lockwood, 1996*].
421 There was even one recent study in which two intervals of energetic ion observations from
422 the Polar space craft were examined, with one showing clear evidence of pulsed merging
423 while the other showed continuous merging [*Trattner et al., 2015*]. There have been a
424 number of ground-based studies presenting convection observations in the cusp region that
425 were attributed to transient merging events [*e.g. Greenwald et al., 1999; McWilliams et al.,*

2001]. In one case [*Greenwald et al.*, 1999] the transient was associated with a significant increase in the convection velocity just poleward of the cusp region with a time scale similar to the velocity fluctuations illustrated in Figure 4, while in another [*McWilliams et al.*, 2001] the convection velocity remained steady while the merging signature propagated through the region of observation. The short term fluctuations of velocity observed in this study could be interpreted as support for transient dayside merging, however no conclusions could be drawn without additional observations to indicate merging signatures in the regions of the fluctuations.

The direct dependence and variability are further illustrated by the scatter plots and histograms, which show that the average values of flow speed in both the throat and the central cap increase with increased driving, however the variability about the trends is large. In both regions, the change in the average value over the full range of driving examined was less than 2.5 times the standard deviation of the lowest bins. In the central cap the average value in the lowest bin was 207 m/s and the standard deviation was about 120 m/s, while in the highest bin the average value was 477 m/s. Hence, predicting a velocity based upon the IMF and solar wind observations would have large error bars. Predicting the velocity is of course exactly what one does when using an empirical convection model keyed to the IMF. The significant differences in convection response to solar wind driving has been noted by other authors [*e.g. Lockwood et al.*, 2009]

The appearance of the scatter plots in this paper is similar to equivalent plots of global parameters given in other papers. The plots show a significant density of points to about plus and minus half the low end average value. For example, plots of the polar cap potential have a low end average value around 40 kV with significant numbers of points

449 at least ± 20 kV about that value. Here, the low end average value in the central cap is
450 200 m/s, and the deviation is about 100 m/s. The spread of points may increase some
451 at the higher driving levels, however it doesn't change by much. The deviations given in
452 Figures 9 and 11 increase with increased driving, but the increase is small. In the central
453 cap the average deviation is 126 m/s, with the value in the lowest bin being 107 m/s and
454 the value in the highest bin being 145 m/s. This may be an indication that the processes
455 creating the variability are not directly related to the solar wind driver.

456 While having the histograms of convection velocity is useful for understanding the de-
457 pendence of the flows on the solar wind parameters, they also provide a way of estimating
458 the probability of observing ranges of velocity for specified conditions, which is arguably
459 the most appropriate way of using IMF and solar wind observations for predicting con-
460 vection. For example in the lowest range of E_{MP} (lower left of Figure 9), the probability
461 of observing a velocity greater than 500 m/s in the polar cap is low, just 1.4%, while in
462 the throat region it was significantly higher, about 25%. In the highest range examined,
463 the probability of observing a velocity greater than 500 m/s in the central cap is 43%, and
464 about 78% in the throat. In both regions, the probability increases monotonically with
465 increasing E_{MP} . It is also interesting to note that there is a finite probability of observing
466 a low velocity for all values of E_{MP} . The probability of observing a speed of less than 200
467 m/s is about 50% in the lowest bin, decreasing monotonically with increasing E_{MP} to a
468 value 2.5% in the highest bin.

469 Another feature of the observations is that the flow speed in both regions is greater
470 than zero for all levels of driving. It should be noted that the SuperDARN radars are
471 biased against measuring a zero convection velocity. The radars measure the Doppler shift

472 of signals scattered from field-aligned plasma density irregularities, which are formed
473 by instabilities in the ionosphere, usually assumed to be the gradient-drift instability.
474 Gradient-drift irregularities form when there is a finite flow velocity across an existing
475 density gradient. Hence, a non-zero flow velocity is required for the irregularities to
476 form. In addition, the standard SuperDARN data processing algorithms for estimating
477 the Doppler shift excludes scatter that can not be distinguished from ground scatter,
478 which comes from signals scattered from the ground after reflection from the ionosphere.
479 The criteria for designating a received signal as ground scatter are that the velocity is
480 below 30 m/s and the spectral width is below 90 m/s. It is rare for signals in the throat
481 and polar cap regions to be labeled as ground scatter since one or both of these criteria is
482 nearly always exceeded. Further, for the southern central polar cap, ground-scatter would
483 have to come from the 3000 m thick polar ice cap, which is not observed. Even with the
484 inability to make zero-velocity observations, it is likely that the observed roll off of the
485 histograms of observed velocity below 200 m/s is geophysical rather than an artifact of
486 the observations or processing. The velocity bins used in Figure 9 were 20 m/s in width,
487 so the lowest two bins could potentially be influenced by the ground-scatter criterion.
488 Even in the lower left hand frame, the lowest solar wind driving, the distributions show a
489 steep roll off beginning at a 100 m/s or above. There is not an abrupt decrease in counts
490 in the two lowest velocity bins, rather the counts appear to follow continuously from the
491 curve through higher velocity bins. The binning in Figure 11 is coarser, however the roll
492 off at low velocities is similar to that in the central cap. From this it can be concluded
493 that under nearly all circumstances there is a finite convection velocity.

494 The plasma velocity's apparent square root dependence on E_{MP} may provide further
495 support to reconnection driving convection rather than direct mapping of the solar wind
496 electric field. E_{MP} characterizes the rate at which magnetic flux enters the polar cap. If
497 the average area of the polar cap increases linearly with E_{MP} , then the average diameter
498 increases as the square root of E_{MP} , which would translate to the average convection
499 velocity having the same dependence.

4. Summary and Conclusions

500 One of the purposes of this study was to examine solar wind and IMF control of convec-
501 tion velocity in the central polar cap and in the dayside throat region. The observations
502 showed good correspondence between flows and the solar wind, illustrating both direct cor-
503 relation between specific IMF signatures and signatures in the flows, and in the increased
504 average flow velocity with increased solar wind driving. There was, however, significant
505 variability in the flow that was not observed in the driver. Some of that variability could
506 be attributed to substorm activity, though probably not all. The short-term variations of
507 as much as 500 m/s observed in the dayside flows occurred over much shorter time scale
508 than the substorm time scale, and they occurred throughout the interval, not just in a
509 certain substorm phase.

510 The characteristics of the flow in the two regions were similar in distribution but with
511 higher average value and higher deviation in the throat than in the cap. The average
512 values and the deviations were both about a factor of two larger in the throat. Flows in
513 both regions showed a similar dependence on E_{MP} and in the average were fit well by
514 the velocity being proportional to the $\sqrt{E_{MP}}$. The shapes of the distributions were also

515 similar and were well represented by skew-normal distributions, with the amount of skew
516 decreasing for higher driving levels.

517 The stated expectation given in the introduction was that the influence of dayside
518 merging at the magnetopause would be strongest in the dayside flows and would decrease
519 with distance. It is certainly true that the flow speed was higher in the throat than
520 in the central cap, but that is likely the result of a geometrical effect since the flow is
521 concentrated in a narrower region. If anything, the dayside flows showed more variability
522 than the central cap flows with large amplitude fluctuations, occurring on time scales of
523 tens of minutes, that were not observed in either the driver or in the central cap flow.

524 The primary conclusion that can be drawn from this set of observations is that the
525 flow velocity in specific regions appears to be predictable with about the same level of
526 precision as global-scale measures of magnetospheric activity. With this level of precision,
527 the best use of solar wind observations in a predictive sense is to forecast probabilities for
528 parameter values rather than predicting the specific values. While such forecasts may not
529 be of use in the current generation of ionospheric specification models, a new generation
530 of empirical convection models could be produced that would generate a time variable
531 convection pattern with the same statistics as the observations.

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538 vations used in this study are available from the SuperDARN database. The IMF and
539 solar wind observations were obtained from the NASA Space Physics Data Facility web
540 page.

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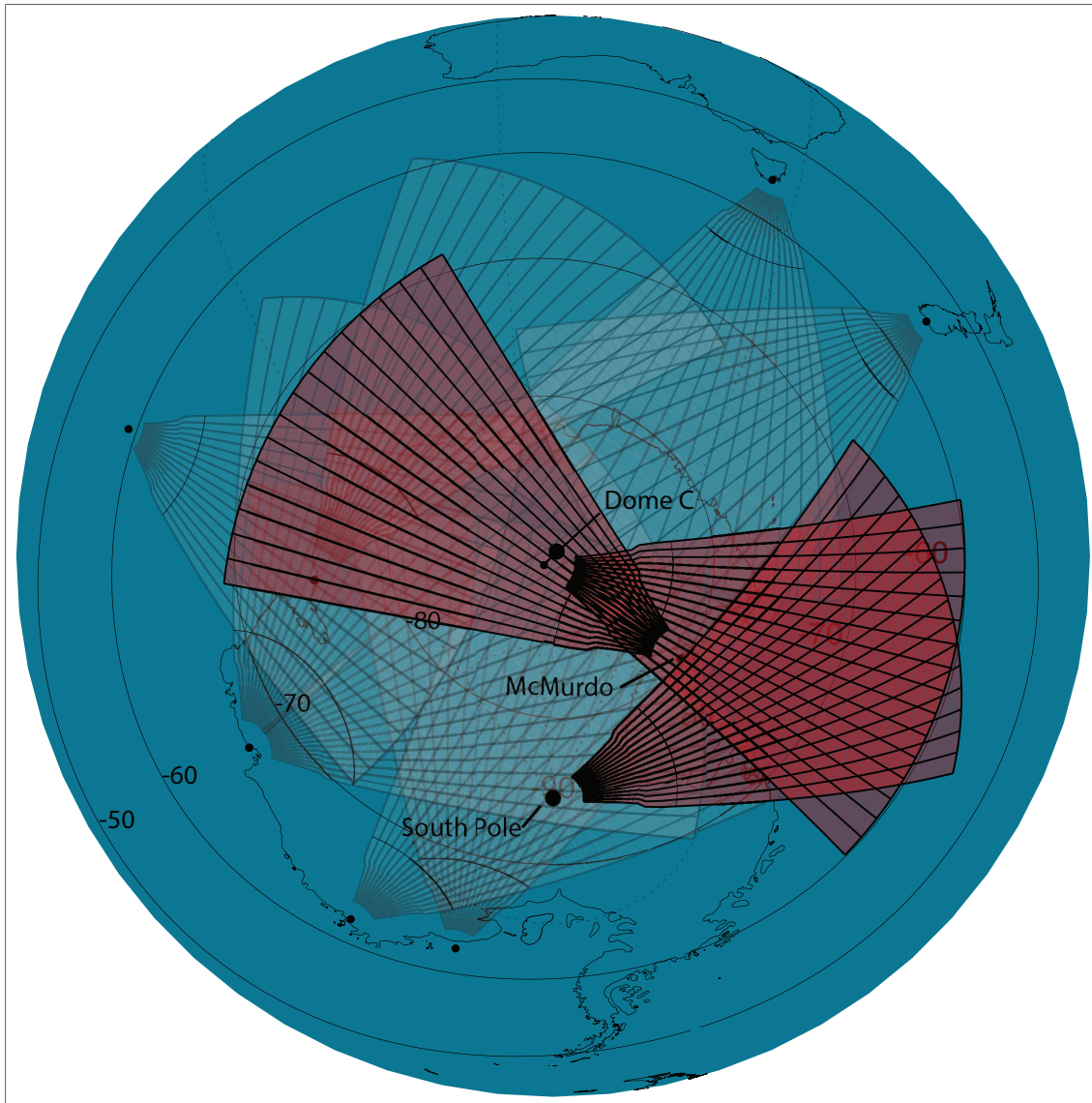


Figure 1. Fields-of-view of the McMurdo, South Pole, and Dome-C radars over contours of magnetic latitude. The radars are located at the vertices of the wedges. The radars sample the returns from the red shaded areas, which extend to 3500 km range from the radar sites. The rest of the southern hemisphere SuperDARN radar fields of view are shaded light gray.

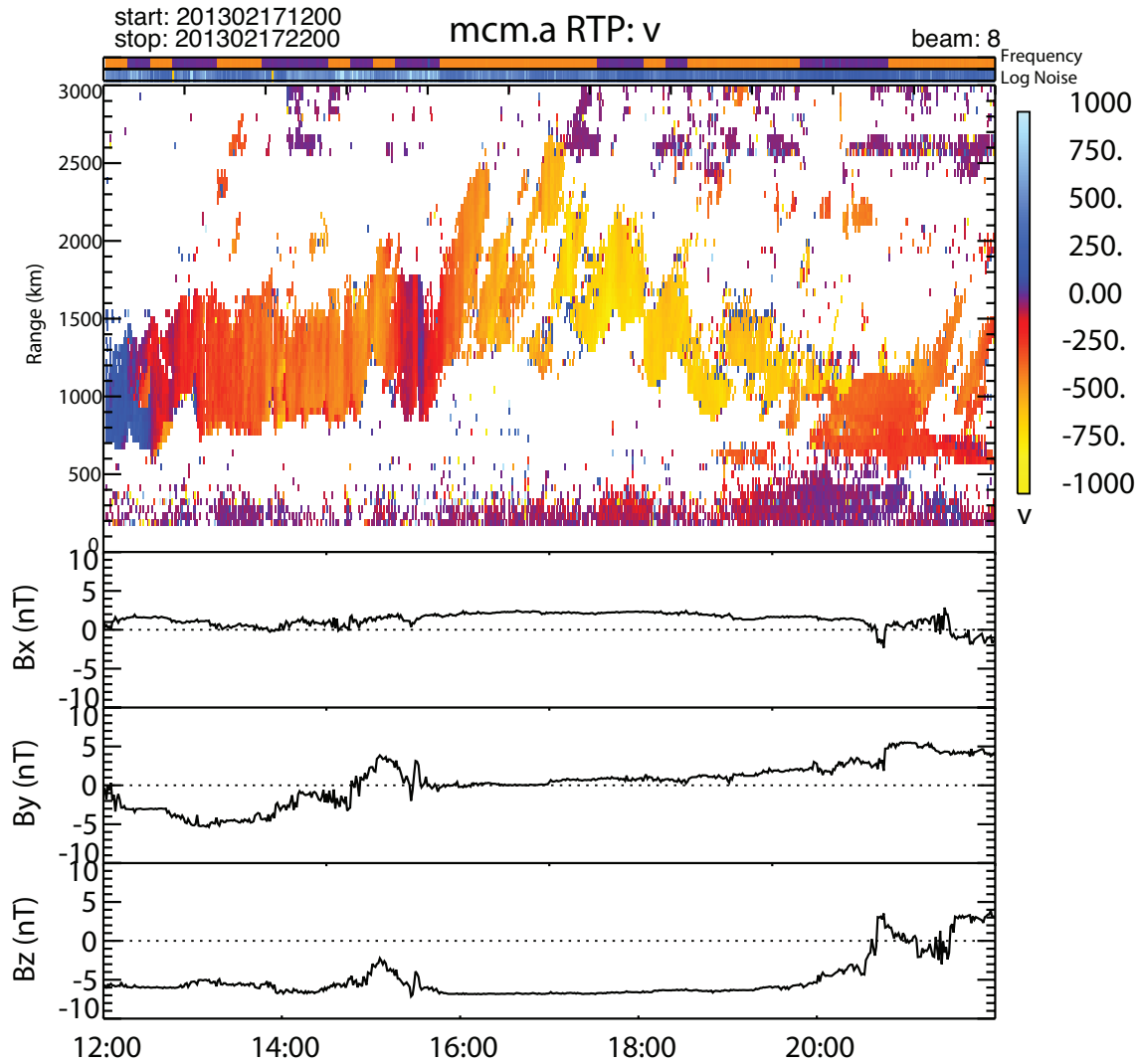


Figure 2. Range-time-velocity plot for returns observed by the McMurdo radar along its central beam, and IMF observations from the ACE space form February 17, 2013 between 1200 UT and 2200 UT. Figure shows the three components B_x , B_y , and B_z in GSM coordinates. The IMF values have been time delayed to the assumed position of the magnetopause

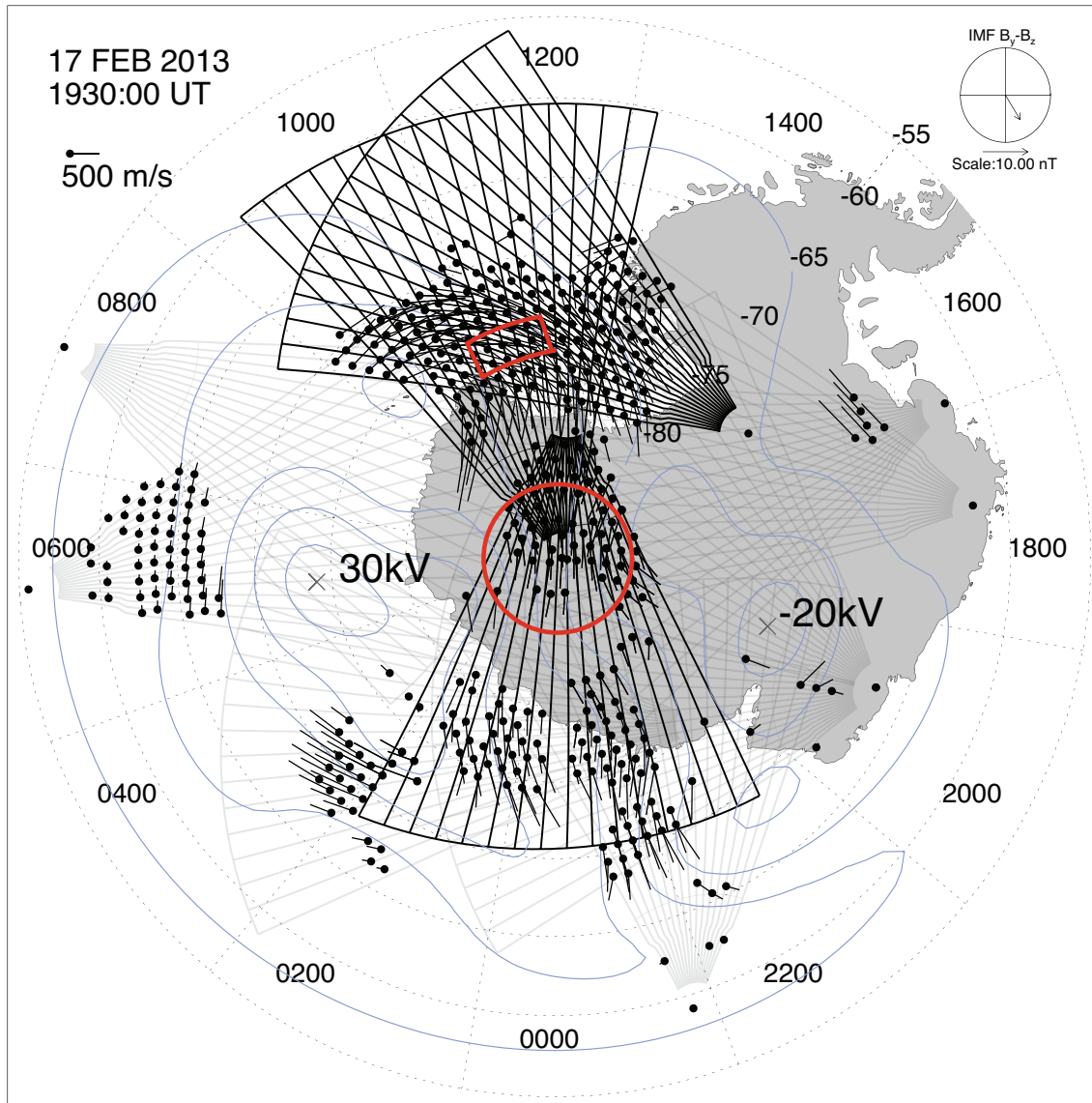


Figure 3. Convection map for 1930 UT on February 17, 2013. Fields of view of the McMurdo, South Pole, and Dome C radars are superposed. The red circle at 85° indicates the area defined as the central polar cap. The red box indicates the area defined as the dayside throat.

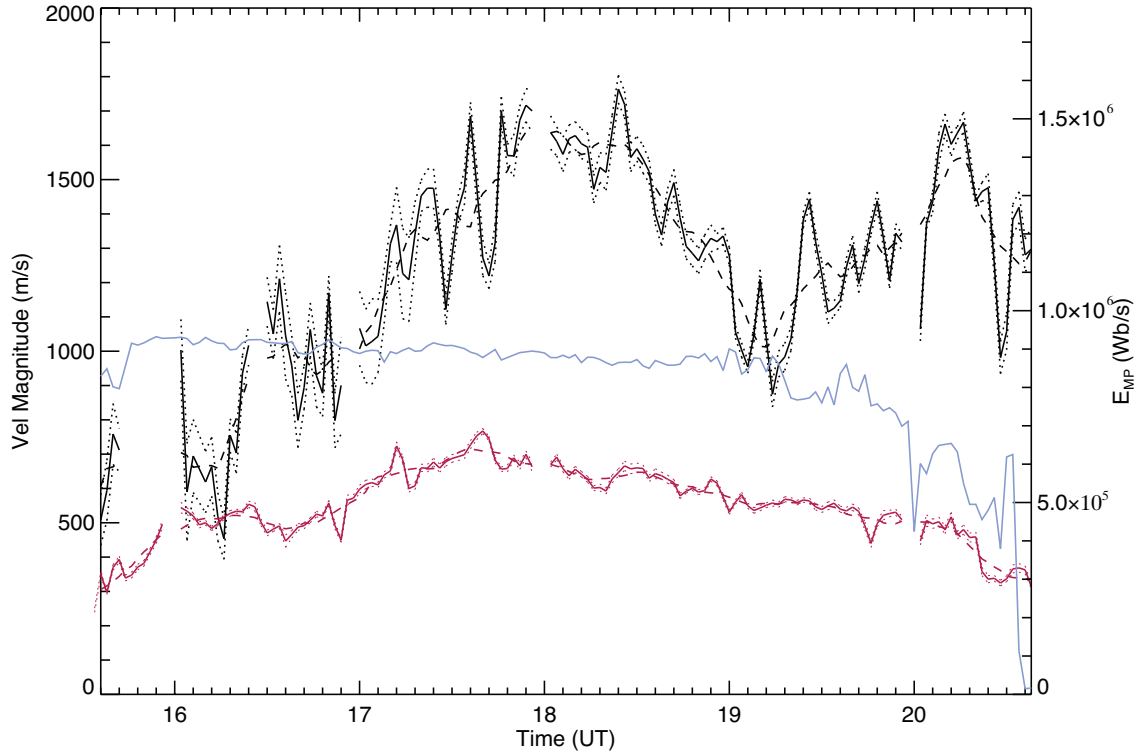


Figure 4. Time series of the solar wind driving function, E_{MP} (blue), the spatially averaged convection in the dayside throat (black) and in the central polar cap (red). The dashed lines are a 16-minute smoothed version of the solid lines.

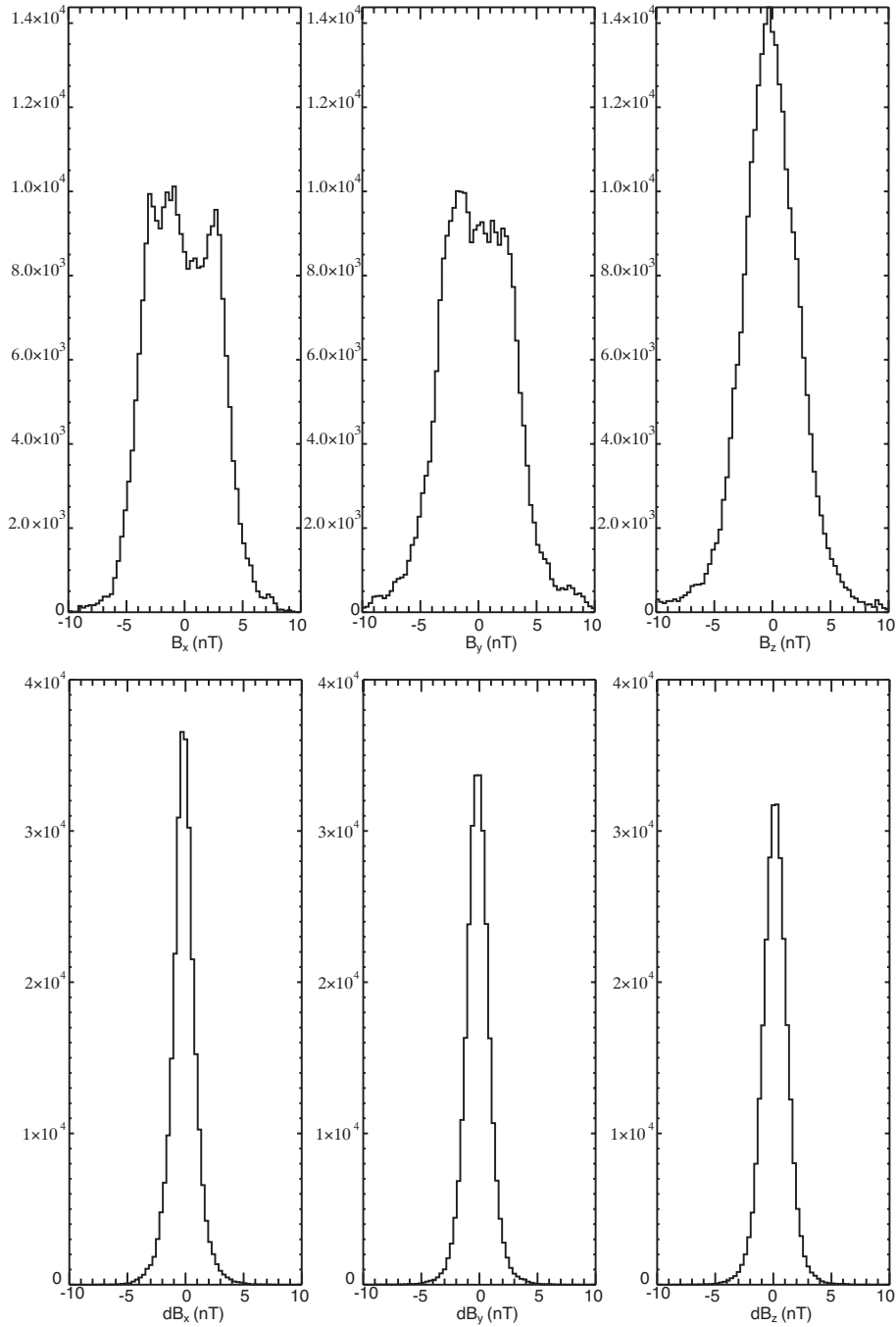


Figure 5. Distributions of the three IMF components, B_x , B_y , and B_z , and their absolute deviations.

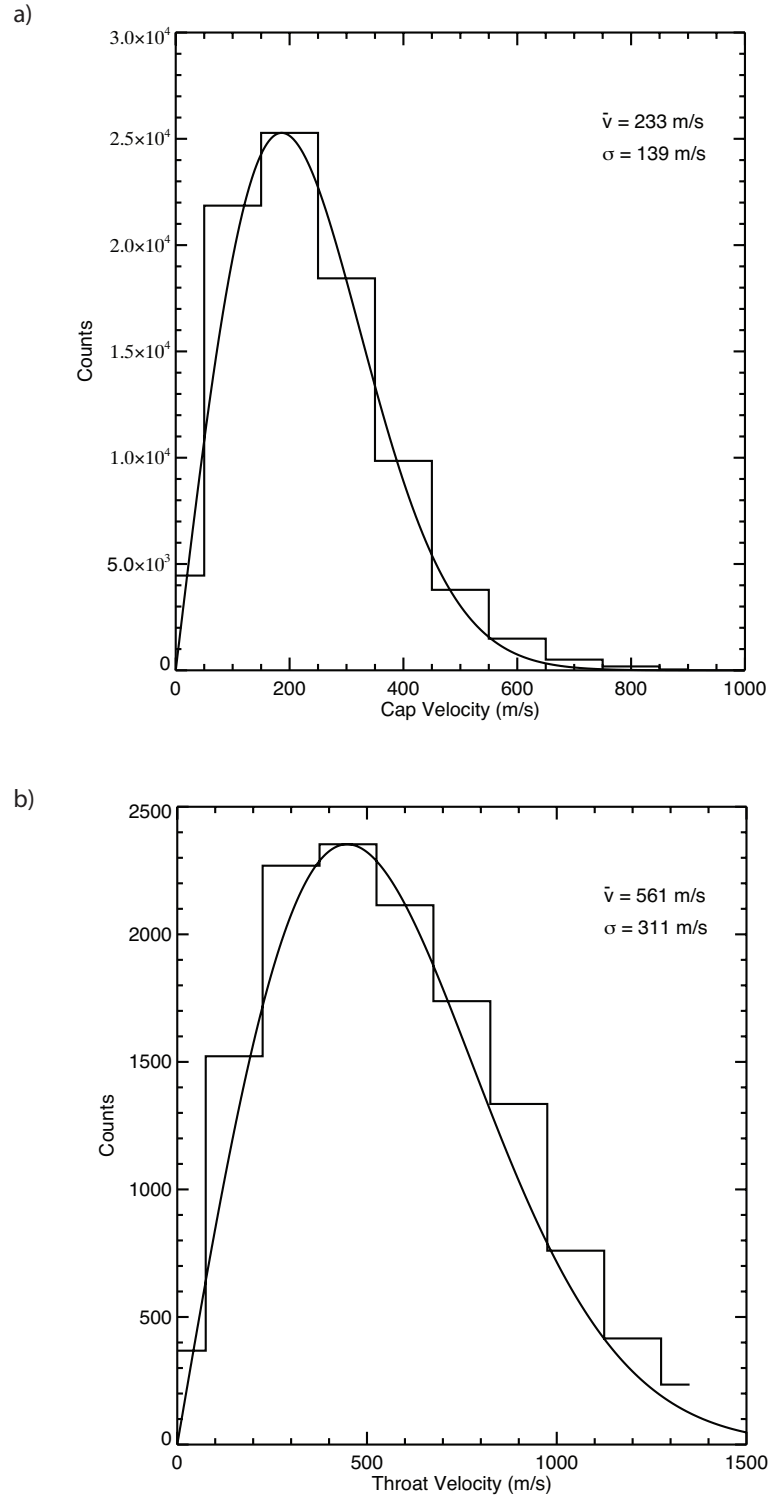


Figure 6. Histograms of observed velocity magnitudes for the total database for (a)the central polar cap, and (b)the region identified as the cusp.

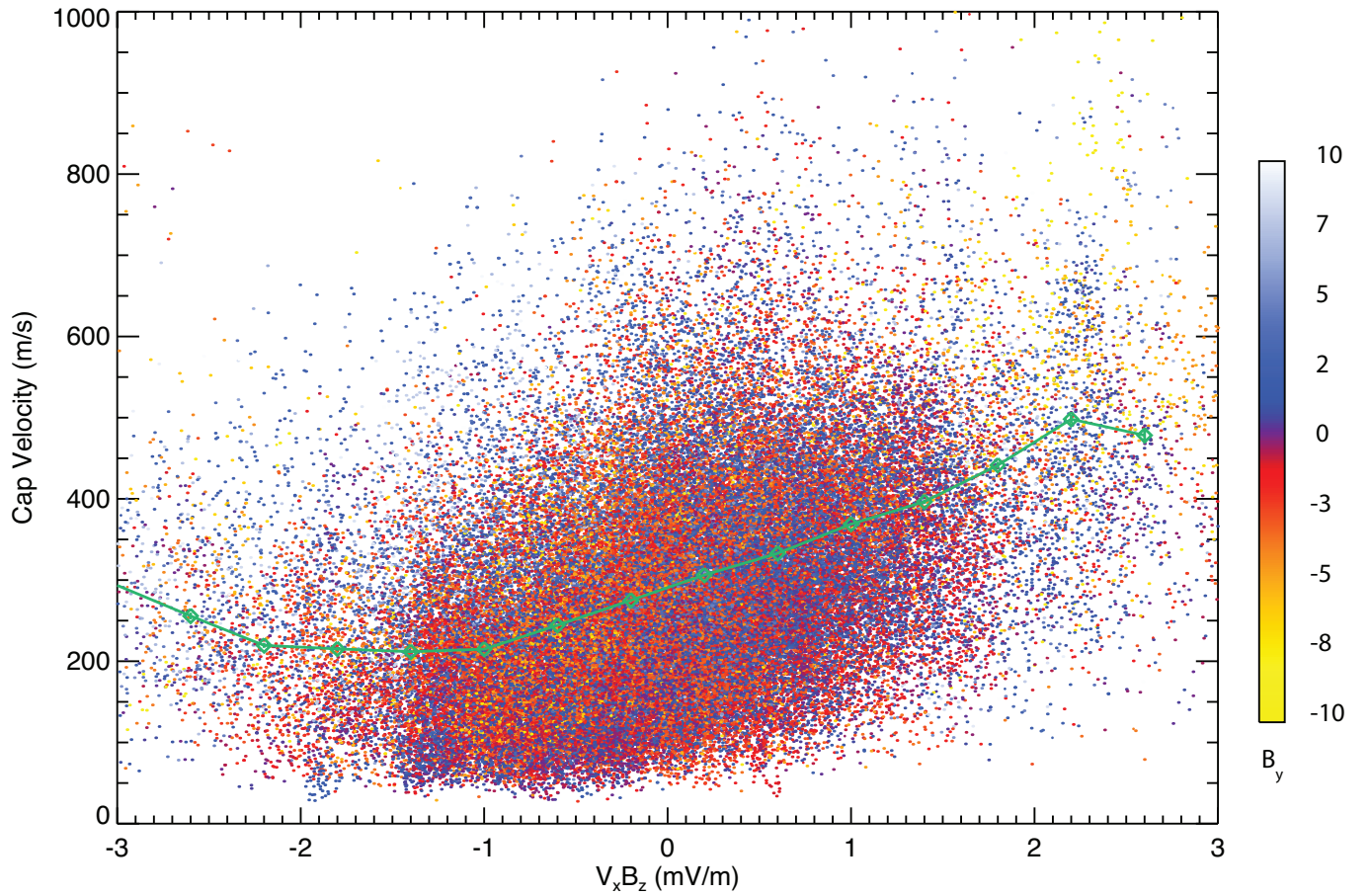


Figure 7. Scatter plot showing the observed velocity in the polar cap versus the product of the radial component of the solar wind velocity with the z-component of the IMF. Each point is an average of all measurements within the 85° latitude circle.

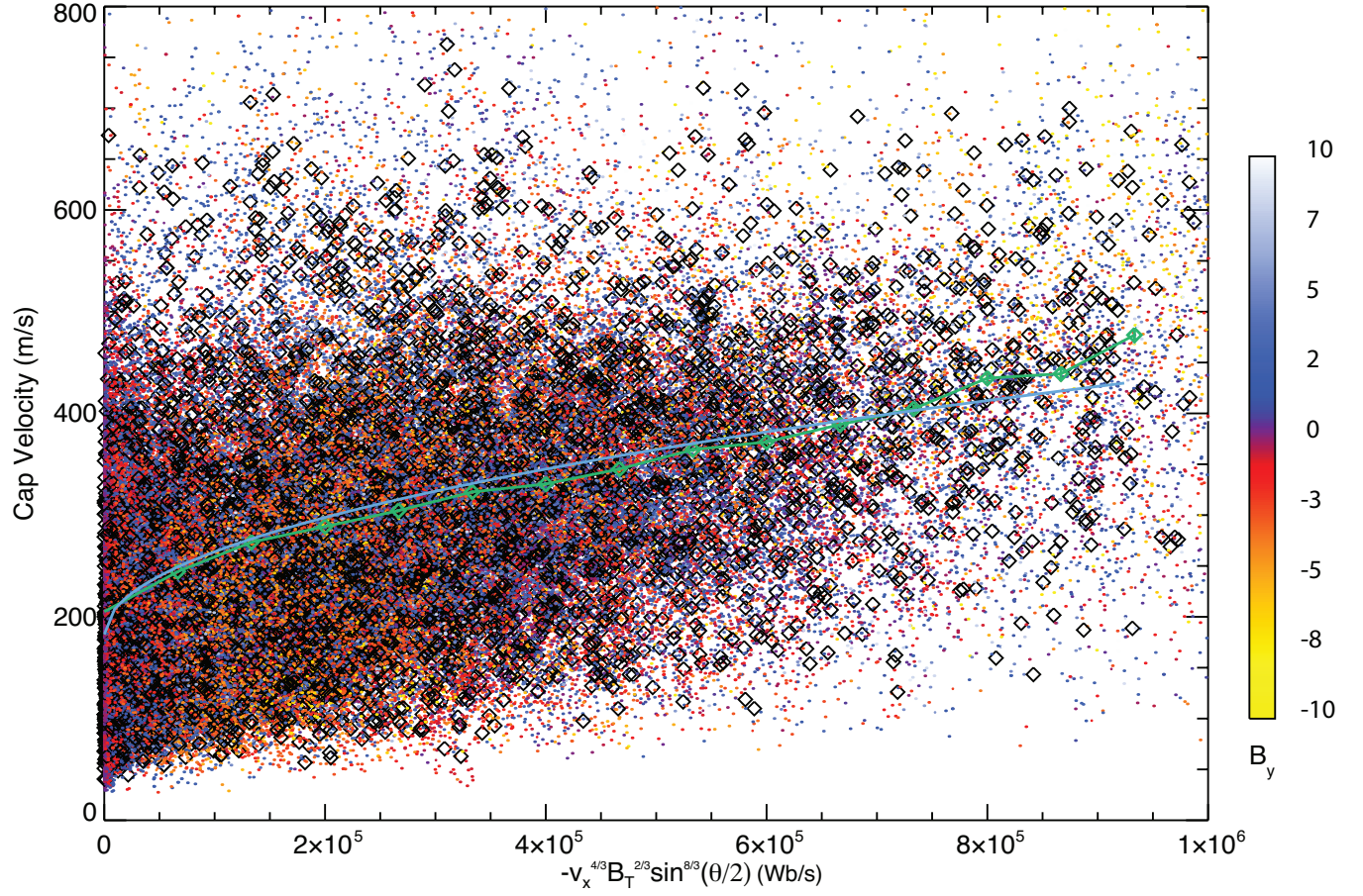


Figure 8. Scatter plot showing the observed velocity in the polar cap versus the E_{MP} parameter. Each point is an average of all measurements within the 85° latitude circle. The black diamonds represent time averages over 15 minutes. The green diamonds and connecting line show the average value in ten bins of E_{MP} . The blue line shows a fit of the averages vs $\sqrt{E_{MP}}$

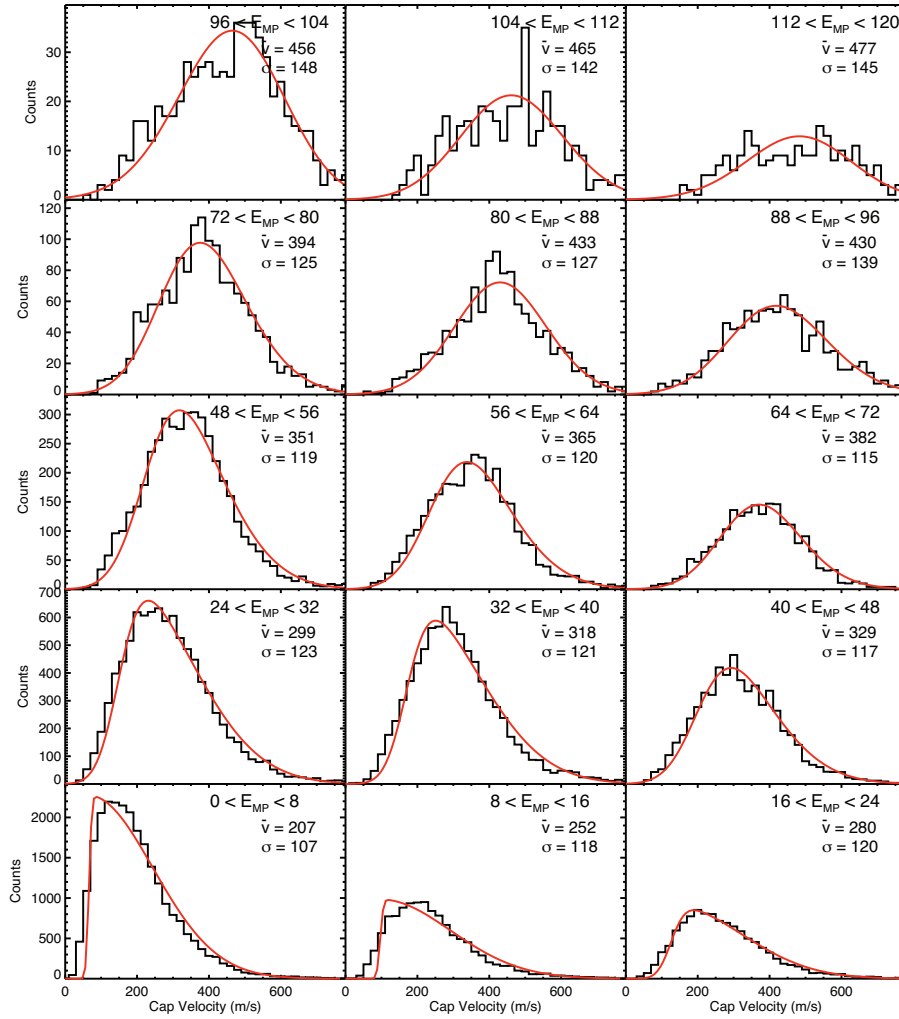


Figure 9. Histograms of observed polar-cap plasma velocity for various levels of the $E_{MP}/10^4$ parameter. The superposed red curves show skew-normal distributions scaled to the peak value of the histograms. The average velocity and standard deviation are given for each E_{MP} level.

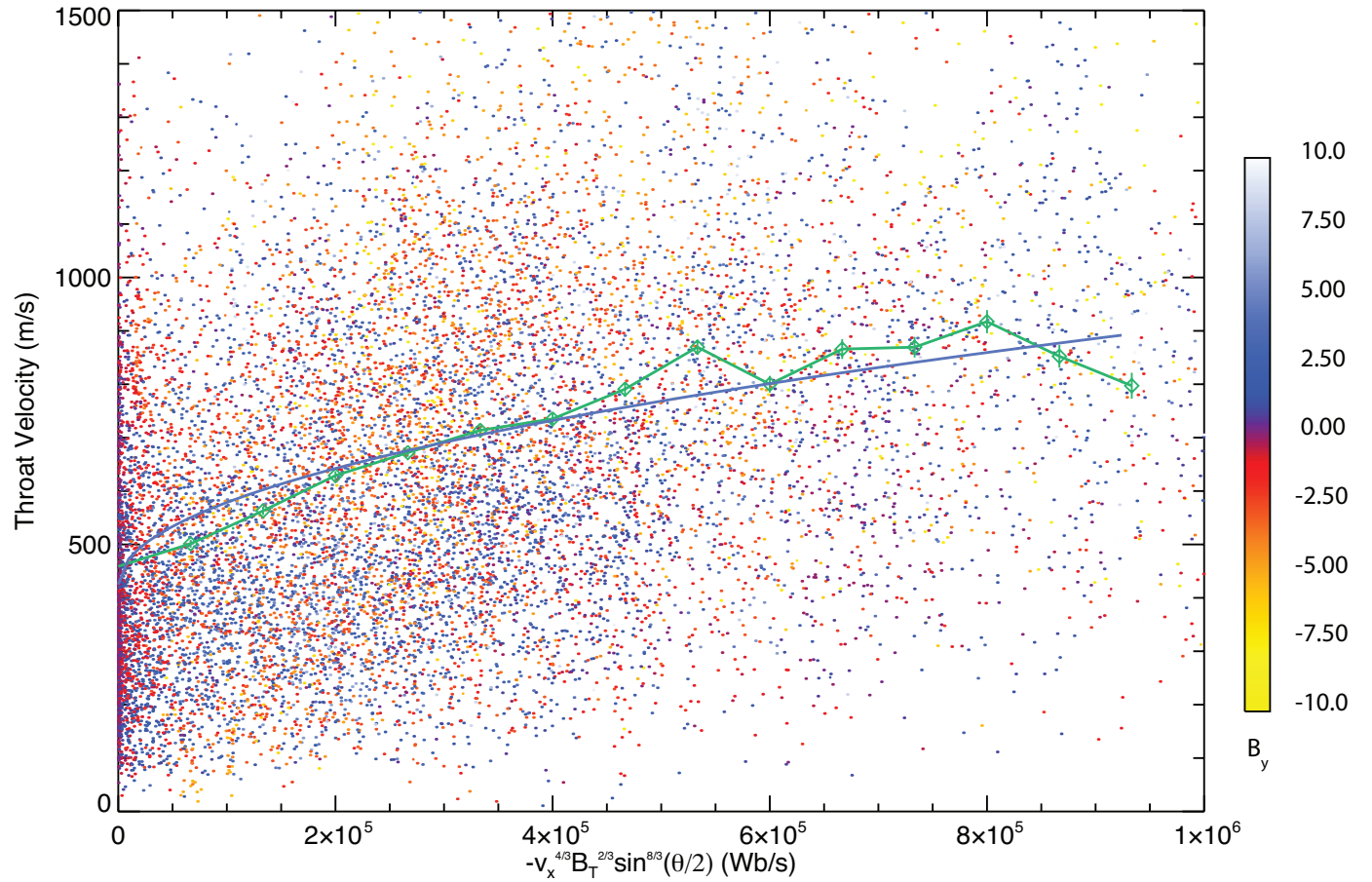


Figure 10. Scatter plot showing the observed velocity in the cusp versus E_{MP} . Each point is an average of all measurements within the 85° latitude circle. The green diamonds and connecting line show the average value in ten bins of E_{MP} . The blue line shows a fit of the averages vs $\sqrt{E_{MP}}$

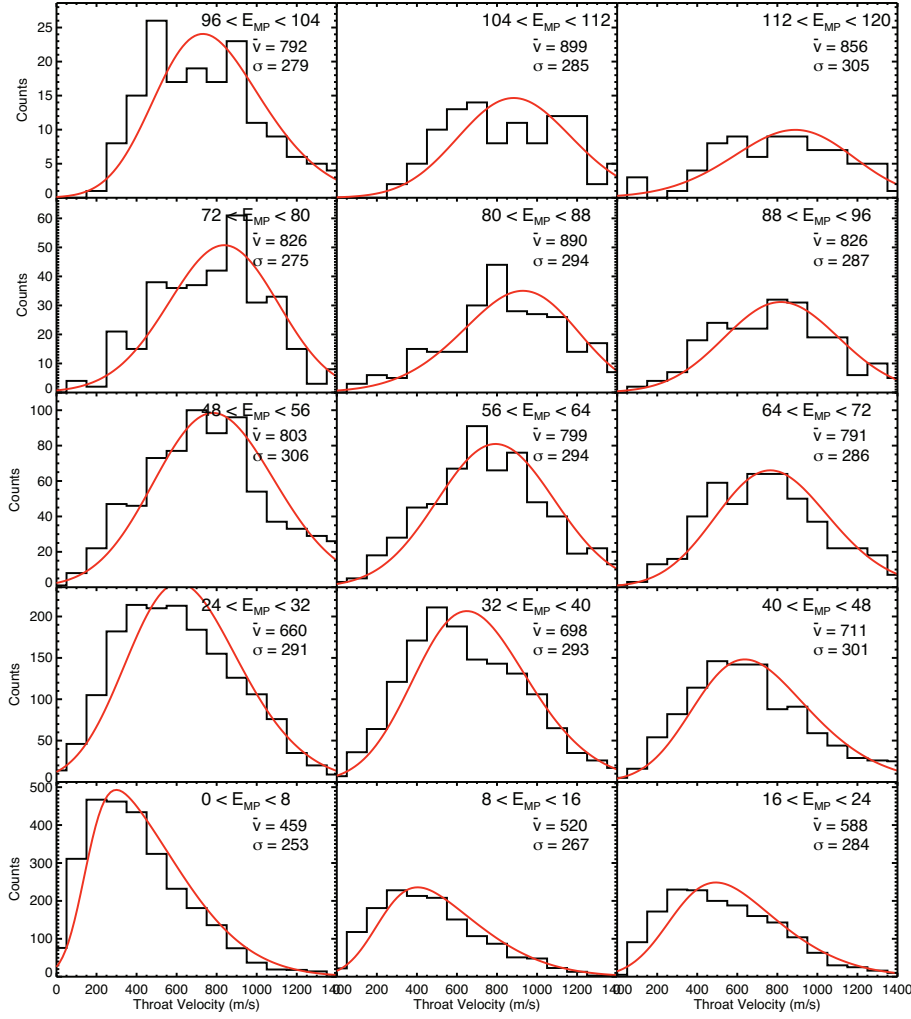


Figure 11. Histograms of observed cusp plasma velocity for various levels of $E_{MP}/10^4$. The superposed red curves show skew-normal distributions scaled to the peak value of the histograms. The average velocity and standard deviation are given for each E_{MP} level.

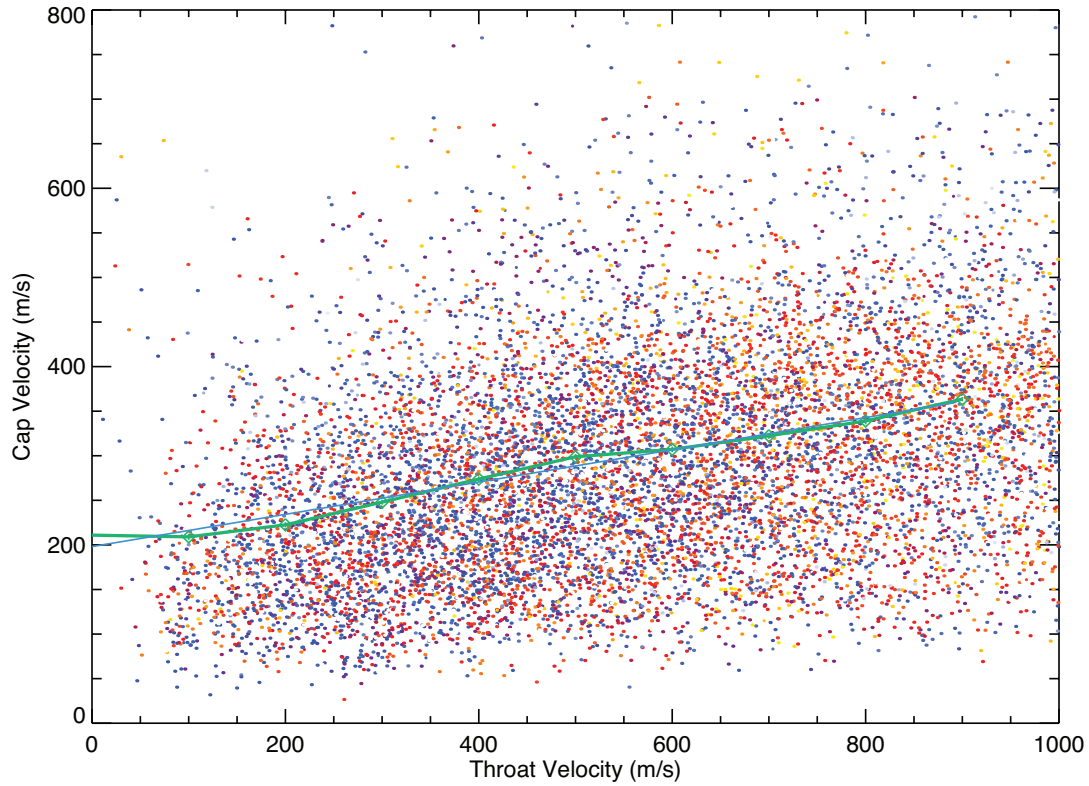


Figure 12. Scatter plot showing the observed velocity in the central cap versus that observed in the dayside throat region. The green diamonds and connecting line show the average value in ten bins of E_{MP} . The blue line shows a linear fit of the averages.