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Fast Auroral Snapshot observations of the dependence of dayside auroral field-aligned currents on solar wind parameters and solar illumination

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[1] The solar illumination dependence of solar wind-magnetosphere coupling has been studied by examining the dependence of auroral zone field-aligned currents on solar wind parameters. A database of Region I currents from ~900 crossings of the auroral zone by Fast Auroral Snapshot (FAST) was parameterized by magnetic local time, invariant latitude, and whether the foot point was illuminated. The magnitudes of dayside currents (~200 events) were correlated with solar wind parameters using the technique of rank correlation. Very significant, strong correlation between dayside sunlit currents and solar wind parameters such as $B_t\sin(\theta/2)v^2$ and $B_t\sin(\theta/2)P_d^{1/2}$ was observed, consistent with a reconnection source. There was no correlation with upstream parameters for dayside Region I currents when the ionospheric foot point was in darkness. This is the first experimental evidence showing that the correlation of dayside Region I currents to upstream parameters depends on ionospheric illumination. Both the strong dependence of the correlation on solar illumination (ionospheric conductivity) and the weakness of observed correlations, compared to those obtained in previous studies of the cross polar cap potential, may be interpreted to imply that the reconnection process is a voltage, rather than a current, source. However, several theoretical studies have suggested that reconnection does not act as either a pure voltage source or a current source. In addition, because the mapping of the field-aligned currents was not examined, the observed difference between the sunlit and dark events could be explained by current preferentially flowing in the hemisphere with the higher conductivity if the source were on closed field lines. *INDEX TERMS:* 2409 Ionosphere: Current systems (2708); 2704 Magnetospheric Physics: Auroral phenomena (2407); 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; *KEYWORDS:* field-aligned currents, Birkeland currents, solar illumination, IMF

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1. Introduction

[2] The efficiency of coupling between the solar wind and the magnetosphere has long been a topic of interest in magnetospheric physics. Numerous studies have detailed the response of magnetospheric parameters such as the cross-polar cap potential, indices of ground magnetic activity such as Ae and Dst, and polar cap size to changes in various solar wind parameters. Many such studies have been reviewed by *Baker* [1986]. Correlation studies of the cross-polar cap potential with solar wind and interplanetary magnetic field parameters [*Reiff et al.*, 1981; *Wygant et al.*, 1983; *Eriksson et al.*, 2000] have indicated that best correlation occurs for models of the reconnection field including both the interplanetary magnetic field (IMF) B_y and B_z components.

[3] Although the cross polar cap potential provides the most direct proxy of the coupling, it is also of interest to examine the dependence of field-aligned currents on various upstream solar wind parameters. *Iijima and Potemra* [1982] compared the magnitude of dayside Region I currents in the northern hemisphere summer to a number of parameters. They found good correlation with IMF B_z for $B_z < 0$ and with similar parameters, consistent with reconnection as the current source. Their data set was separated by the sign of IMF B_y because previous studies showed changes in the region of maximum current with this parameter [*Potemra et al.*, 1979] and restricted to summer because *Fujii et al.* [1981] showed changes in the size of current with season.

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Note that a more detailed study showed that the field-aligned current magnitude depends on conductivity at all local times [*Fujii and Iijima*, 1987]. Many studies have concentrated on the shifts in the dayside currents in response to changes in IMF B_y [*Erlandson et al.*, 1988; *Zhou et al.*, 2000]. Other studies have addressed the influence of the IMF and the solar wind density and velocity by identifying a class of currents [e.g., *Ohtani et al.*, 2000] or by studying a specific extreme event [e.g., *Le et al.*, 1998; *Cattell et al.*, 1998].

[4] In this study, we examine the solar illumination dependence of solar wind coupling to dayside currents by correlating various solar wind parameters with the size of the Region I field-aligned currents using an existing database of currents from the Fast Auroral Snapshot (FAST) satellite [*Peria et al.*, 2000]. The study was designed to address the effects of solar illumination on the coupling. A limitation of this study is that the mapping of each current sheet to the outer magnetosphere was not examined. The mapping was not examined due to the large errors inherent in mapping from the ionosphere to the outer magnetosphere. The data sets and methodology are described in section 2. The results of the statistical correlations are presented in section 3. Conclusions and a discussion of their possible significance and relation to theoretical studies are presented in section 4.

2. Data Sets and Methodology

[5] The FAST satellite [*Carlson et al.*, 2001] is in a polar orbit with apogee of ~4300 km and perigee of ~400 km, and obtains data in all local time sectors due to the precession of its orbital plane. *Peria et al.* [2000] developed an automatic algorithm to identify field-aligned currents from the three-axis fluxgate magnetometer data. The algorithm, utilized on approximately every tenth orbit from October 1996 through January 1998, examined the magnetic field perturbations for consistency with a steady field-aligned current sheet. Details are given by *Peria et al.* [2000]. The resulting database covers all local times, and altitudes from ~300 to ~4300 km. Because the focus of the study described herein is solar wind-magnetosphere coupling, it was necessary to identify the 'Region I' current from the many current sheets identified within each auroral pass in the Peria et al. database. This was done by a new program, which utilized the Peria et al. database, examining the currents found in each hemisphere, finding the polar cap crossing time, and then combining the small-scale size currents sheets in the database into larger scale size regions with the same current flow direction. An example of this process is shown is Figure 1 for four different auroral zone crossings, one sunlit event and one in darkness for both morning and afternoon. The start and stop times of each individual current in the Peria et al. database are indicated by the vertical red and green lines and the magnitude by the blue dot. The start and stop times of the combined sheets are shown as black brackets and the magnitude as an 'x.' The 'Region I' current selected by the algorithm is circled in red. The magnitudes of the currents were "normalized" to account for geometric effects of flux tube mapping due to altitude and latitude. The magnitudes of normalized currents do not depend on the altitude of FAST.

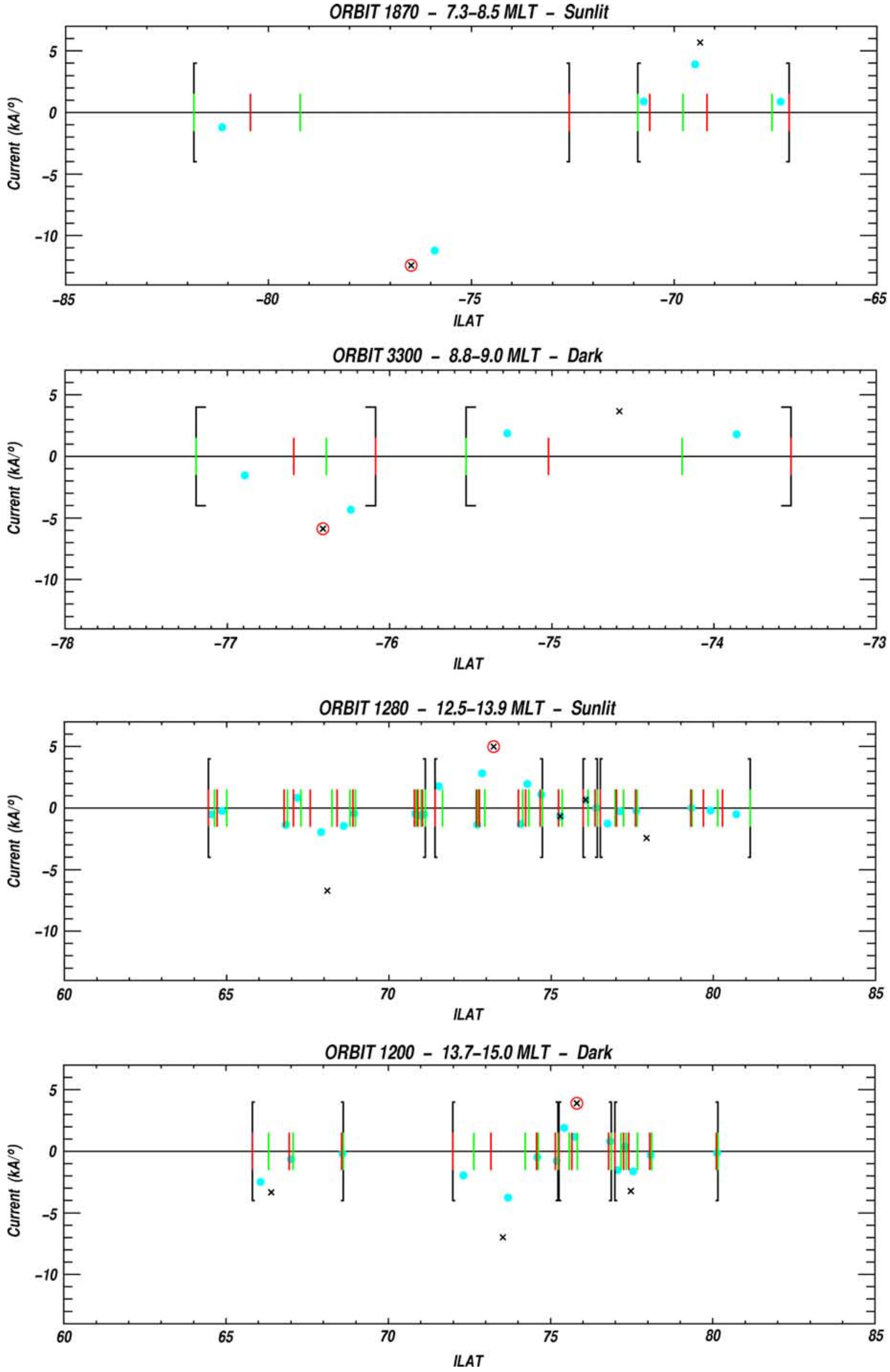
[6] Figure 2 presents the distribution of the complete database of Region I field-aligned currents obtained by the method described above. The direction of the currents versus magnetic local time is plotted in Figure 2a as red (upward) or green (downward) points. The large scatter in the locations of the observed currents is not unexpected because a wide range of activity levels are included. It can be seen that, on average, the currents on the morning (evening) side are downward (upward). There are, however, a number of current sheets in the 'wrong' direction, some of which are due to misidentification of the Region I current by the automatic algorithm, and some of which are due to cases where there was not a clear Region I–Region II system. Note that only currents in the proper Region I sense are included in the correlation study.

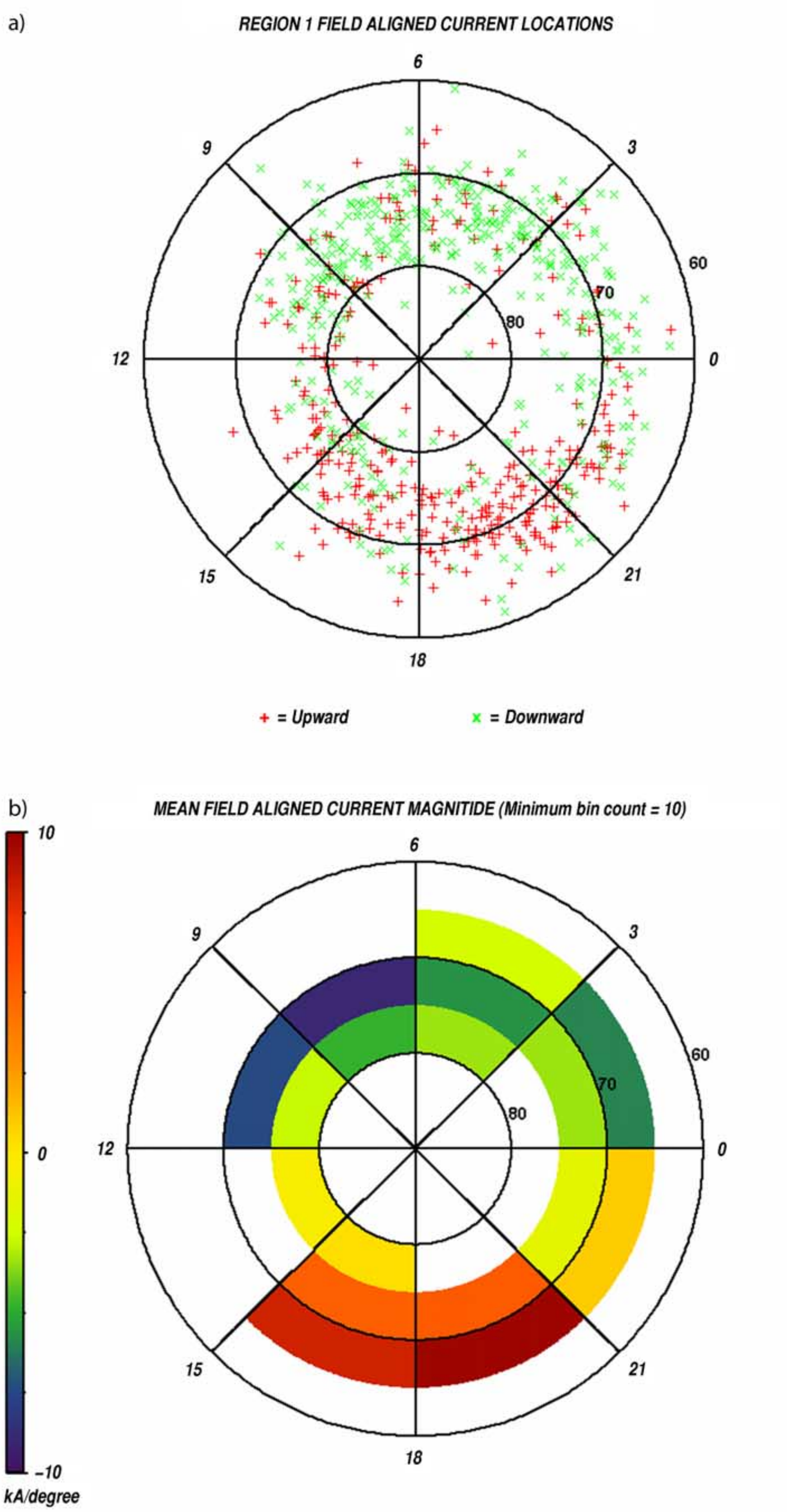
[7] The standard Region I sense can be seen when the individual currents are averaged over invariant latitude-local time bins, as plotted in Figure 2b for bins with more than 10 currents. The typical Region I current directions are seen except in the most poleward bin for the 21–24 MLT sector which is the local time sector where substorm-related currents often complicate the simple Region I/Region II pattern. In addition, the peak currents are upward and occur from 18–21, with the 15–18 bin being almost as strong. It can be seen that there is a wide latitude range over which the RI current sheet can occur. The largest currents tend to occur at the lower latitudes, consistent with large currents being associated with an expanded polar cap and active periods.

[8] The database of currents was divided into two local time sectors, morning (8–11 MLT) and afternoon (13–16 MLT), with the currents from 11–13 MLT excluded to avoid contamination from cusp currents and the local time shift of RI currents due to IMF By. In addition, to facilitate comparison with *Iijima and Potemra* [1982], morning (8–13 MLT) and afternoon (11–16 MLT) sectors, both separated by the sign of IMF B_y and by hemisphere were examined. The requirement was that IMF B_y be positive for the northern (southern) hemisphere morning (afternoon) events and negative for the northern (southern) hemisphere afternoon (morning) events. Note that this requirement reduced the number of events in each sector.

[9] The solar wind data utilized in this study were obtained by the Wind satellite. The magnetic field [*Lepping et al.*, 1995] and plasma [*Lin et al.*, 1995] key parameter data at 1 minute resolution were accessed through the IGPP/UCLA web site. Because studies [*Russell et al.*, 1980; *King*, 1986] comparing ISEE 1 and 3 have shown the limitations of an upstream monitor which is far from the Earth-Sun line, some comparisons were done only for the cases where Wind was at $(Y_{gse}^2 + Z_{gse}^2)^{1/2} < 50\ R_e$ and $X_{gse} < 90\ R_e$. There were no biases in the data set with respect to MLT, ILAT, altitude, illumination of foot point, or location of WIND. The maximum, minimum, mean and standard deviation of the

Figure 1. (opposite) An example of the output of the algorithm used to combine the small-scale currents of the *Peria et al.* [2000] database to find the Region I current. The top two panels are for morning events, and the bottom two are for afternoon events.


ORBIT 1870 – 7.3–8.5 MLT – Sunlit
Current (kA/°)
5
0
−5
−10
−85
−80
−75
−70
−65
ILAT
ORBIT 3300 – 8.8–9.0 MLT – Dark
Current (kA/°)
5
0
−5
−10
−78
−77
−76
−75
−74
−73
ILAT
ORBIT 1280 – 12.5–13.9 MLT – Sunlit
Current (kA/°)
5
0
−5
−10
60
65
70
75
80
85
ILAT
ORBIT 1200 – 13.7–15.0 MLT – Dark
Current (kA/°)
5
0
−5
−10
60
65
70
75
80
85
ILAT


a)
REGION 1 FIELD ALIGNED CURRENT LOCATIONS
6
9
3
60
70
80
12
0
15
21
18
+ = Upward
x = Downward
b)
MEAN FIELD ALIGNED CURRENT MAGNITIDE (Minimum bin count = 10)
10
0
−10
kA/degree
6
9
3
60
70
80
12
0
15
21
18

magnitude of the current and the corresponding solar wind parameters (B_z and $P_d\ B_t\ \sin(\theta/2)$) were also compared for each data set. No significant biases were found between event sets utilized in this study, with the exception (discussed in more detail below) that the mean current was larger for sunlit events compared to dark events.

[10] The magnetospheric responses, specifically the auroral Region I field-aligned currents, were compared to a large set of solar wind coupling parameters, most of which have been used in previous studies (see *Baker* [1986] and *Wygant et al.* [1983] for references). All the upstream quantities to compare to the currents can be expressed by the following formula: $(V^n\ B^m\ W)^p$, where V is either the solar wind velocity, v, or the dynamic pressure (P_d); n = 0, 1, or 2; B is B_z, B_s ($B_s = -B_z$ if $B_z \leq 0$, and = 0 if $B_z > 0$), $B_t\sin(\theta/2)$, or $B_t\sin^2(\theta/2)$, where $B_t = (B_y^2 + B_z^2)^{0.5}$ and θ = clock angle, from 0° to 180°; m = 1 or 2; W = 1 or $\sin(\theta/2)$; and p = 1 or 0.5. In particular, this encompasses some of the common parameters, for example, B_z, vB_s, $vB_t\sin(\theta/2)$, $vB_t\ \sin^2(\theta/2)$, $vB_t\ \sin^3(\theta/2)$; $vB_t^2\sin^4(\theta/2)$ or ε, as well as two new parameters, P_dB_s and $P_d\ B_t\ \sin(\theta/2)$ suggested by *Song and Lysak* [1994, 1997]. The method described by *Eriksson et al.* [2000] was utilized to determine the solar wind interval over which to average for each event. Because *Eriksson et al.* [2000] showed that the main response observed in the polar cap potential occurred at time delay of 15 minutes min from the magnetopause, our initial comparisons utilized that lag time.

[11] Most studies correlating magnetospheric response to solar wind parameters have utilized parametric tests, in particular the linear correlation coefficient. The use of this method in coupling studies and some of its limitations have been discussed by *Baker* [1986]. Three major problems are (1) the method assumes that the data are sampled from a normal distribution, which is not the case for our data; (2) outliers can significantly affect the correlation; and (3) the significance of a correlation and the relative significance of a set of correlations can't be assessed [*Press et al.*, 1986]. Use of a non-parametric or rank correlation method bypasses these problems. Because the focus of this study is to determine whether there is a significant correlation between solar wind parameters and Region I currents and which parameter provides the most significant correlation, the Spearman rank-order correlation [*Press et al.*, 1986] will be used. This technique ranks both the quantity to be correlated and the parameter in numerical order and performs a linear correlation on these ordinal numbers. The significance of differences in the observed rank correlations can then be assessed using complementary error function analysis which also requires that data are normally distributed [*Press et al.*, 1986].

3. Statistical Results

[12] Figure 3 presents the results for the dayside current sectors, excluding 11–13 MLT, to avoid the cusp region and IMF B_y effects. The significance of the rank correlation is plotted in panel a, the rank correlation coefficient in panel b, and the usual linear correlation coefficient in panel c. The color bars indicate the size of each correlation. The two left-hand columns refer to morning events when the ionosphere is sunlit and in darkness, and the two right-hand columns refer to afternoon events. Note that the lowest values (white and red) of the rank significance correspond to the most significant correlations. The top set of plots all refer to parameters with B_s, and the bottom sets of plots to parameters with $B_t\sin(\theta/2)$. For both the morning (54 events) and afternoon (30 events) sunlit currents, the correlation is very significant for all parameters of $B_t\ \sin(\theta/2)$. The largest rank correlation is for $B_t\sin(\theta/2)v^2$, with $B_t\sin(\theta/2){P_d}^{1/2}$ and its square root also having strong correlations. The correlation with parameters containing B_s is much weaker. There are no significant correlations for the currents for which the foot of the field line is in darkness. In addition, no significant correlations were observed for the case of current sheets that were not in the usual Region I direction.

[13] We also examined the correlations for the local time sectors chosen to replicate the study of *Iijima and Potemra* [1982], i.e., for the morningside (8–13 MLT) currents with By > (<) 0 in the northern (southern) hemisphere, and for the afternoon (11–16 MLT) currents with IMF By < (>) 0 in the northern (southern) hemisphere. Because currents were excluded on the basis of the polarity of IMF B_y, there were fewer currents in this case. The results obtained were very similar to those described above, although the correlations were somewhat weaker. In addition, as also seen by *Iijima and Potemra* [1982], the correlations in the afternoon were somewhat stronger than in the morning.

[14] The correlations are shown in a more traditional manner in Figure 4 which presents scatterplots of the magnitude of the field-aligned currents versus $B_t\sin(\theta/2)v^2$. Currents observed when the ionospheric foot point was illuminated (dark) are shown as 'x's (triangles). The rank significance, rank correlation coefficient, linear correlation coefficient are shown and the line plotted corresponds to the linear correlation.

4. Conclusions

[15] The solar illumination dependence of coupling of the solar wind to auroral field-aligned currents observed by the FAST satellite has been studied using the technique of rank correlation. For dayside 'Region I' currents, the strongest and the most significant correlations were obtained for parameters including $B_t\sin(\theta/2)$ and the dynamic pressure or the solar wind velocity. A good correlation with these parameters is consistent with a reconnection source. Note, however, that the mapping of the currents was not examined. The largest rank correlation coefficient was obtained for $B_t\sin(\theta/2)v^2$. Strong, significant correlations were only observed for events when the ionospheric foot point of the current sheet was illuminated and not when it was in

Figure 2. (opposite) The complete set of 'Region I' currents determined from the *Peria et al.* [2000] data set. (a) All individual Region I currents plotted as red '+' (green 'x') points corresponding to currents out of (into) the ionosphere; (b) the average of the Region I current density in each MLT-ILAT bin (for bins with more than 10 Region I current sheets). Yellow and red colors refer to currents out of the ionosphere and green and blue refer to currents into the ionosphere.

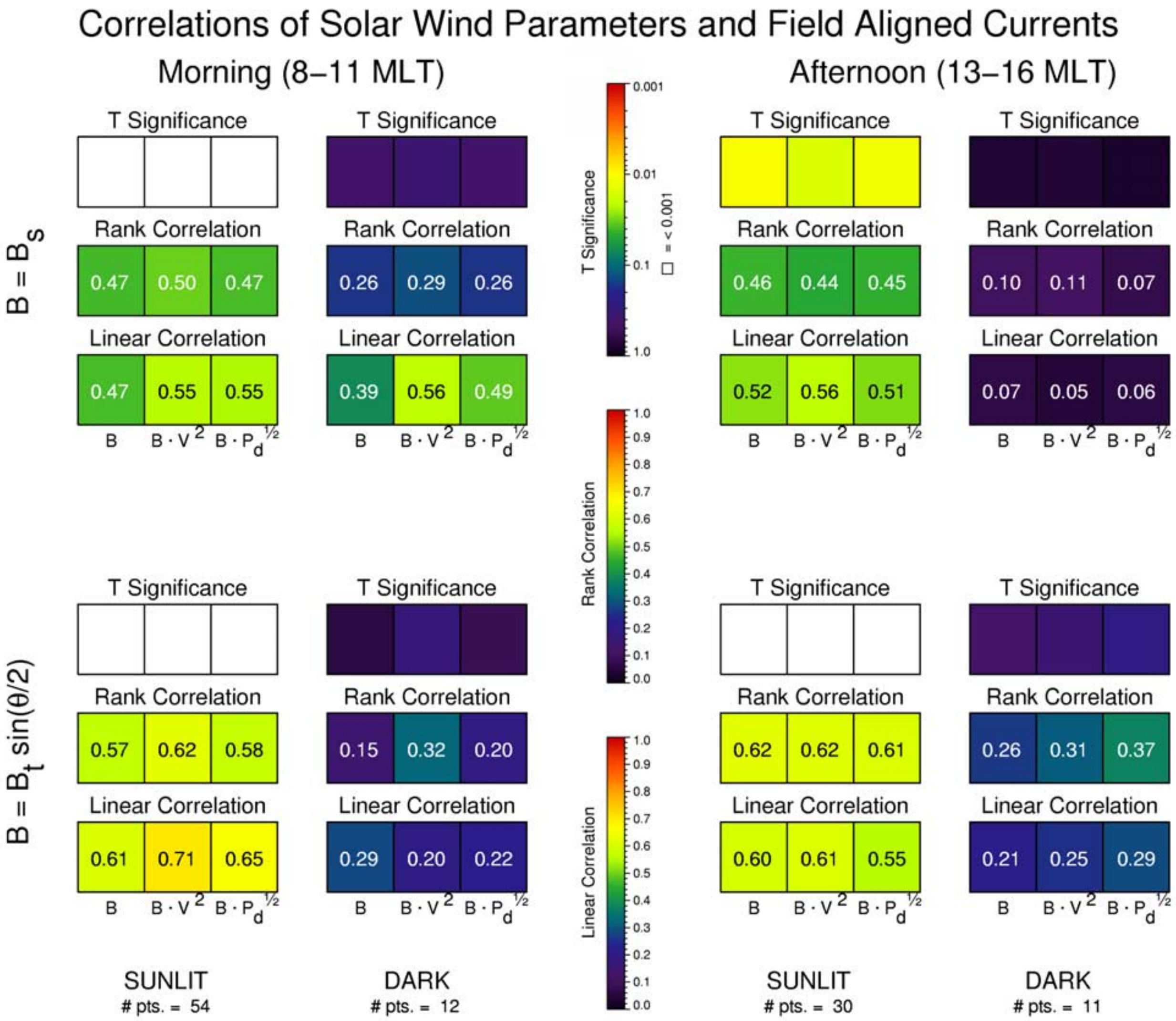


Figure 3. The rank correlation 'T' significance, the rank correlation coefficient and the linear correlation coefficient for a selected set of solar wind parameters for morning (8–11) currents; and afternoon (13–16) currents. The top three rows of plots refer to solar wind parameters that include B_s, while the bottom three rows refer to solar wind parameters that include $B_t\sin(\theta/2)$.

darkness. This is the first observational study to explicitly show a solar illumination (i.e., ionospheric conductivity) dependence of the correlation between the magnitude of dayside Region I currents and solar wind parameters. Because the mapping of the currents was not examined, this result does not explicitly show that ionospheric conductivity modifies solar wind magnetosphere coupling. In combination with simulation studies (discussed below), it is suggestive of such an effect. However, because the mapping of the field-aligned currents was not examined, the observed difference between the sunlit and dark events could be explained by current preferentially flowing into the hemisphere with the higher conductivity if the source were on closed field lines. Note that, based on their observations of periods with no Region I current, *Ohtani et al.* [2000] also speculated that ionospheric conductivity modified solar wind-magnetosphere coupling. *Newell et al.* [1996] suggested that the solar illumination dependence of intense auroral electron acceleration events was due to the conductivity dependence of magnetosphere-ionosphere coupling.

[16] Our results for sunlit events are consistent with *Iijima and Potemra* [1982], who found the strongest correlation for the afternoon sector for $(P_d)^{1/2}B_t\sin(\theta/2)$. Because the Iijima and Potemra study was restricted to data obtained in the Northern Hemisphere from May to August (i.e. primarily sunlit cases), they did not examine whether there was a difference between the correlation for illuminated and dark events. For almost all of the solar wind parameters shown in their Table 1, the correlation coefficient was larger for the afternoon than for the morning, which they suggested was due to the fact that the morning data set had fewer points than the afternoon one. The results presented herein show the correlations are comparable in the morning and afternoon sectors when currents within 1 hour of noon are excluded (Figure 3).

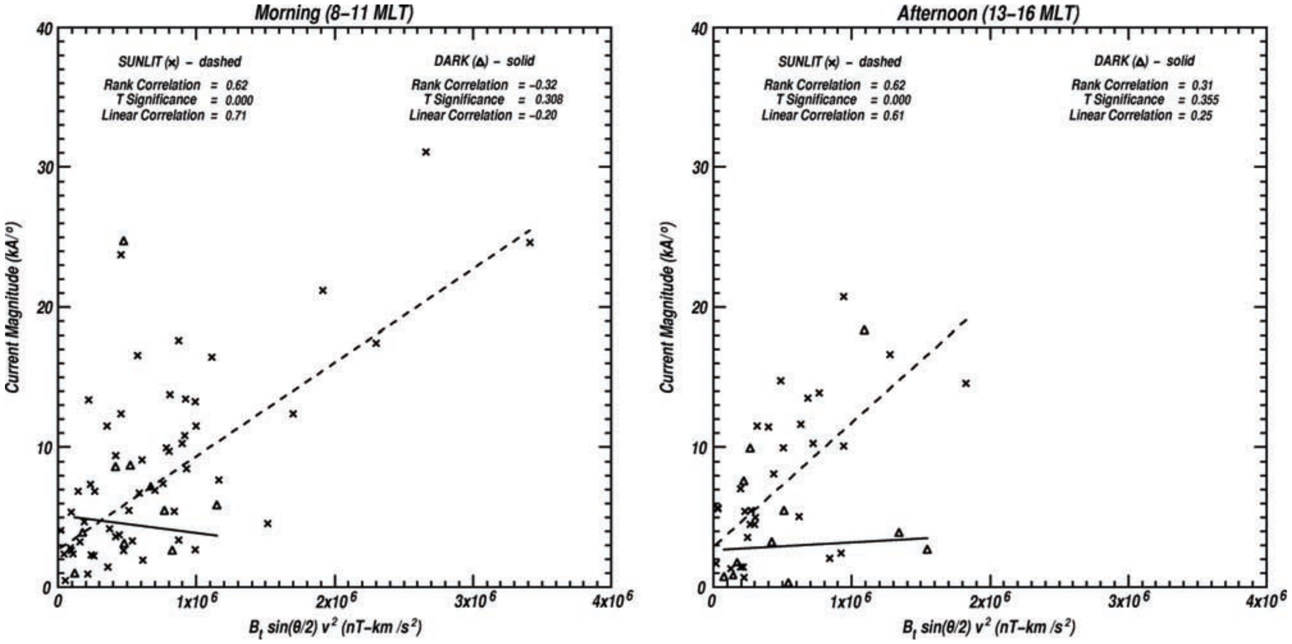


Figure 4. Scatterplots of field-aligned current intensity versus $B_t \sin(\theta/2)v^2$ for (a) 8–11 MLT and (b) 13–16 MLT. Currents observed when the ionosphere was illuminated (dark) are shown as "x" (triangles).

[17] The very strong solar illumination dependence of the correlation of Region I currents with solar wind parameters shown herein may provide evidence in favor of the suggestion that the dominant coupling (i.e. reconnection) produces a voltage source (the cross-polar cap potential), rather than a current source. For a given potential, the largest current will occur in the sunlit hemisphere (this mechanism has been invoked by many other authors to explain the solar illumination dependence of field-aligned currents). In the case where the ionosphere is in darkness, the conductivity will be primarily due to particle precipitation. Whereas the conductivity due to solar illumination is relatively uniform, the conductivity due to precipitation varies both in location and in size. Because the field-aligned current depends on the divergence of the horizontal ionospheric current, its magnitude will be more variable for a given electric field (or cross polar cap potential) for cases when the ionosphere is not illuminated. This effect might result in reduction of the significance of the correlation and in smaller correlation coefficients for the events in darkness compared to those in daylight. However, another possibility is that the dominant coupling is neither a pure voltage source nor a pure current source, and that the applied potential and/or current depend on the ionospheric conductivity.

[18] For our dayside data set, the average current is larger for the sunlit events compared to those in darkness, as was previously shown by *Fujii et al.* [1981] and *Fujii and Iijima* [1987]. For the events between 8–11 MLT, the mean current for sunlit (dark) events was 8.6 (6.0); for 13–16 MLT sector, the mean was 7.7 (5). This dependence has been used by previous studies, including *Fujii et al.* [1981], as evidence that the currents are due to a voltage source. Other studies have also addressed the question of whether the magnetosphere acts as a constant current source or a voltage source. On the basis of correlations between electric and magnetic fields, *Vickrey et al.* [1986] concluded that, at scale sizes between 3 km and 80 km, the magnetosphere acts as a current source on both open and closed field lines. Two theoretical studies concluded that ionospheric conductivity modified solar wind-magnetospheric coupling. *Fedder and Lyon* [1987] provided evidence that, due to magnetosphere-ionosphere coupling, the dynamo does not act as purely a voltage source or a current source. *Ridley et al.* [2001] showed that the magnitude of the cross-polar cap potential (the field-aligned current) obtained in their MHD simulations decreased (increased) as the ionospheric conductivity increased (for the same solar wind conditions), consistent with the Fedder and Lyon conclusions.

[19] The fact that the observed correlations are rather weak, especially compared to those obtained in previous studies of the cross polar cap potential, also suggests that the magnetopause reconnection process is not primarily a current source for auroral Region I currents. However, feedback mechanisms between the auroral ionosphere and the magnetopause which are dependent on ionospheric conductivity and/or the sign of the field-aligned current may invalidate these simple explanations. For example, a feedback mechanism between the magnetopause and its boundary layer and the ionosphere which depended on the sign of the field-aligned current might result in the better correlation for the afternoon (upward) currents than for the morning (downward) currents. It is interesting to note that the best correlation obtained between the cross-polar cap potential and solar wind parameters was reported by *Eriksson et al.* [2000], who examined polar cap crossings by FAST during a 17 day period in July in the Northern Hemisphere. It is very likely that the polar cap was fully illuminated or almost fully illuminated for all the events. If there were conductivity effects on the solar wind coupling, this study would not have seen them. Earlier studies of the

polar cap potential [*Reiff et al.*, 1981; *Wygant et al.*, 1983] were obtained over much longer time periods and, therefore, included events with a wide range of polar cap conductivity distributions. It is possible that the lower correlation coefficients they obtained were due to differences in the coupling modulated by the conductivity. This possibility is given credence by several studies addressing the effects of ionospheric conductivity and/or field-aligned currents and parallel electric fields on one specific phenomenon at the magnetopause, the Kelvin-Helmholtz instability. *Lotko et al.* [1987] showed that damping of vortices at certain scale-sizes occurred due to ionospheric conductivity effects. Utilizing a 3d, non-linear model, *Lysak et al.* [1994] indicated that the magnetic field perturbation due to the field-aligned current would have a stabilizing effect. As mentioned above, *Fedder and Lyon* [1987] and *Ridley et al.* [2001] provided evidence that ionospheric conductivity modified solar wind-magnetosphere coupling. Additional experimental and theoretical studies will be needed to untangle the conductivity and current modulated magnetosphere-ionosphere coupling effects on the reconnection process at the magnetopause.

[20] There are a number of effects not included in this study which could modify the observed relationships. As is the case with most coupling studies, the solar wind measurements were made far away from the Earth, whereas, ideally, they would be measured in the magnetosheath. The dynamic pressure coupling predicted by *Song and Lysak* [1994, 1997] also includes the effect of magnetosheath beta; however, due to lack of plasma measurements in the magnetosheath, this effect could not be included in this study. It is possible that inclusion of beta would improve the correlation for the dynamic pressure parameters. *Wygant et al.* [1983] showed that the cross polar cap potential decayed with time after B_z turned northward, reaching a minimum value after the interplanetary magnetic field was northward for four hours. They also showed the potential saturated for large values of B_z southward when the field had been southward for two or more hours. Such time-dependent effects may also occur for the Region I currents and affect the observed correlations.

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