GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L08102, doi:10.1029/2008GL033545, 2008

Interplanetary magnetic field control of fast azimuthal flows in the nightside high-latitude ionosphere

A. Grocott,[1] S. E. Milan,[1] and T. K. Yeoman[1]

Received 5 February 2008; revised 18 March 2008; accepted 26 March 2008; published 24 April 2008.

[1] SuperDARN radar data from both hemispheres for the interval January 1999 to November 2006 have been inspected for evidence of high-speed azimuthal flows in the nightside high-latitude ionosphere. In the northern hemisphere, 88% of the westward directed fast flows occurred during IMF B_Y negative intervals and 83% of the eastward flows occurred during IMF B_Y positive intervals. In the southern hemisphere 82% of the westward flows occurred during IMF B_Y positive intervals and 74% of the eastward flows occurred during IMF B_Y negative intervals. ~74% of these fast flows occurred when the IMF was within the $30° < |\theta| < 100°$ clock angle range and the AE index was below 150 nT. These results support the hypothesis that highly dynamic magnetospheric activity can be associated with predominantly northward, but B_Y-dominated IMF driving conditions and subsequent non-substorm reconnection in a twisted magnetotail.
Citation: Grocott, A., S. E. Milan, and T. K. Yeoman (2008), Interplanetary magnetic field control of fast azimuthal flows in the nightside high-latitude ionosphere, *Geophys. Res. Lett.*, *35*, L08102, doi:10.1029/2008GL033545.

1. Introduction

[2] Understanding large-scale magnetospheric dynamics is crucial if we are to develop a complete picture of the coupled solar-terrestrial system. It is already known that the interplanetary magnetic field (IMF) plays a significant role in controlling the nature of convection in the magnetosphere and ionosphere. The steady state pictures in particular have been derived from radar data [*Ruohoniemi and Greenwald*, 2005] and satellite data [*Haaland et al.*, 2007] for different orientations and strengths of the upstream IMF. These studies have revealed the IMF B_Y asymmetry between dusk and dawn, as well as the existence of reverse convection for northward IMF. The time dependence of this convection has also been discussed, with observations of dayside convection during southward IMF [e.g., *Milan et al.*, 2000] and northward IMF [e.g., *Imber et al.*, 2007] being considered in some detail. On the nightside it is largely considered that magnetospheric substorms drive the major large-scale component of the convection [e.g., *Cowley et al.*, 1998], and recent studies by, for example, *Grocott et al.* [2002] and *Provan et al.* [2004] have revealed that, for southward IMF at least, this is indeed the case. However, exactly how the behavior of the magnetotail during northward IMF fits into this large-scale picture is not so clear.

[3] Recently, a nightside component of magnetospheric convection has been discussed [e.g., *Senior et al.*, 2002; *Grocott et al.*, 2003, 2007] which consists of large-scale bursts of fast azimuthal flow across the midnight sector ionosphere and associated bursty bulk flows (BBFs) [*Angelopoulos et al.*, 1992] in the magnetotail. These azimuthal flow bursts are observed to occur more commonly during prolonged intervals of northward IMF and recur on timescales of tens of minutes with associated modest contractions of the polar cap (equating to flux closure rates of ~30–50 kV). They are not, however, associated with any substorm activity and are therefore interpreted as the ionospheric signatures of reconnection and flux transport in the more distant tail. They have consequently been termed TRINNIs (tail reconnection during IMF-northward, non-substorm intervals). A mechanism for the flux transport associated with this phenomenon was proposed by *Grocott et al.* [2007] after further case studies revealed both IMF B_Y and interhemispheric related asymmetries [*Grocott et al.*, 2004, 2005]. Based on earlier work by *Taguchi and Hoffman* [1996] and *Nishida et al.* [1998], their results explain the observed asymmetries in terms of the reconfiguration of a twisted tail, itself caused by a modest, but persistent, level of dayside reconnection between the terrestrial field and a northward, but B_Y-dominated IMF.

[4] Whist it is clear, therefore, that TRINNIs are an extremely important mechanism for flux transport in the tail, individual case studies alone cannot reveal any general trends regarding their significance and phenomenology. In the present study a statistical approach is taken in which radar data from an 8 year interval spanning 1999 to 2006 have been inspected for evidence of fast azimuthal flows in the nightside ionosphere in order to determine whether there is a general tendency for flows of this nature to adhere to the characteristics of TRINNIs previously identified. The results reveal that during these 8 years such flows persisted for approximately 3% of the time, with ~80% having a direction consistent with the orientation of IMF B_Y. Approximately 74% occurred when the IMF clock angle was in the $30° < |\theta| < 100°$ range and the AE index was below 150 nT. A superposed epoch analysis of the nightside convection patterns reveals that eastward-type flows appear to be associated with a more distorted pattern than westward-type flows, irrespective of hemisphere (or, therefore, IMF orientation) and that IMF B_Y-negative intervals appear to produce stronger nightside convection than B_Y-positive intervals. These results are discussed in more detail below.

2. Data Selection

[5] This study is based on an analysis of the nightside high-latitude ionospheric flows, provided by the Super Dual

[1]Department of Physics and Astronomy, University of Leicester, Leicester, UK.

0094-8276/08/2008GL033545$05.00

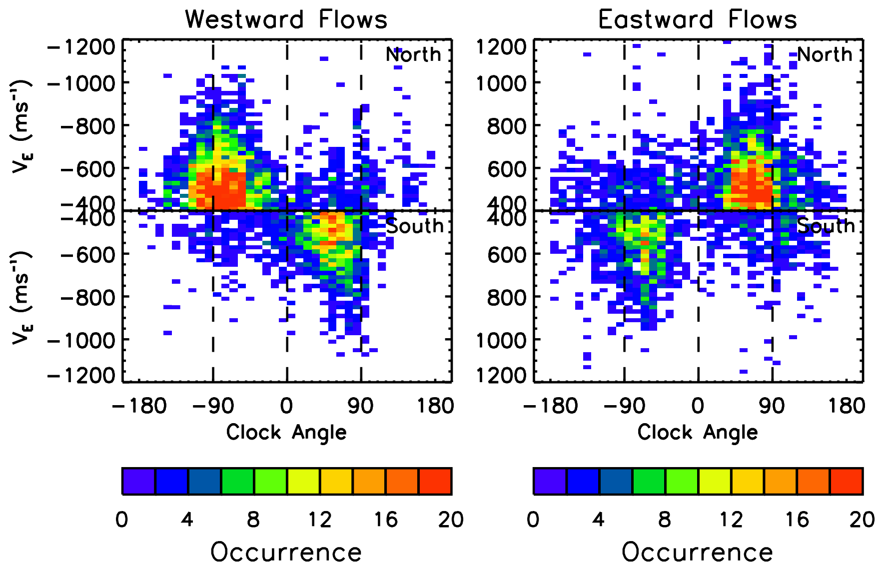

Figure 1. IMF clock angle vs. the eastward component of the ionospheric velocity from the central box location (in Figure 3a) for westward (left-hand side) and eastward (right-hand side) fast flows in the northern and southern hemispheres. The occurrence of the flows is scaled according to the bars at the bottom.

Auroral Radar Network (SuperDARN), from the eight year interval January 1999 to November 2006. The SuperDARN network of HF radars provides almost continuous measurements of ionospheric convection velocities in the auroral regions of both hemispheres [*Greenwald et al.*, 1995; *Chisham et al.*, 2007] and this facilitates the routine production of large scale maps of the high-latitude convection using the "Map Potential" technique [*Ruohoniemi and Baker*, 1998]. However, in order to facilitate a study of such a large volume of data (the 8 year interval studied here consists of literally millions of 2-minute convection maps for each hemisphere) a reduced statistical database has been derived from the results of the full Map Potential analysis. This database consists of values of the convection velocity (and associated information on data coverage) for 40 locations evenly distributed over the polar cap, along with information on the upstream interplanetary magnetic field (IMF) from the MAG instrument [*Smith et al.*, 1999] on board the ACE spacecraft [*Stone et al.*, 1998], which has been propagated to the dayside ionosphere via the method described by *Khan and Cowley* [1999]. The velocity is derived for the centre point of a set of boxes, the locations of which are fixed in magnetic local time (MLT) but are scaled in magnetic latitude according to the overall size of the convection pattern. In other words, the lowest latitude boxes are located at the equatorward boundary of the convection pattern (lat_0), with a further three sets of boxes at latitudes evenly distributed between lat_0 and the pole. The boxes themselves delimit the area in which "local" data coverage is defined.

[6] Three of these statistical boxes from the lowest latitude range (at magnetic local times of 22:40, 00:00 and 01:20) can be seen in Figure 3a, which compares an example symmetrical flow pattern (left panel) with a flow pattern from a previously identified TRINNI event (right panel), the most obvious feature of the latter being the band of fast azimuthal flow across the midnight meridian. Intervals have then been selected based on the velocities from these 3 locations and the criteria that (1) there were at least 2 data points in each box, (2) the east-west flow velocity was in excess of 400 m s^{-1} at midnight and 300 m s^{-1} at the two adjacent points and (3) the east-west component of the flow was in the same direction for all three points. Of the ~8 years of convection maps available, 6826 (3473) hours of data surveyed in the northern (southern) hemisphere (10% and 5%, respectively) met criterion 1, and 183 h (103 h) met criteria 2 and 3. These data and their further analysis are described below.

3. Statistical Results

3.1. IMF Control of Fast Nightside Flows

[7] To date, the factor most associated with controlling TRINNI activity is the orientation of the IMF. Figure 1 therefore presents the occurrence statistics of the high-speed ionospheric flows, with their velocities plotted vs. IMF clock angle for the northern (top panels) and southern (bottom panels) hemispheres. Here, the clock angle is defined as the angle between the IMF vector (projected into the *y-z* plane) and the *z*-direction, such that 0° clock angle corresponds to a transverse field purely in the +*z* direction (northward), ±90° to ±*y* (respectively), and ±180° to −*z* (southward). The mean IMF vector from the 2 hours prior to each interval is used to (1) remove rapid fluctuations in the data, (2) account for the uncertainty in propagating the ACE observations to the ionosphere and (3) allow for some delay 'through' the magnetosphere to the nightside ionosphere. The left-hand panels show the fast westward flows and the right-hand panels show the fast eastward flows. The occurrences are then scaled according to the bar shown at the bottom of each panel.

[8] The data presented in Figure 1 reveal that the fastest flow speeds observed were around 1200 m s^{-1}, with the majority being under 800 m s^{-1}. These high-occurrence populations show a clear IMF clock angle dependence, which reveals that in the northern hemisphere, 88% of the

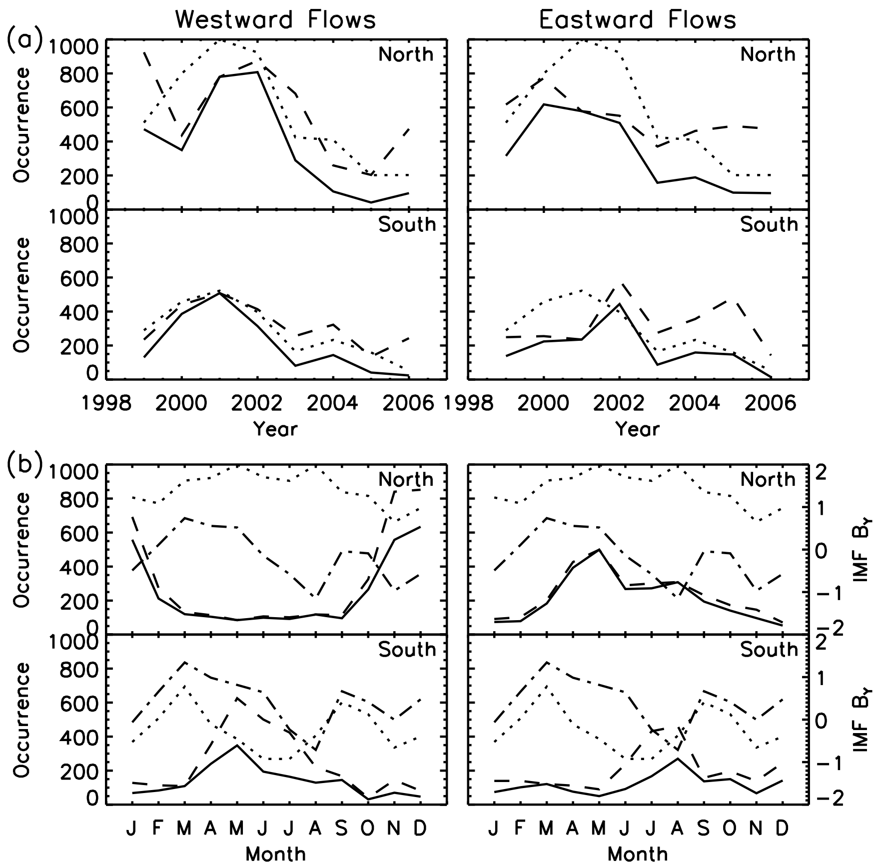

Figure 2. The occurrence of fast flows vs. (a) year and (b) month for westward and eastward directions in the northern and southern hemispheres (solid lines). In each case the corresponding variation in radar data coverage (normalized, and scaled to the plot y-axis) is indicated by the dotted line and the fast-flow occurrence scaled by the level of radar data coverage is indicated by the dashed line. In Figure 2b mean monthly values of IMF B_Y are also shown (dot-dash line) scaled to the y-axis on the right-hand side of the plots.

westward directed fast flows occurred during IMF B_Y negative intervals and 83% of the eastward flows occurred during IMF B_Y positive intervals whilst in the southern hemisphere, 82% of the westward flows occurred during IMF B_Y positive intervals and 74% of the eastward flows occurred during IMF B_Y negative intervals. It is interesting to note that the westward flows appear to be more consistent with IMF orientation than the eastward flows (as well as being more common in general, by approximately 5:4). This may be related to the differences between the eastward- and the westward-type flow patterns discussed in section 3.3. The southern hemisphere flows also appear to be less consistent with IMF orientation than northern hemisphere flows, as well as having generally lower occurrences, although this could be due to the different coverage, locations, and pointing directions of the radars contributing data in each case. There are then much smaller populations of examples which appear to exhibit the opposite IMF B_Y relationship, with a general trend towards very low velocities only for very strongly northward IMF. Of greatest significance, however, is the fact that the largest populations and the fastest flows occur during intervals of IMF clock angle $30° < |\theta| < 100°$, i.e. predominantly during intervals of positive IMF B_Z. This suggests that not all modes of magnetospheric activity are strongest when the IMF is southwards.

3.2. Solar Cycle and Seasonal Dependence

[9] The data available for this study span the declining phase of the last solar cycle, thus enabling a rudimentary comparison with solar activity to be made. Figure 2a therefore presents the occurrence of fast flows vs. year (solid lines), again separated by hemisphere and east-west flow direction. Because the amount of HF radar backscatter is variable, a "good radar intervals" parameter (henceforth referred to as 'GRI') has been defined as the number of intervals satisfying criterion 1 in section 2, to put the fast flow occurrence variability into context. This is represented in Figure 2a by the dotted lines (normalized, and scaled to the plot y-axes) with the fast-flow occurrence scaled to GRI shown by the dashed lines. An initial inspection suggests that the flows are indeed dependent on solar cycle, with their occurrence decreasing in general between the year 2000 (the last solar maximum) and 2006. Although the GRI also decreases during this period, the scaled flow occurrence suggests that there is still some decline in the number of fast flow intervals towards solar minimum. A possible explanation for this could be related to coronal mass ejections (CMEs), which are more common during solar maximum and are associated with stable IMF conditions which could be a prerequisite for this mode of non-substorm magnetospheric dynamics. This would also be consistent with the

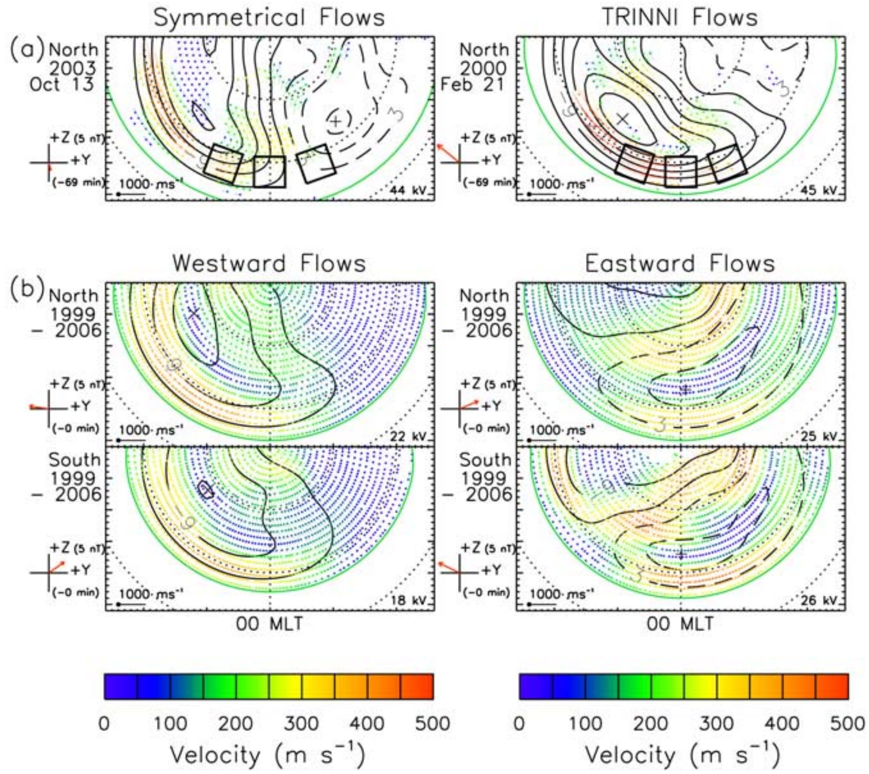

Figure 3. Streamlines and flow vectors of ionospheric convection patterns derived from SuperDARN velocity measurements. These data are shown on geomagnetic latitude-MLT grids, with midnight at the bottom and dusk to the left. (a) (left) A 'typical' symmetrical convection pattern and (right) a typical TRINNI convection pattern. The three boxes in the midnight sector indicate the regions which contribute to the statistical data used in the study. (b) Average nightside ionospheric convection patterns derived using radar data from all of the fast flow intervals. The arrow in the bottom left indicates the average magnitude and orientation of the interplanetary magnetic field in the Y-Z plane.

fact that substorms have been shown to be less frequent during solar maximum [e.g., *Hiebert et al.* 2004]. A fuller investigation of the influence of solar activity on magnetospheric dynamics is certainly warranted, however, this is beyond the scope of the present study.

[10] The seasonal dependence of the flows is illustrated in Figure 2b, which presents their occurrence vs. month in the same format as Figure 2a, but also shows the monthly mean variability of IMF B_Y (dot-dash lines) scaled to the y-axes on the right-hand side of the plots. If we consider first the occurrence of westward flows in the northern hemisphere there is a striking anti-correlation with GRI, with the majority of the flows occurring during the winter months, despite this being when the least GRIs are observed. Eastward flows in the same hemisphere, however, exhibit a different trend with a peak at spring equinox and a secondary peak in the autumn, more resembling the variation in GRI. In the southern hemisphere the trend in GRI differs from the northern hemisphere, having peaks at equinox. The main peaks in southern hemisphere flows are then somewhat out of phase with the GRI, being post-spring equinox for westward flows and pre-autumn equinox for eastward flows.

[11] The peaks near equinox can be largely explained by considering the seasonal variation of IMF B_Y (dot-dash lines). Positive B_Y peaks primarily at spring equinox, which could explain the peaks in northern hemisphere eastward flows and southern hemisphere westward flows, although this does not address why they lag the B_Y peaks by $\sim$2 months. Negative B_Y peaks at the same time as the southern hemisphere eastward flows as might be expected, but the winter peak in northern hemisphere westward flows does not seem to correlate with IMF B_Y. This winter peak for northern hemisphere westward flows (and the 2-hour lag towards summer associated with the B_Y-positive flows mentioned above) could, however, be related to the fact that the statistical convection pattern for negative B_Y is most asymmetrical during winter whereas that for positive B_Y is most asymmetrical during summer [*Ruohoniemi and Greenwald*, 2005].

3.3. Statistical Convection Patterns

[12] To illustrate the generic convection patterns associated with these fast flow events, the full radar datasets have been binned according to hemisphere, and whether they revealed eastward or westward flow and then processed into four single convection maps using the Map Potential analysis. In order to minimize the "contamination" by possibly misidentified events only intervals which fall into the $30° < |\theta| < 100°$ regime have been used. The nightside sectors of these convection patterns are presented in Figure 3b and a number of features are evident. Firstly, westward flow intervals appear to be dominated by a single, large, dusk convection cell with essentially stagnant flow at

dawn. Eastward flow intervals on the other hand, retain a twin-cell pattern, but one with a considerable dusk-dawn asymmetry. This is in agreement with the statistical nature of ionospheric convection in general which shows that the B_Y-asymmetric convection pattern is more asymmetric when the dawn cell spans midnight than when the dusk cell does, irrespective of hemisphere (and hence the sign of IMF B_Y). Secondly, dawn cell flows appear to be more intense, with the fast flows reversing further pre-midnight than the dusk cell flows do pre-midnight.

3.4. Relationship to Substorms

[13] The results discussed above suggest that these fast azimuthal flows are in general consistent with previous observations of TRINNIs. However, whilst their tendency to occur when the IMF is northward suggests an association with non-substorm intervals, a rudimentary inspection of the levels of auroral activity has been performed as an additional check. It is found that the mean (median) AE for the intervals is 118(90) nT, with ~74 % of the flows occurring when AE < 150 nT. It is therefore reasonable to conclude that in a statistical sense these fast flows are not associated with major substorm activity.

4. Conclusions

[14] This paper has investigated the nature of fast azimuthal flows in the nightside high-latitude ionosphere which have previously been associated with intervals of northward, but B_Y-dominated IMF. It is found that the direction of the flows is generally consistent with the orientation of IMF B_Y, such that in the northern (southern) hemisphere the flows are eastward (westward) for positive IMF B_Y and westward (eastward) for negative IMF B_Y. Significantly, the largest populations and the fastest flows occurred during intervals of IMF clock angle $30° < |\theta| < 100°$ (i.e. predominantly during intervals of positive IMF B_Z) and ~74 % of the flows occurred during intervals of AE < 150 nT. This association with predominantly northward IMF and low auroral activity is consistent with previous observations of TRINNIs. This implies that, whilst the magnetosphere may well be highly active during intervals of southward IMF and substorm activity, there is also a highly dynamic mode of convection in play during more northward IMF intervals, and that the magnetosphere is far from 'quiet' under such conditions.

[15] **Acknowledgments.** We would like to thank the PIs of the SuperDARN radars for provision of the radar data, R. J. Barnes of the Johns Hopkins University for the 'Map-Potential' algorithm software, and Norman Ness and Charles Smith of the Bartol Research Institute for the ACE magnetometer data. AG was supported during this study by STFC grant PP/E000983/1. SuperDARN operations at the University of Leicester are supported by STFC grant PP/E007929/1.

References

Angelopoulos, V., W. Baumjohann, C. F. Kennel, F. V. Coroniti, M. G. Kivelson, R. Pellat, R. J. Walker, H. Lühr, and G. Paschmann (1992), Bursty bulk flows in the central plasma sheet, *J. Geophys. Res.*, *97*, 4027–4039.

Chisham, G., et al. (2007), A decade of the Super Dual Auroral Radar Network (SuperDARN): Scientific achievements, new techniques and future directions, *Surv. Geophys.*, *28*, 33–109.

Cowley, S. W. H., H. Khan, and A. Stockton-Chalk (1998). Plasma flow in the coupled magnetosphere-ionosphere system and its relationship to the substorm cycle, in *Substorms-4*, edited by S. Kokobun and Y. Kamide, pp. 623–628, Terra Sci., Tokyo.

Greenwald, R. A., et al. (1995), DARN/SuperDARN: A global view of the dynamics of high-latitude convection, *Space Sci. Rev.*, *71*, 761–796.

Grocott, A., S. W. H. Cowley, J. B. Sigwarth, J. F. Watermann, and T. K. Yeoman (2002), Excitation of twin-vortex flow in the nightside high-latitude ionosphere during an isolated substorm, *Ann. Geophys.*, *20*, 1577–1601.

Grocott, A., S. W. H. Cowley, and J. B. Sigwarth (2003), Ionospheric flows and magnetic disturbance during extended intervals of northward but By-dominated IMF, *Ann. Geophys.*, *21*, 509–538.

Grocott, A., S. V. Badman, S. W. H. Cowley, T. K. Yeoman, and P. J. Cripps (2004), The influence of IMF By on the nature of the nightside high-latitude ionospheric flow during intervals of positive IMF Bz, *Ann. Geophys.*, *22*, 1755–1764.

Grocott, A., T. K. Yeoman, S. E. Milan, and S. W. H. Cowley (2005), Interhemispheric observations of the ionospheric signature of tail reconnection during IMF-northward non-substorm intervals, *Ann. Geophys.*, *23*, 1763–1770.

Grocott, A., T. K. Yeoman, S. E. Milan, O. Amm, H. U. Frey, L. Juusola, R. Nakamura, C. J. Owen, H. Rème, and T. Takada (2007), Multi-scale observations of magnetotail flux transport during IMF-northward non-substorm intervals, *Ann. Geophys.*, *25*, 1709–1720.

Haaland, S. E., G. Paschmann, M. Foerster, J. M. Quinn, R. B. Torbert, C. E. McIlwain, H. Vaith, P. A. Puhl-Quinn, and C. A. Kletzing (2007), High-latitude plasma convection from Cluster EDI measurements: Method and IMF-dependence, *Ann. Geophys.*, *25*, 239–253.

Hiebert, T., E. Donovan, and B. Jackel (2004). Substorm seasonal and solar cycle dependence, paper presented at 7th International Conference on Substorms, Finn. Meteorol. Inst., Levi.

Imber, S. M., S. E. Milan, and B. Hubert (2007), Observations of significant flux closure by dual lobe reconnection, *Ann. Geophys.*, *25*, 1617–1627.

Khan, H., and S. W. H. Cowley (1999), Observations of the response time of high latitude ionospheric convection to variations in the interplanetary magnetic field using EISCAT and IMP-8 data, *Ann. Geophys.*, *17*, 1306–1335.

Milan, S. E., M. Lester, S. W. H. Cowley, and M. Brittnacher (2000), Convection and auroral response to a southward turning of the IMF: Polar UVI, CUTLASS and IMAGE signatures of transient magnetic flux transfer at the magnetopause, *J. Geophys. Res.*, *105*, 15,741–15,775.

Nishida, A., T. Mukai, T. Yamamoto, S. Kokubun, and K. Maezawa (1998), A unifield model of the magnetotail convection in geomagnetically quiet and active times, *J. Geophys. Res.*, *103*, 4409–4418.

Provan, G., M. Lester, S. B. Mende, and S. E. Milan (2004), Statistical study of high-latitude plasma flow during magnetospheric substorms, *Ann. Geophys.*, *22*, 3607–3624.

Ruohoniemi, J. M., and K. B. Baker (1998), Large-scale imaging of high-latitude convection with Super Dual Auroral Radar Network HF radar observations, *J. Geophys. Res.*, *103*, 20,797–20,811.

Ruohoniemi, J. M., and R. A. Greenwald (2005), Dependencies of high-latitude plasma convection: Consideration of interplanetary magnetic field, seasonal, and universal time factors in statistical patterns, *J. Geophys. Res.*, *110*, A09204, doi:10.1029/2004JA010815.

Senior, C., J.-C. Cerisier, F. Rich, M. Lester, and G. K. Parks (2002), Strong sunward propagating flow bursts in the night sector during quiet solar wind conditions: SuperDARN and satellite observations, *Ann. Geophys.*, *20*, 771–786.

Smith, C. W., M. H. Acuña, L. F. Burlaga, J. L'Heureux, N. F. Ness, and J. Scheifele (1999), The ACE Magnetic Field Experiment, *Space Sci. Rev.*, *86*, 613–622.

Stone, E. C., A. M. Frandsen, R. A. Mewaldt, E. R. Christian, D. Margolies, J. F. Ormes, and F. Snow (1998), The Advanced Composition Explorer, *Space Sci. Rev.*, *86*, 1–22.

Taguchi, S., and R. A. Hoffman (1996), Ionospheric plasma convection in the midnight sector for northward interplanetary magnetic field, *J. Geomagn. Geoelectr.*, *48*, 925–933.

A. Grocott, S. E. Milan, and T. K. Yeoman, Department of Physics and Astronomy, University of Leicester, Leicester LE1 7RH, UK. (a.grocott@ion.le.ac.uk)