TRANSIENT IONOSPHERIC CONVECTION FEATURES ASSOCIATED WITH SUBSTORMS AND BBFS

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ABSTRACT

High time resolution operation of the SuperDARN HF radars regularly results in observations of pulsed, vortical ionospheric convection velocities during the substorm expansion phase. Pulsed flow is often preceded by an interval of suppressed flow and enhanced ionospheric Hall conductance. Such features, which propagate both westward and eastward away from the meridian where the substorm is centred, have been interpreted as ionospheric current vortices associated with field-aligned current pairs. HF radar observations will be discussed, and related to ground based magnetic field and optical observations of similar phenomena, as well as spacecraft measurements in the near magnetotail. Their possible relationship with bursty Earthward plasma flow and magnetotail reconnection is discussed.

INTRODUCTION

The use of HF radar data in to characterise ionospheric electric fields and boundaries at the footprint of the magnetospheric cusp, and hence explore reconnection processes at the dayside magnetopause is well established (e.g. Pinnock *et al.*, 1995; Provan *et al.*, 1998; Milan *et al.*, 1999). The extensive fields-of-view of high frequency (HF) coherent scatter ionospheric radars also make them excellent instruments for the investigation of the larger-scale spatial and temporal development of the ionospheric electric fields during the substorm cycle. This is especially true for the SuperDARN network, which offers an extensive network of such radars in the northern and southern hemispheres. Extensive progress has been made in the use of such radar systems to characterise the ionospheric electric fields during substorms: During the substorm growth phase the equatorward boundary of the HF radar backscatter in the nightside ionosphere has been demonstrated to respond to the expansion of the polar cap due to the addition of open flux following reconnection processes on the dayside (Lewis *et al.*, 1998). At expansion phase onset, localised electrojet features in which ionospheric flows were suppressed to values as low as 50 m s^{-1} and accelerated up to values as high as 1 km s^{-1} within a few minutes have also been observed at the western edge of the substorm-disturbed electrojet, accompanied by conductance variations between 20 and 100 S (Morelli *et al.*, 1995). Auroral phenomena during the substorm recovery phase (Ω-bands) have also been studied in detail (Wild *et al.*, 2000). As yet, however, the identification of the direct signatures of magnetotail reconnection at its ionospheric footprint have proven more difficult. One possible candidate phenomenon, observed during the substorm expansion phase, are dynamic convection features, which correspond to azimuthally propagating field aligned current systems, identified by Yeoman and Lühr, (1997) and Yeoman *et al.* (1998) in high time resolution (HTR) coherent radar data (illustrated in Figure 1 and discussed in detail below). It has been suggested that these features may be related to reconnection and bursty bulk flows (BBFs) in the magnetotail.

Spacecraft studies of the terrestrial magnetotail have established that the near-Earth plasma sheet, whilst predominantly a region of slow flow, is punctuated by short-lived, rapid earthward flow bursts (e.g. Baumjohann *et al.*, 1990, Angelopoulos *et al.*, 1992; 1996). Such flow enhancements, Bursty Bulk Flows, are responsible for the majority of the magnetic flux transport past the spacecraft, and are associated with transient field dipolarizations and temperature increases. The events are statistically correlated with AE index activity, and thus substorms, although a one-to-one correlation is hard to establish, presumably due to instrumental limitations. The events are generally thought to be associated with reconnection processes in the near-Earth neutral line, although they have also been observed in association with distant tail processes (Sergeev *et al.*, 1990).

BBFs appear to play a key role in the substorm process. Their evolution in the magnetotail has been discussed in terms of plasma bubbles (e.g. Sergeev *et al.*, 1996) and the deceleration of the high speed flow in the dipolar region has been implicated in the triggering of the near-Earth substorm expansion phase onset signatures (Shiokawa *et al.*, 1997). The thinly-sampled nature of *in situ* spacecraft data makes the case for attempting an identification of the ionospheric signatures at the footprint of such a bursty flow structure a strong one, as it would bring to bear powerful diagnostic instruments which have done much to improve our understanding of analogous dayside processes. It has been suggested that BBFs might manifest themselves as a characteristic optical auroral signature. Candidates include north-south auroral structures (Henderson *et al.*, 1998) and poleward boundary intensifications (Lyons *et al.*, 1999). Their possible relationship with transient structures in the

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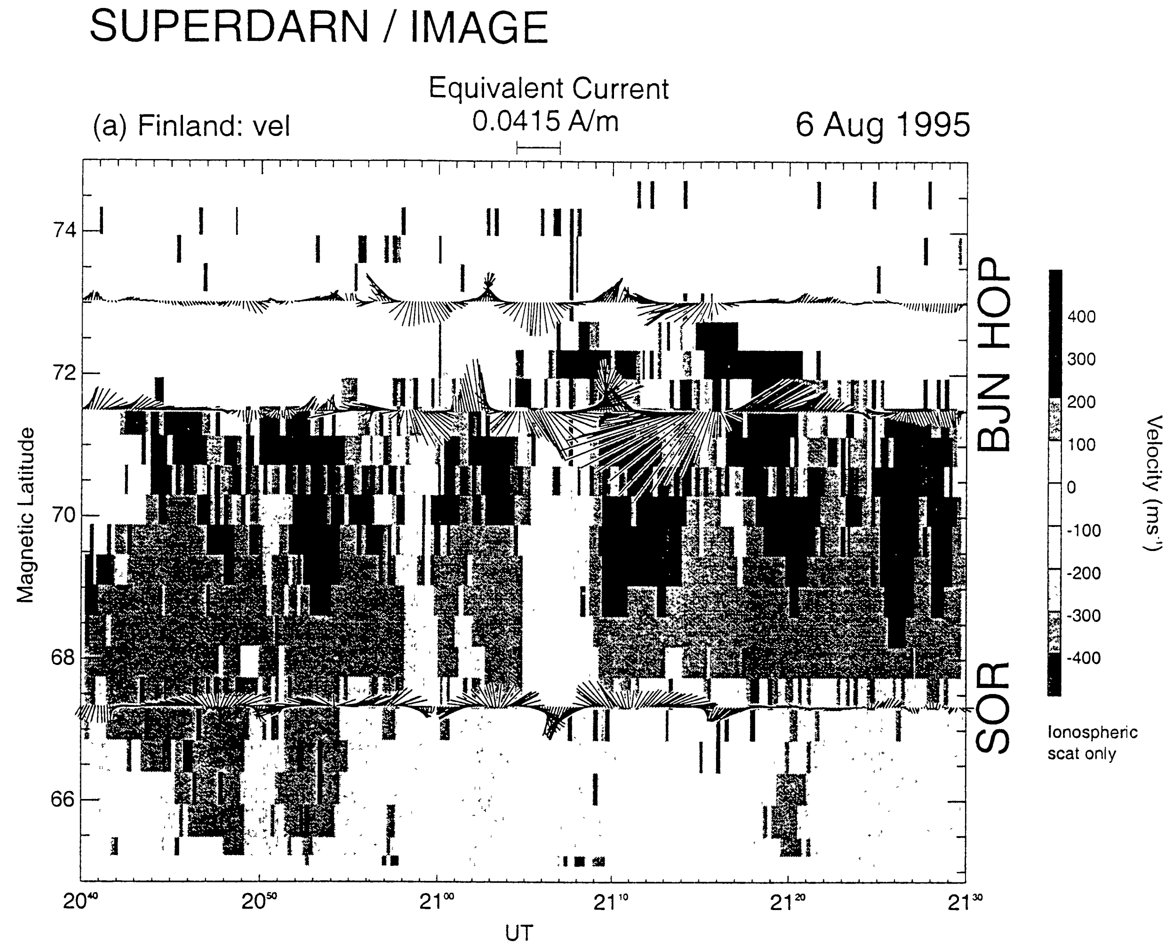

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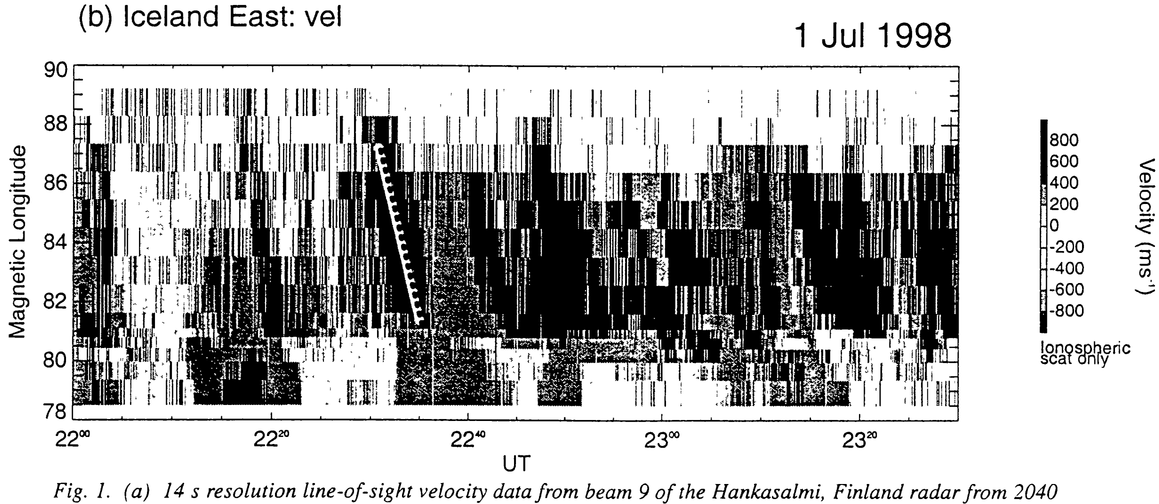

Fig. 1. (a) 14 s resolution line-of-sight velocity data from beam 9 of the Hankasalmi, Finland radar from 2040 - 2130 UT on 6 August 1995. A number of equatorward flow bursts are seen. Equivalent currents derived from IMAGE magnetometer data are also shown, and reveal vortical current signatures. (b) Line-of-sight velocity data from beam 15 of the Þykkvibær, Iceland radar from 2200 - 2330 UT on 1 July, 1998. A westward propagating convection vortex (propagating away from the substorm onset location) is observed at 2230 UT (marked with a dashed line).

ionospheric electric field has also been suggested, as outlined above. Here we review the characteristics of such electric field transients and their potential to constrain substorm theories.

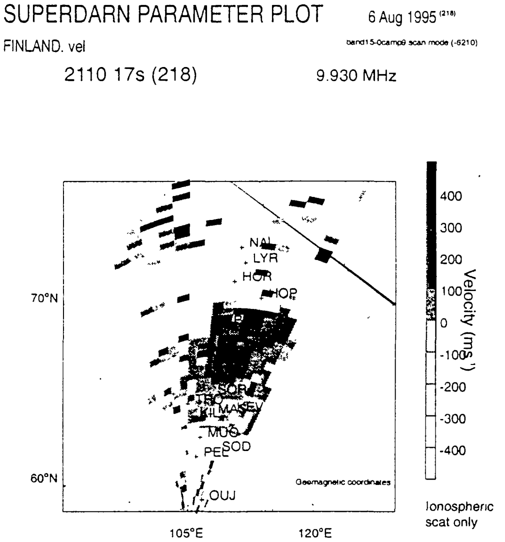

Figure 2: The appearance of one of the intervals of enhanced equatorward flow illustrated in Figure 1 in the 2-D field of view of the Hankasalmi radar. A considerable longitudinal extent is shown.

INSTRUMENTATION

The ionospheric convection velocities in this study are provided by the Co-operative UK Twin-Located Auroral Sounding System (CUTLASS). CUTLASS is a bistatic HF coherent radar, with stations at Hankasalmi in Finland and Þykkvibær in Iceland, and forms part of the international SuperDARN chain of HF radars (Greenwald *et al.*, 1995). The radars form 16 beams of separation 3.24°. Each beam is gated into 75 range bins, each of length 45 km in standard operations. During standard operations the dwell time for each beam is 7 s, giving a full 16 beam scan, covering 52° in azimuth and over 3000 km in range (an area of over 4 x 10^6 km^2), every 2 min. High time resolution data is obtained during non-standard operations of the radar systems by virtue of either decreasing the integration period, or running different scan patterns, or both. As an example the Hankasalmi radar, rather than the usual anticlockwise sweep through beams 15, 14, 13,..., 0 often employs the sequence 15, 9, 14, 9, 13, 9, ...,1, 9, 0, 9. This allows the construction of full 16 beam scans at a reduced temporal resolution of 4 min, in addition to the provision of high time resolution (14 s) data along a single (meridional) look direction.

OBSERVATIONS

Transient, azimuthally propagating convection features were first noted by Yeoman and Lühr (1997). The features were manifested as bursts of equatorward flow, with a typical duration of 5 min, and an inter-pulse interval of around 3 min, observed in 14 s resolution data from the meridionally pointing beams of the Hankasalmi radar. The peak line-of-sight flow was ~600 m s^{-1}. They had a spatial extent of 400-500 km in longitude and 300-400 km in latitude. An interval of such data is illustrated in Figure 1a. This displays data from beam 9 of Hankasalmi. A number of such equatorward flowbursts are seen. Equivalent currents from the underlying IMAGE magnetometers show the strongest currents proceed the flowbursts, presumably as a consequence of high conductivity, low electric field conditions associated with particle precipitation and visible aurora. A representation of the 2-D appearance of the events within the Hankasalmi field of view is presented in Figure 2.

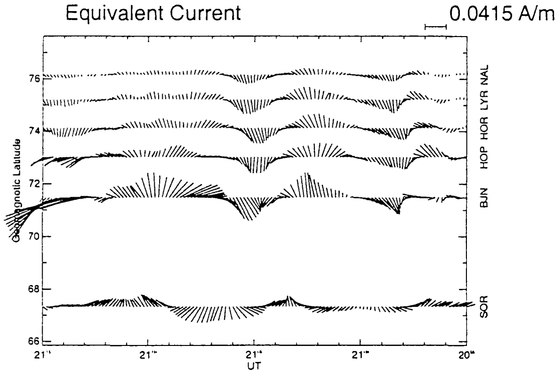

Figure 3: Equivalent current patterns deduced from IMAGE magnetometer data, plotted on an inverted time axis in order to visualise the spatial structure for an eastward propagating feature. Data for HOP have been shifted by 40 s to account for the propagation delay to this azimuthally separated station.

The region of enhanced equatorward flow can be seen to occupy a considerable longitudinal extent, although the temporal resolution of the full scan limits the 2-D information available about the features. The ground magnetometer data also reveals a vortical current structure, and a comparison of azimuthally separated IMAGE stations HOR and HOP implies an eastward azimuthal velocity of up to 6 km s^{-1}. The vortical nature of the equivalent current signatures of the features is best illustrated in a time-reversed format, which gives a correct spatial picture for an eastward-propagating event. Such a plot is presented in Figure 3, and the vortical current signatures are clear in 6 high-latitude IMAGE stations. The direction of azimuthal propagation is away from the centre of the substorm onset activity with which the events are associated,

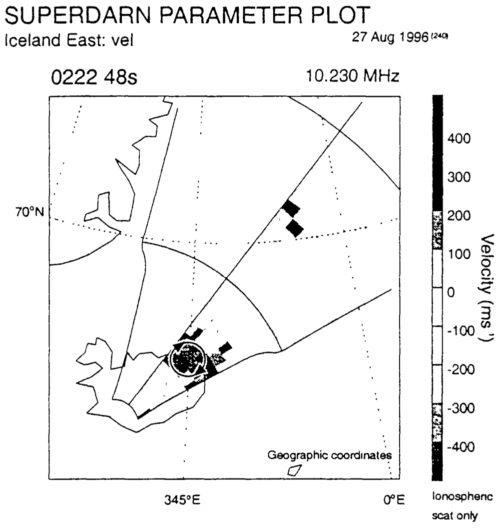

Figure 4: A scan of half the f-o-v of the Þykkvibær radar on 02:22:48 UT on 27 August 1996. The expected flows due to a Hall current vortex flowing around an upward FAC are indicated, and are consistent with the flows observed.

which lies to the west of the instrumentation presented here. Such events have been termed Azimuthally Propagating Vortical Currents (APVCs). The azimuthal propagation of these features can be directly measured by the zonal beams of the Þykkvibær radar. An example of data from this radar is shown in Figure 1b. Here Þykkvibær beam 15 is sampled at a resolution of 4 s, and a convection feature is seen propagating westward at 2230 UT. The substorm onset occurred to the east of the radar, thus this feature is also propagating away from the onset region. The zonal beams of the Þykkvibær radar can also be used to confirm the vortical nature of the flows during APVC events in 2-D. Figure 4 presents a spatial plot of APVC data from 0222:48 UT on 27 August, 1996 during an 8-beam scan. This scan illustrates a bipolar line-of-sight velocity feature, in this case an event propagating eastward through the radar field of view away from a substorm onset to the west. The proposed region of vortical flow is overlaid on the near ranges of the radar. The temporal resolution of such 8 beam scans in this case was only 2 minutes, so such spatial information is again limited. The proposed vortical flow, field aligned current structure and propagation for the two events dipicted in Figure 1 is shown schematically in Figure 5. A field aligned current pair leads to a region of enhanced equatorward flow between them, which is detected by the Hankasalmi radar. Similar vortical currents will give bipolar signatures in the zonal beams of Þykkvibær, and the azimuthal propagation of the vortex causes the observed signature to move up or down the radar beam as time progresses.

Although the SuperDARN radars run the majority of the time in standard 1 min or 2 min, 16 beam scans, which have insufficient temporal resolution to delineate APVCs, over 2100 hours of suitable HTR data have now been collected for the Hankasalmi and Þykkvibær radars, some 7% of the total data collected. This dataset has produced 25 examples of APVC events. Given the overall statistics for obtaining good quality ionospheric scatter over a sufficient area to analyse the characteristics of such transient phenomena, this suggests that APVCs are a relatively common occurrence, and sufficient events have been detected to enable the typical characteristics of APVCs to be determined. Data from Þykkvibær indicates that typical flows within the vortical current regions is ~800 m s^{-1}, with an azimuthal propagation speed of ~ 1 km s^{-1}. The longitudinal extent of the features is typically 6°. The radar data suggest that the vortical current systems may occur singly (20 % of events studied), or more commonly in small trains. The vortical currents are only observed in the sense expected around upward field aligned currents.

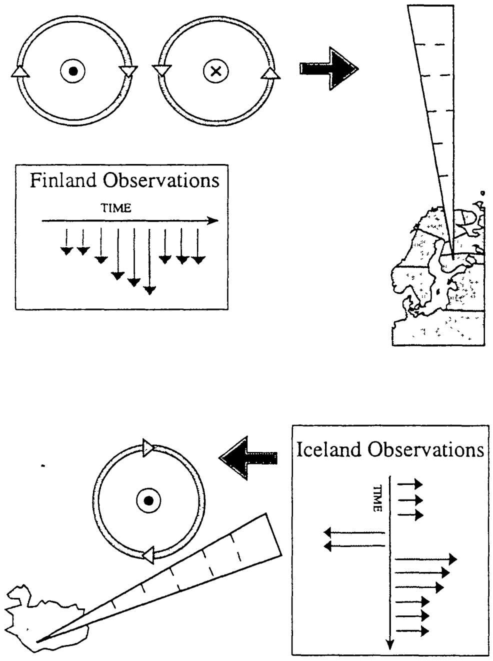

Figure 5: A schematic diagram of our interpretation of the cause of the line-of-sight velocity signatures in the meridionally-directed beams of the Hankasalmi radar and the zonal beams of the Þykkvibær radar. The transiently observed features are interpreted as being due to ionospheric current vortices associated with field aligned current pairs generated during the substorm expansion phase. In Figure 1 Hankasalmi detects eastward-propagating events whereas Þykkvibær detects a westward-propagating event.

Clearly both upward and downward currents are required for current closure, thus the lack of radar observations of downward currents is presumably a consequence of the the precipitating electrons associated with upward field aligned currents playing a role in producing the ionospheric instabilities which the coherent radars require as targets. The time of the first observation of the APVCs relative to the time of the substorm onset or intensification has been examined. This is displayed in Figure 6 as a normalised occurrence rate. The events observed in the radar data can be seen to occur almost exclusively after substorm onset, with 50 % of events occurring within 1 hour of substorm expansion phase onset, and over 90 % occurring within 2 hours. In fact only one event occurred before substorm onset (the APVC leading the substorm by 16 minutes).

The propagation speed and direction of the events has also been examined, with reference to the longitudinal separation of the APVC event and the substorm onset region with which it is associated. In Figure 7 the events can be seen to have a consistent propagation speed, and their propagation is directed away from the longitude of the substorm onset/intensification. This is illustrated schematically in the lower panel of Figure 7.

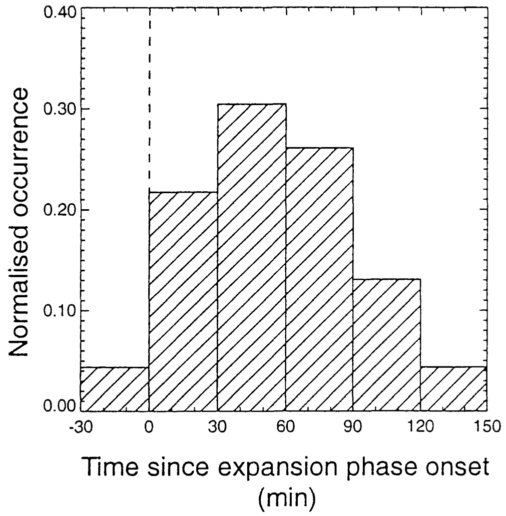

Figure 6: A histogram of the normalised occurrence rate of APVCs relative to the substorm onset time. The dashed vertical line represents the time of substorm onset.

DISCUSSION

High time resolution HF radar data has revealed that APVCs are a common observation in the ionospheric convection during the substorm expansion phase. The events have a duration of a few minutes, involve flows of ~ 800 m s^{-1}, and propagate azimuthally at ~ 1 km s^{-1} with a scale size of a few 100 km. They propagate away from the substorm onset region, and appear somewhat analogous to the travelling convection vortices which have been observed previously on the dayside. The radar instrumentation appear to only be sensitive to vortical structures associated with upward field aligned currents. The APVCs are rather similar to the vortical flow patterns associated with reconnection processes on the dayside, and they are thought to be the ionospheric signature of, or an ionospheric response to, BBFs in the magnetotail. Evidence to support this, employing data from the *Geotail* spacecraft was presented by Yeoman *et al.* (1998).

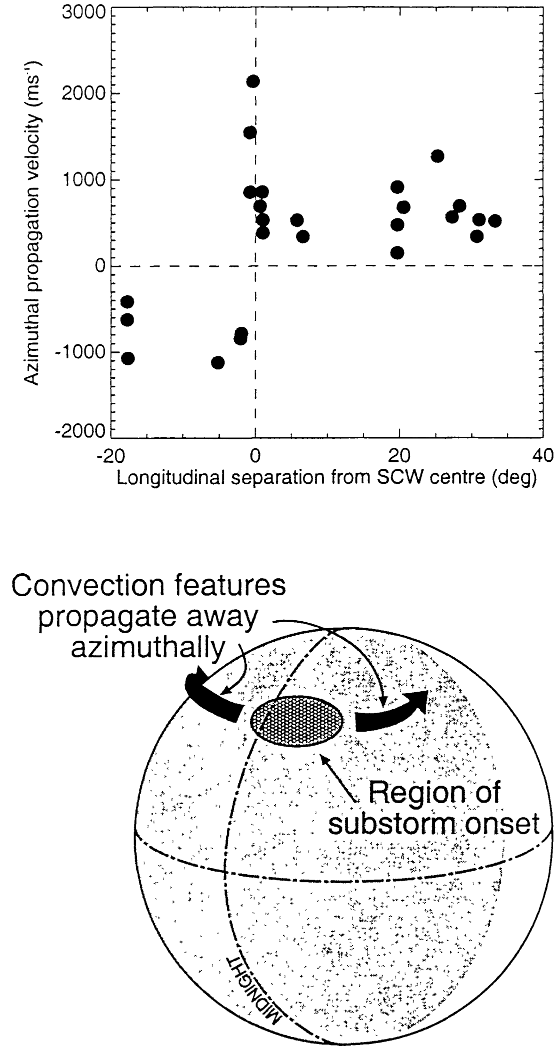

Figure 7: (a) The relationship between azimuthal propagation velocity for APVCs and the longitudinal separation from the region of substorm onset. Positive velocities indicate eastward propagation (b) Schematic representation of the propagation of APVCs away from the region of substorm intensification.

In that case *Geotail* lay displaced considerably from local midnight, towards dawn and thus did not see classical BBF activity. Additional examples of high speed plasma flows have subsequently been reported in this region by Nakamura *et al.* (1999). The deceleration of high speed Earthward plasma flow has been related to an onset mechanism for the near-Earth substorm phenomena by Shiokawa *et al.* (1997), although this view remains controversial (Lui *et al.*, 1999). If the behaviour of these decelerating flows in the near-Earth tail is indeed important for the substorm process, the study of their ionospheric footprint may provide key information on this most intriguing element of the substorm. The observed APVC events share similarities in occurrence with respect to substorm phase, duration and repetition rates with other ionospheric phenomena also associated with BBFs, such as north-south aurora (Henderson *et al.,* 1998) and poleward boundary intensifications (Lyons *et al.*, 1999). However the azimuthal motion which characterises APVCs has not previously been noted with these phenomena. Future multi-instrument studies should enable the relationship between these various phenomena to be established. APVCs notably have not often been detected before or immediately after the substorm expansion phase onset. This may be an instrumental effect: observations immediately after the expansion phase onset are often hampered by HF radar data loss, due to either HF absorption or propagation changes, or a loss of the ionospheric irregularities which provide targets for the radar systems. The timing and location of the APVCs may, however, have important implications for the substorm process.

Future developments of the HF radar technique should help address these issues. HTR radar modes are now run more commonly, and developments such as the artificial backscatter technique (e.g. Wright and Yeoman, 1999) will allow for increased time resolution and electric field accuracy, and improved data coverage of substorm intervals.

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