SuperDARN observations of ionospheric convection during magnetospheric substorms

A. Grocott and T. K. Yeoman

Abstract: The coupled nature of the magnetosphere-ionosphere system makes measurements of ionospheric convection, such as those provided by the SuperDARN HF radars, extremely useful in diagnosing magnetospheric dynamics. Flux Transfer Events (FTEs) at the dayside magnetopause, for example, are well-resolved in ionospheric flow data as Pulsed Ionospheric Flows (PIFs). Similarly, Bursty Bulk Flows (BBFs) associated with the earthward transport of flux in the tail have a discernable flow signature in the nightside ionosphere. The large-scale convection associated with magnetospheric substorms is also readily identifiable in ionosphere flow data. During the growth phase, for example, the expansion of the polar cap due to enhanced open flux production is evidenced in the equatorward motion of radar backscatter. On the nightside, fast equatorward flows emanating from the polar cap after substorm onset, followed by a poleward contraction of the flow reversal boundary, provide evidence for tail reconnection and the closure of open flux. The complex electrodynamics associated with substorms, however, ensures immense variety in the nature of the flow signatures which are observed. Some studies, for example, have reported a reduction in the nightside flows at the time of substorm onset, possibly resulting from enhancements in auroral conductivity associated with substorm energetic particle precipitation which imposes a limit on the size of the local electric field. Enhanced electric field phenomena such as Substorm-Associated Radar Auroral Surges (SARAS) and Auroral Westward Flow Channels (AWFC) provide additional constraints on the global substorm picture. This paper provides an overview of these and other important convection signatures associated with substorms and briefly discuss how future developments of SuperDARN can further enhance our understanding of substorm physics.

Key words: SuperDARN, Convection.

1. Introduction

Magnetospheric substorms are a major contributing factor to large-scale magnetosphere-ionosphere dynamics and give rise to some of the most significant auroral and magnetospheric disturbances that occur in the terrestrial system. As a consequence they have been extensively studied over the past 40 years and many aspects of their large-scale behaviour are now very well understood. Early studies of substorm current systems identified two distinct patterns of ionospheric currents [5]. The first of these, referred to as DP-2 (disturbance polar of the second type), corresponds to the twin-vortex current pattern driven by magnetospheric convection, and the resulting eastward and westward convection electrojets in the dawn and dusk auroral zones. This current system is associated with a substorm growth phase in which energy extracted from the solar wind is stored in the magnetosphere [33]. During this interval an enhancement in magnetospheric and ionospheric convection, being driven by reconnection at the dayside magnetopause, causes an increase in the size of the polar cap and a growth in the convection electrojets. The second pattern, DP-1, corresponds to the ionospheric portion of the substorm current wedge and takes the form of an enhanced westward current in the midnight sector auroral zone called the substorm electrojet [1]. This current system is governed by enhancements in conductivity rather than in the electric field [27] and as such it is not representative of the flow. HF radars, however, make direct measurements of the ionospheric convection and are therefore able to observe the electric field during all phases of a substorm. This paper presents a review of HF radar studies which have contributed to our current understanding of substorm physics.

2. SuperDARN

The Super Dual Auroral Radar Network (SuperDARN) is an international array of HF coherent radars spanning the auroral regions of both the northern and southern hemispheres [16]. At the present time, the northern hemisphere network consists of ten radars and the southern hemisphere network consists of seven. In standard operating mode, SuperDARN scans through 16 beams of azimuthal separation 3.24°, producing the full fields-of-view shown in Fig. 1 (the grey field-of-view is that of the first mid-latitude StormDARN radar, discussed below). Each radar dwells for 3 or 7 seconds on each beam, along which line-of-sight measurements of the convection velocity are obtained, with a full scan therefore taking either 1 or 2 minutes. Large-scale maps of the high-latitude convection can be derived from these measurements using the ‘Map Potential’ model [42]. In this model the line-of-sight velocities are mapped onto a polar grid and used to determine a solution for the electrostatic potential which is expressed in spherical harmonics. The equipotentials of the solution then represent the plasma streamlines of the modelled convection pattern. Information from a statistical model [41], parameterised by concurrent IMF conditions, is used to stabilise the solution where no measurements are available.

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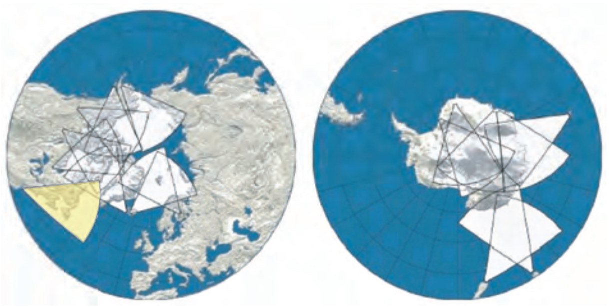

Fig. 1. Fields-of-view of the northern (left) and southern (right) hemisphere SuperDARN HF radars

3. Growth Phase Convection

Whilst there are various phenomena associated with growth phase intervals, the primary effect leading to an expansion phase onset is the addition of open flux to the magnetotail lobes via reconnection at the dayside magnetopause. Flow is then excited as this newly reconnected flux is distributed around the polar cap, which consequently expands equatorward. Shown in Fig. 2 is a latitude-time-velocity plot of SuperDARN data, grey-scaled to velocity either towards (positive) or away (negative) from the radar's location (from [28]). The vertical line indicates the time of substorm onset, prior to which the radar scatter can be seen to have moved to lower latitudes as the polar cap expanded. Observations such as these are common during substorm growth phases, and fairly straightforward to interpret. As can be seen, however, after substorm onset the nature of the scatter changes - in places it actually disappears - and in general interpretation of the data becomes a lot more complicated, and to a certain degree, more interesting.

4. Expansion Phase Observations

Although there is still much to be learned about the complex nature of substorm electrodynamics, the basic flow features associated with the expansion phase were revealed by one of the earliest studies using HF radars [35]. These features are illustrated in the example of Fig. 3, which shows the local convection pattern derived from SuperDARN data during the evolution of a substorm [48]. The top panel shows the pre-onset conditions, which consist of a nominal twin-cell convection pattern. Then, just after onset (2nd panel) a suppression of the flow becomes evident at the location of the substorm bulge, with faster flows being diverted around the sides. About 10 minutes into the expansion phase (3rd panel) the twin-vortex pattern reappears as the falling conductivity 'frees up' flux which can be convected away.

As was mentioned earlier, in addition to the suppression of flow, there is sometimes a loss of data altogether during the substorm expansion phase. This was investigated by a number of studies and was found to be due to absorption of the HF radio signal by the enhanced electron densities in the precipitation region [34]. Whilst observing the expansion phase using HF radars can therefore prove problematic, there are often large areas of radar scatter still present in the vicinity of the substorm disturbed region which can reveal much about the electrodynamics. In the example presented in Fig. 4, a number of substorm cycles are shown (onsets marked with the vertical dashed lines) where there are continuous data over much of the interval [47]. Between 2130 and 2200 UT there was evidence of an ongoing growth phase, with scatter continuing to expand equatorward. After this time, between 2200 and 2230 UT, a clear poleward motion of the scatter is evident, implying a contraction of the polar cap, presumably due to the removal of open flux by tail reconnection.

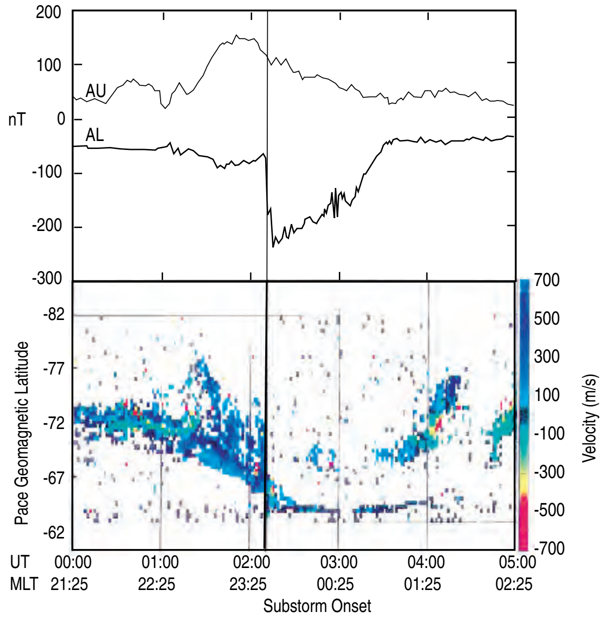

Fig. 2. Line-of-sight SuperDARN radar data illustrating the equatorward motion of backscatter during the substorm growth phase, from [28]

4.1. Large-scale Convection

The ability to combine observations from a large number of radars makes SuperDARN ideally suited to investigating large-scale convection. Following earlier work on boundary motions and flows [40, 44, 13] it was supposed that significant large-scale twin-vortex flows should be excited during substorms, corresponding in essence to the DP-2 current systems associated with dayside-driven convection cited above [6]. Observations have been reported of surges of transpolar flow into the midnight sector associated with a substorm intensification, which it was suggested were due to bursts of reconnection in the tail [12]. Analyses of SuperDARN flow data obtained during isolated substorms have also been presented, that found evidence for the excitation of twin-vortex flow cells centred in the nightside ionosphere, which enhance the transpolar voltage by ∼40 kV compared with pre-onset values [17, 18]. This is illustrated in Fig. 5, which shows maps of the northern hemisphere high-latitude convection before (top panel) and after (bottom panel) the onset of a substorm. The excitation of flow (e.g. longer vectors on the bottom map) and enhanced voltage are clearly evident. Following this work, a statistical study of substorm flows was conducted which also revealed enhancements across the polar cap and in the low-latitude return flow region during the expansion phase [39]. A systematic increase in the transpolar voltage from ∼40 kV 2 minutes before on-

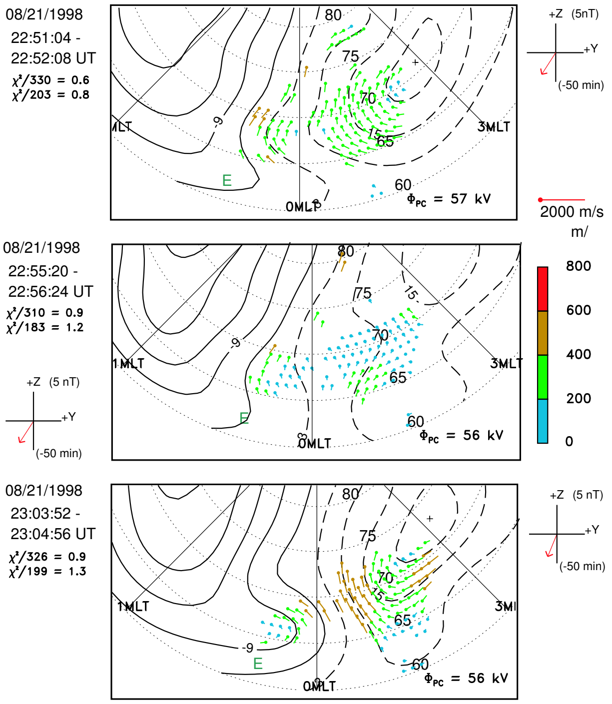

Fig. 3. SuperDARN convection maps showing the development of substorm flows, from [48]

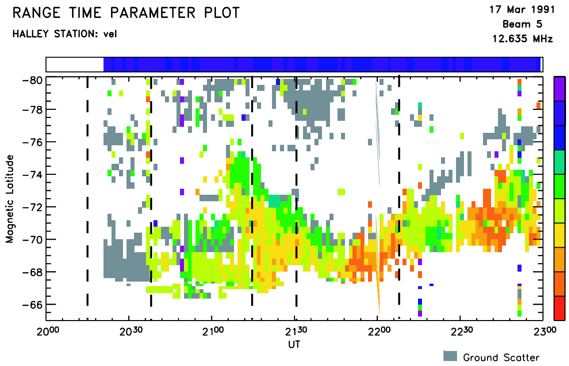

Fig. 4. SuperDARN line-of-sight velocity data showing the development of the ionospheric flows during a number of substorm cycles, from [47]

set to ∼75 kV 12 minutes after was also found, and this was attributed to the removal of open flux from the polar cap by nightside reconnection.

Other studies of the ionospheric response to substorms have suggested that convection enhancements occur simultaneously across the ionosphere, with an imposed electric field affecting the global current systems. For example, measurements of the electric field response some 90° of longitude away from the onset region have revealed enhancements coincident with onset [36]. In contrast to this, observations of a global reduction in ionospheric convection at the time of substorm onset have also been reported [32]. This reduction occurred in concert with a northward turning of the IMF, however, which is something often found to precede a substorm onset and will itself cause a reduction in the solar wind driven flows. If no direct evidence of substorm driven flows is observed by SuperDARN on the nightside, then the level of global convection will indeed appear to be reduced. Recent studies of the dayside convection response to substorms, which occurred during steady IMF conditions such that changes in the level of solar wind driven convection are not apparent, have indeed revealed enhancements in the convection, beginning about 10-15 minutes after the time of substorm onset observed by ground magnetometers [25].

Finally, recent work has discussed the possibility of two distinct flow systems in the substorm convection pattern [29, 26]. The first is a post-midnight anticlockwise convection vortex (PoACV) at higher latitudes and the second is an azimuthally extended clockwise vortex at lower latitudes. These are explained in terms of a combination of the nightside reconnection driven twin-vortex flows and those resulting from field line slippage processes associated with dipolarisation [30].

4.2. Mesoscale Convection Features

Whilst it is thus becoming clear that large-scale electric fields play a significant role in the electrodynamics of the substorm expansion phase, it is also apparent that mesoscale phenomena are integral to the substorm process. For example, azimuthally-localised impulsive events have been observed in which auroras are first intensified at the poleward boundary of the nightside auroral zone, and then expand equator-

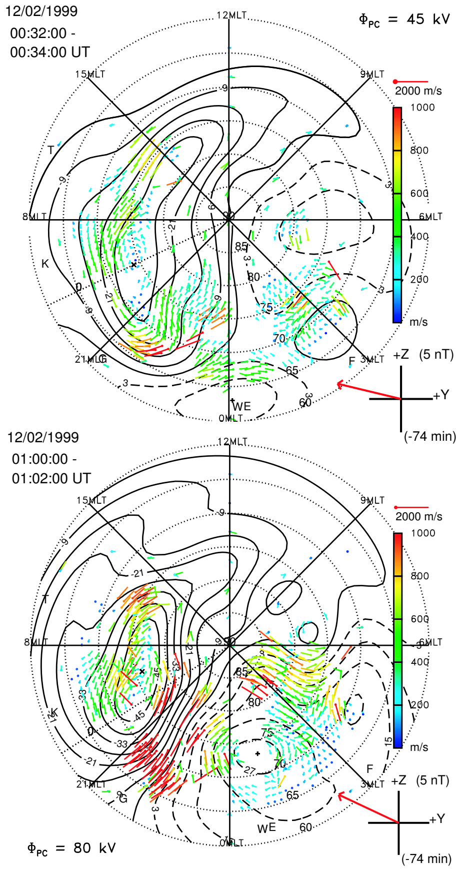

Fig. 5. SuperDARN convection maps showing the pre-onset flows (top) and expansion phase flows (bottom) during an isolated substorm, from [18]

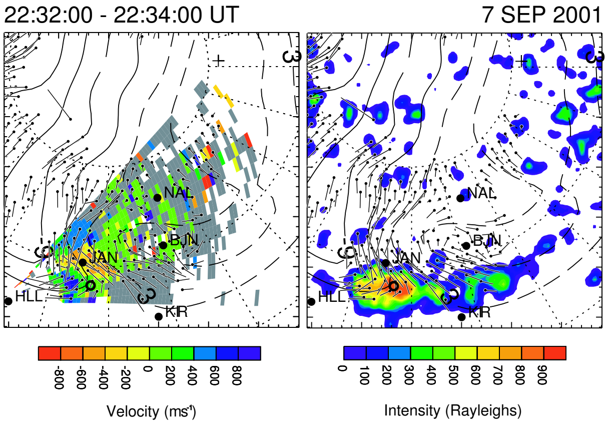

Fig. 6. SuperDARN line-of-sight radar data and IMAGE FUV auroral data of the ionospheric signature of a Bursty Bulk Flow, from [20]

ward, reaching to near the equatorward boundary of the oval emissions after ∼5 min [23]. These events, termed ‘poleward boundary intensifications’ (PBIs) [31], have been found to occur in all phases of the substorm cycle, including during long intervals of magnetic quiet, though they appear to be more frequent during substorm expansion phases. They are associated with azimuthally-localised ‘bursty bulk flows’ (BBFs) in the near-Earth plasma sheet [3, 4] and the excitation of flow in the ionosphere [9, 46, 20, 21]. These features are strongly suggestive of the occurrence of localised impulsive reconnection in the tail [7, 8]. Pseudobreakups, occurring during substorm growth phase, have also been associated with BBFs [20] and have been shown to accompany significant enhancements in the nightside flux closure rate [24].

The ionospheric counterpart of a BBF which occurred during a pseudobreakup in the course of a substorm growth phase, about 10 min after a southward turning of the IMF and ∼50-60 min before a major expansion phase onset, was recently studied in some detail [20]. This was the first study showing both the ionospheric flow pattern and the auroral activation associated with the simultaneous observation of a flow burst in the magnetosphere. Ionospheric observations during the flow event observed by the CUTLASS radars (the eastern most pair of SuperDARN) and the FUV auroral imager on the IMAGE spacecraft are shown in Fig. 6. A small, negative excursion in the X component of the magnetic field with an amplitude of 10 nT and some Pi2 activity, were observed at ground stations close to the footprint of Cluster during the BBF (not shown). Clear signatures associated with the BBF are observed in the ionospheric flow obtained by CUTLASS, as well as in the auroral precipitation pattern in the IMAGE UV data.

An extended study of the ionospheric signatures of BBFs and their relationship to the substorm cycle is currently being undertaken (e.g. [21]) and some examples are shown in Fig. 7. The top example shows the signature of a BBF observed during the recovery phase of a substorm. As can be seen in the figure, this BBF occurred in association with a poleward boundary intensification and was accompanied by an enhancement in the auroral zone flows. The middle panel shows the flow signature of a BBF which occurred during an interval of northward IMF. Here, the flow pattern developed into an azimuthal configuration, which has been previously related to tail reconnection under the continued influence of IMF By [19, 22]. In the bottom panel, the flows associated with a BBF that occurred during a small (∼100 nT) substorm are shown and appear to take the form of enhanced return flow in the dawn convection cell. Observations such as these require further investigation if we are to fully understand the role of BBFs in magnetospheric flux transport.

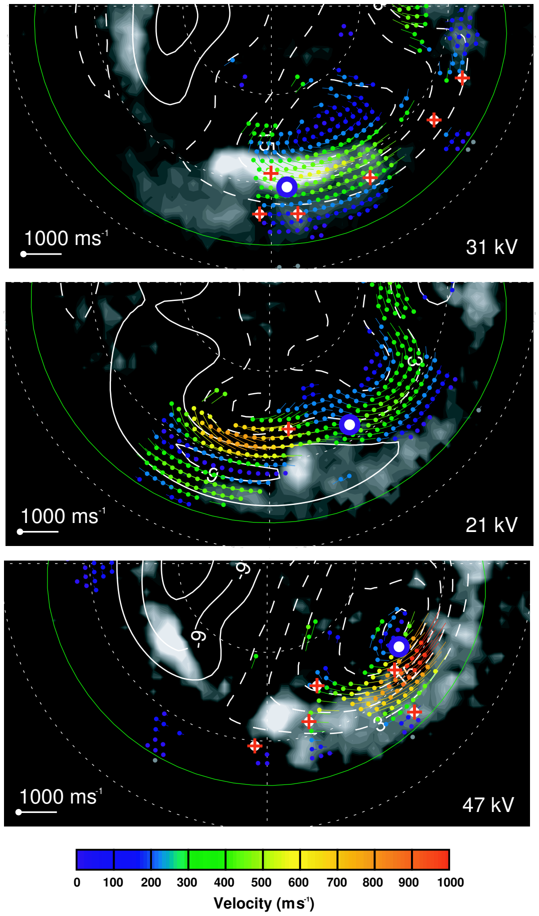

Fig. 7. SuperDARN convection maps with superimposed IMAGE FUV auroral data showing the ionospheric signature of a selection of Bursty Bulk Flows.

Another series of substorm related phenomena believed to drive magnetospheric circulation are the polarisation jets (PJs) [15], or sub-auroral ion drifts (SAIDs) [45]. PJ/SAIDs are fast (1 - 4 km s^{-1}) narrow (1 - 2°) channels of westward plasma flow which occur just equatorward of the equatorward edge of the auroral oval in the evening sector. Related phenomena identified in radar data include substorm-associated radar auroral surges (SARAS) [14, 43] and auroral westward flow channels (AWFCs) [37, 38]. AWFCs, however, have been observed to appear any time between substorm onset and recovery [38] whereas PJ/SAIDs identified in satellite data appear during recovery [2]. The term ‘sub-auroral polarisation stream’ (SAPS) is used to encompass all of these phenomena [10], which includes broader (3 - 5°), weaker (100 - 400 m s^{-1}), background

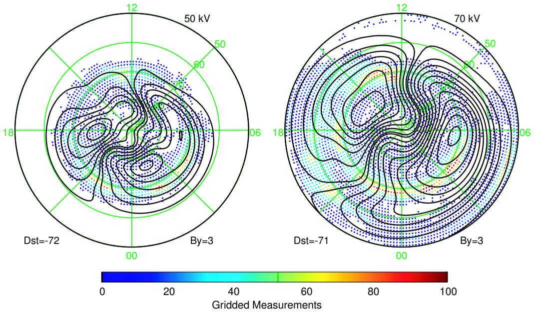

Fig. 8. An illustration of the effect on the SuperDARN convection patterns of including data from the mid-latitude radar on Wallops Island. The shaded areas indicate gridded radar measurements (courtesy, Jo Baker).

flows which persist beyond midnight into the predawn sector. These sub-auroral electric fields play critical roles in energising and transporting ring current ions as well as convecting thermal plasma in the inner magnetosphere and mid- to low-latitude ionosphere [11].

5. StormDARN

Finally, it is worth briefly mentioning the future of SuperDARN, called StormDARN, which consists of a series of mid-latitude radars, ultimately extending SuperDARN coverage down to about 40° north. One such radar is already in operation (shown in grey on Fig. 1) on Wallops Island. Data from this radar have been used to produce the illustration shown in Fig. 8, which reveals the effect on the convection pattern of adding in lower-latitude data. It is clear that during active times, when substorms generally occur, these new radars will be essential if we are to fully observe the substorm disturbed region.

6. Summary

There is little doubt that HF radar observations, such as those provided by SuperDARN discussed above, have revealed much about substorms and substorm-related phenomena. What is still yet to be achieved, however, is an overall synthesis of these observations which is essential if we are to fully understand the role of substorms in coupled magnetospheric-ionospheric dynamics. Clearly, the multi-instrument, multi-scale approach afforded to us by current Cluster-SuperDARN studies and by the advent of Themis, KuaFu, and StormDARN, is our passport to a more complete understanding of substorm physics.

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