High-time resolution radar observations of high-latitude flows during an isolated substorm

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Abstract. On 21st August 1998 the IMF underwent a southward turning after approximately 20 hours of northward orientation. Shortly after this southward turning a substorm occurred in the Scandinavian sector situated at ~01:00 MLT. Instrumental coverage during this substorm was particularly favourable with both radars of the CUTLASS pair operating in a high-time resolution discretionary mode. In addition, the EISCAT Svalbard and the mainland VHF EISCAT incoherent scatter radars were operational with the beams of both being encompassed by the CUTLASS field-of-view. During the substorm recovery phase regions of poleward ionospheric flow reaching ~800 m s^{-1} were observed to propagate towards the pole at speeds of ~1100 m s^{-1}. The electric and magnetic structure of these features are characterised and their significance to substorm recovery phase processes discussed.

1. Introduction

Although usually less dramatic than the substorm expansion phase, the recovery phase is nevertheless associated with significant auroral activity, such as morning sector omega bands (Opgenoorth *et al.*, 1994; Wild *et al.*, 2000). Ionospheric conditions during the recovery phase are particularly suitable for coherent HF radar observations since extensive areas can be observed at high temporal and spatial resolution without suffering from the serious loss of backscatter associated with expansion phase onset (Milan *et al.*, 1996). Furthermore, by combining observations of ionospheric plasma motion from several radar systems providing coverage of many hours of magnetic local time it is possible to make estimates of the large-scale high-latitude ionospheric convection pattern (e.g. Ruohoniemi and Baker, 1998).

Incoherent scatter radars are able to provide a much more extensive range of directly measured or inferred ionospheric parameters than coherent scatter systems (Rishbeth and Williams, 1985) however their fields-of-view are, in general, much more restricted. Consequently, coincident coherent and incoherent observations complement each other most favourably, the combination yielding excellent measurements of the overall ionospheric configuration in addition to detailed ionospheric observations at several key locations (e.g. Milan *et al.*, 1999). This paper presents the preliminary results of such a

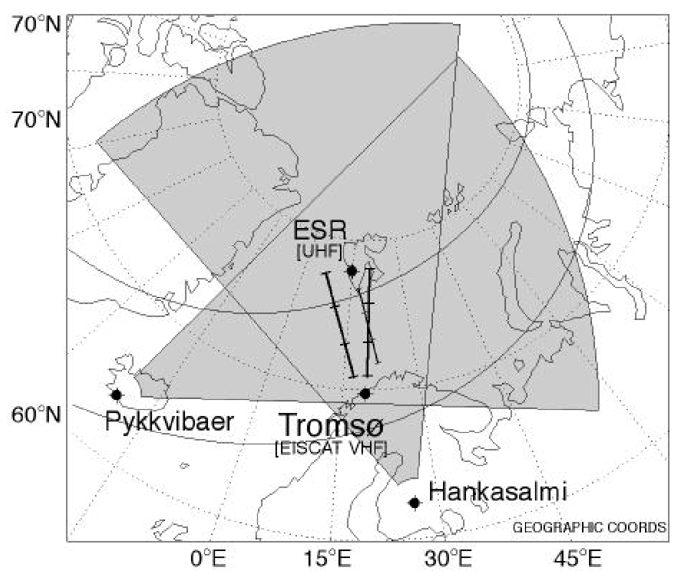

Figure 1. Locations and fields-of-view of the CUTLASS radars (*shaded areas*) and the approximate directions of EISCAT Tromsø VHF radar beams and the ESR UHF radar beam (*crossed heavy lines*). The statistical location of the auroral oval (Feldstein and Starkov, 1967) for K_P=3 is also included.

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combined coherent/incoherent study of aurora-associated ionospheric flows during the recovery phase of an isolated magnetospheric substorm.

2. Instrumentation

The Co-operative UK Twin-Located Auroral Sounding System (CUTLASS) is a bi-static HF coherent radar with stations in Hankasalmi, (Finland) and Pykkvibær (Iceland) as shown in Figure 1. CUTLASS makes up the easternmost pair of radars of the international SuperDARN chain (Greenwald *et al.,* 1995). Between 00 UT on 20th August 1998 and 00 UT on 25th August 1998 both of the CUTLASS radars were operating in a high-time resolution, camped beam mode (6 s resolution on beam 9).

During this interval the European Incoherent Scatter (EISCAT) radars were implementing the UK special program SP-UK-CSUB over 4-hour intervals between 21-01 UT each evening. The EISCAT Svalbard Radar (ESR) beam was pointing southward with a geographic azimuth of 161.6° and an elevation of 31.0°. The ESR is a UHF system and was transmitting a multi-frequency long pulse during this experiment providing observations over the altitude range 110-500 km.

The EISCAT VHF system located at Tromsø was operating in a split beam mode during the SP-UK-CSUB experiment. One beams was directed along the boresight corresponding to a geographic azimuth of 359.5° whilst the other was phased westward to point at an azimuth of 345.0°. Both beams were elevated 30° from horizontal. The VHF system transmits both power profile and long pulse codes the latter of which provides observations over an altitude range beginning at ~ 280 and extending to over 1000 km. Data from both the Tromsø VHF radar and the ESR UHF system have been analysed at 10 s resolution for this study.

Finally, data from the Magnetic Fields Investigation (MFI) instrument on board the *Wind* spacecraft (Lepping *et al.*, 1995) have been employed in order to characterise the IMF conditions prevailing during the interval under scrutiny.

3. Observations

On 21st August 1998 the *Wind* spacecraft was located at co-ordinates 80,-33, -5 R_E (*X, Y, Z,* GSE). The observed solar wind velocity at this time was ~ 300 km s^{-1} implying that a propagation delay of ~ 33 minutes to the subsolar magnetopause is appropriate. The IMF had been oriented northward for ~ 20 hours prior to 20:25 UT and the IMF B_Y component had been positive for ~ 4 hours. At 20:25 UT (~20:58 at the magnetopause) both the B_Y and B_Z components abruptly switched polarity (Figure 2). Assuming an additional 2 min delay for the effect of the IMF reorientation to reach the ionospheric footprint of the subsolar magnetopause and 15 min for the resulting reconfiguration of the ionospheric convection pattern to expand to the nightside (Cowley and Lockwood, 1992), the effects of the southward turning would be expected to reach the nightside ionosphere at ~21:15 UT. Over the next several hours the IMF orientation could be broadly classified into the 4 regimes indicated in Figure 2.

Figure 3 presents line-of-sight (l-o-s) backscattered power and Doppler velocity from the Finland radar as a function of magnetic latitude and universal time. Observations of the equatorward motion of the equatorward boundary of HF radar backscatter began at ~ 21:40 UT, a characteristic that has previously been associated with the substorm growth phase (Lewis *et al.*, 1997).

At 22:50 UT, Pi2 pulsations are clearly observed at mid-latitude stations of the IMAGE magnetometer array (not shown) indicating the expansion phase onset (Rostoker *et al.*, 1980). The Pi2 pulsation burst coincides with a strong negative bay in the *X* component auroral magnetograms indicating a substorm-enhanced westward electrojet. The onset is then observed to propagate poleward reaching ~ 74° magnetic latitude by 23:18 UT.

At ~ 22:50 UT there is a marked reduction in backscatter observed by the CUTLASS Finland radar that extends to over 10° of magnetic latitude by ~ 23:20 UT. This loss of backscattered signal is frequently observed during the substorm expansion phase and is a result of D-region absorption of the radar signal due to energetic

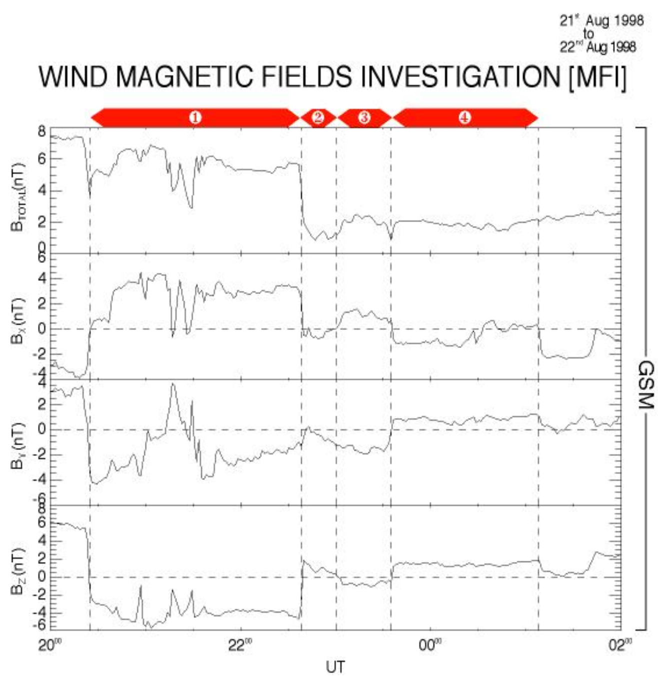

Figure 2. IMF B_{TOTAL}, B_X, B_Y, and B_Z components in GSM co-ordinates as observed by the *Wind* spacecraft between 20:00 UT on 21-8-98 and 02:00 UT on 22-8-98. Intervals referred to in the text are bounded by *vertical dashed lines*.

particle precipitation (Milan *et al.*, 1996; . Milan *et al.*, 1999).

The complex flows that arise due to the expansion phase onset during this interval are the subject of a study by Yeoman *et al.* (2000) and will therefore not be discussed in detail here. By ~ 23:45 UT ionospheric backscatter was again observed over a comparable latitudinal range to that prior to onset.

At 00:32 UT a region of flow located at ~ 73° with a l-o-s component directed away from the radar (≤ 800 m s^{-1}) begins to drift poleward. This poleward motion encompasses ~ 7° over the subsequent 8 min, equivalent to a poleward propagation velocity of some 1100 m s^{-1}. Ground magnetometers in close proximity to the location of the backscatter feature observed only very weak (~ 10 nT), short-lived perturbations during its poleward motion (not shown).

Figure 4 presents electron density, electron temperature, ion temperature and l-o-s ion velocity observation from beam 2 (359.5° geographic azimuth) of the EISCAT VHF radar. Prior to the 22:50 UT substorm onset EISCAT observations suggest that the ionosphere is relatively undisturbed. Equatorward drifting arcs (most clearly visible as enhancements in the electron and ion temperature) were observed prior to 22:30 UT. There is excellent agreement between observations from the CUTLASS Finland and EISCAT radars during the growth phase. The southward migration of the equatorward flow region (colour-coded blue) immediately prior to onset is particularly clear in both Figures 3 and 4.

Beginning at ~00:30 UT, a region of poleward ion flow (≤ 800 m s^{-1}) is observed to propagate polewards over 6° of magnetic latitude at a velocity comparable with poleward moving feature observed by the CUTLASS radar. This feature is also associated with a depletion in the electron density, a weak enhancement of the electron

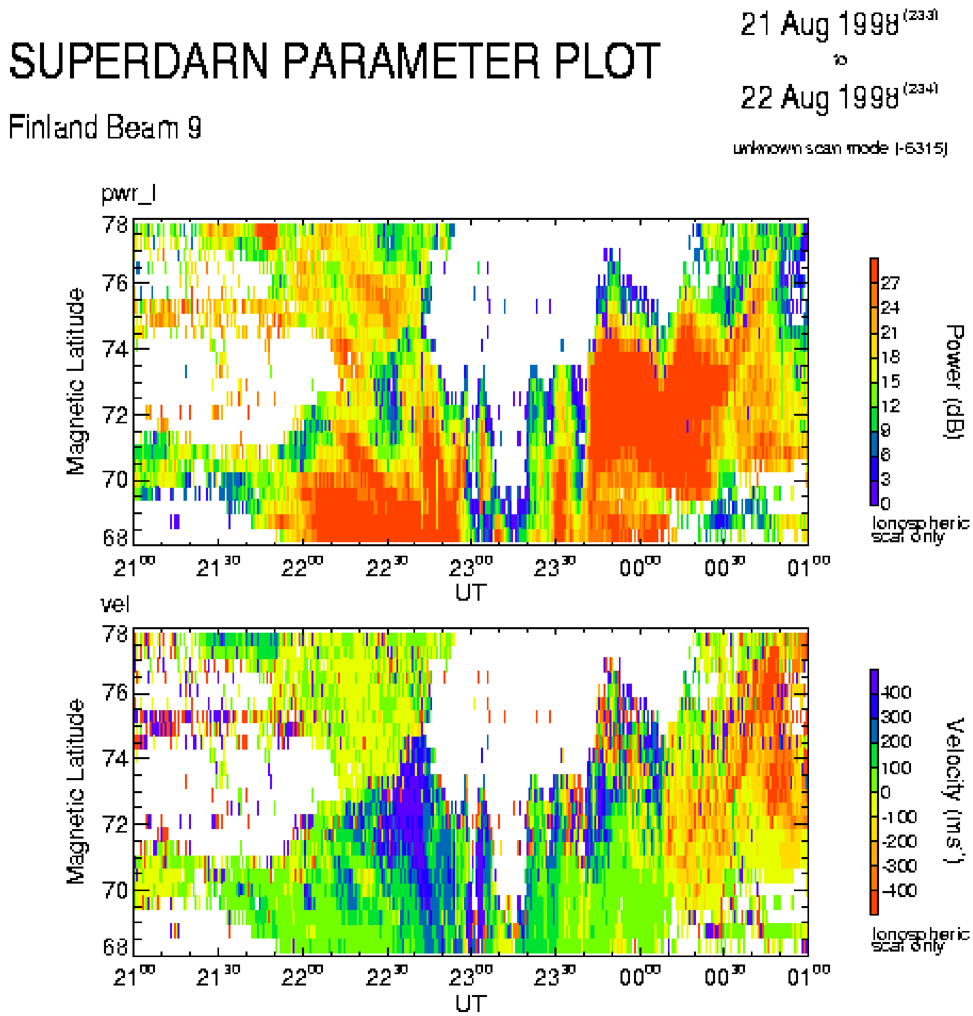

Figure 3. Line-of-sight backscattered power (*upper panel*) and ionospheric Doppler velocities (*lower panel*) observed by the CUTLASS Finland radar plotted as a function of magnetic latitude and universal time. Velocities are colour-coded with *blue* representing flows toward the radar (approximately equatorward since the presented beam is aligned almost meridionally) and *red* representing flows away from the radar (approximately poleward).

temperature and a strong enhancement of the ion temperature. The agreement in timing, flow speed and apparent motion of the CUTLASS and EISCAT observation presented are interpreted as simultaneous observations of a single ionospheric feature.

4. Discussion

In order to more clearly study the evolution of the backscatter feature observed by the CUTLASS Finland radar, Figure 5 presents three scans of l-o-s velocity data.

Prior to the observations of strong poleward flows, at 23:59 UT (Figure 5, left hand panel) the majority of the ionospheric backscatter lies inside the statistical auroral oval. Within the oval, a strong eastward zonal flow dominates with the l-o-s flow component directed toward the radar in the west of the field-of-view and away in the east.

By 00:44 UT (Figure 5, centre panel) this zonal flow has weakened considerably. The region of poleward flow has clearly migrated poleward, now lying at ~78°

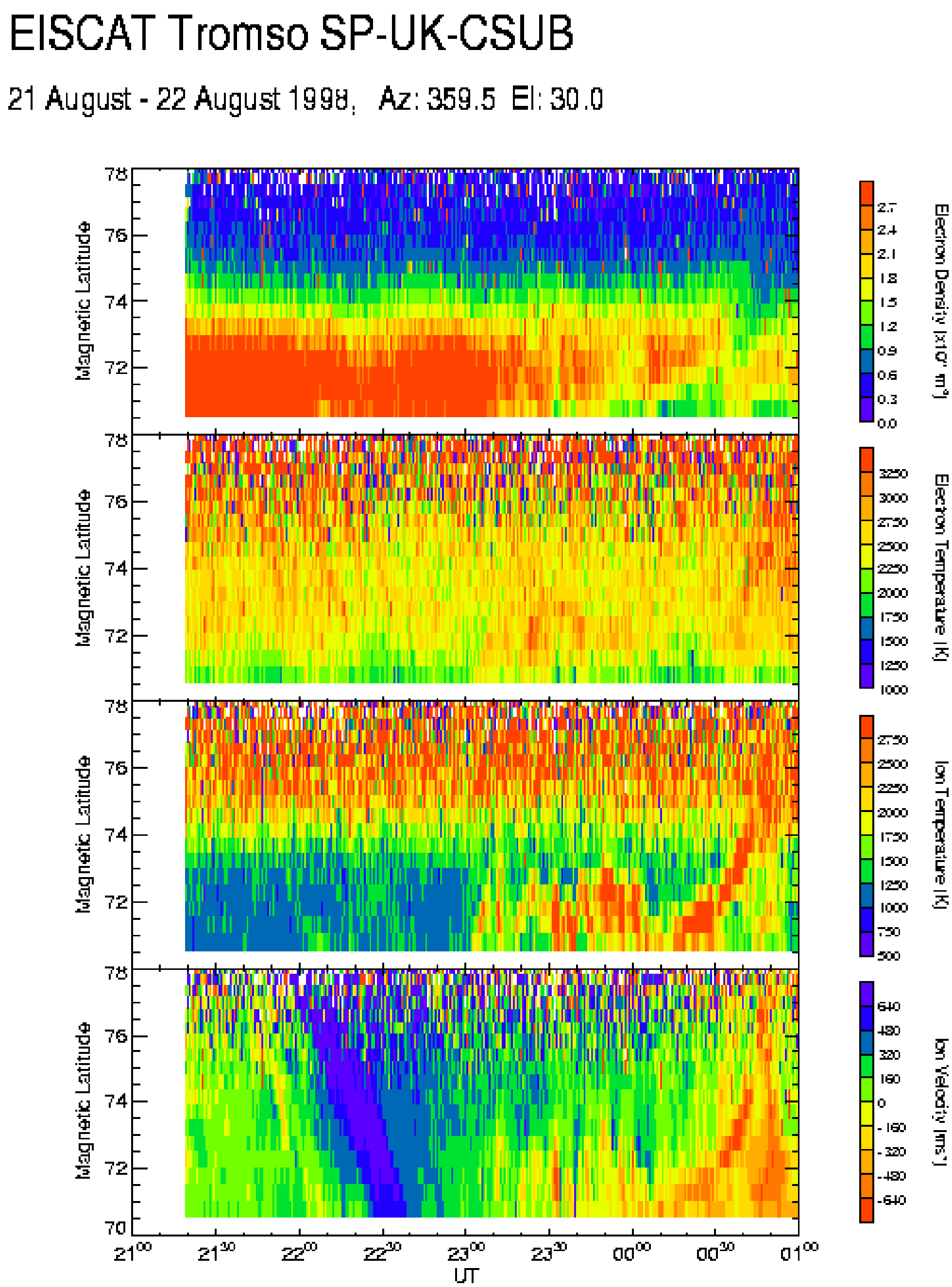

Figure 4. EISCAT VHF observations of electron density, electron temperature, ion temperature and ion velocity plotted as a function of magnetic latitude and universal time. Velocity colour codes are consistent with those for CUTLASS observations (Figure 3)

magnetic latitude. Although truly 2-dimensional bistatic Doppler velocities are not available (the CUTLASS Iceland radar observed significantly less backscatter during this interval than CUTLASS Finland) an estimate of the 2-dimensional flow can be made using a beamswinging technique (Villain *et al.*, 1987; Ruohoniemi *et al.*, 1989). This technique (not presented) reveals a poleward turning of the zonal flow in the eastern portion of the field-of-view away from east and into the polar cap.

The poleward extending prominence is still apparent some 20 min later (Figure 5, right hand panel) extending from the poleward edge of the expected auroral oval position toward the magnetic pole.

The faint enhancement of electron temperature observed by the EISCAT system is comparable to that in the equatorward drifting arcs observed earlier in the interval suggesting that the poleward moving feature may in fact be an auroral arc of some kind. The strong enhancement of ion velocity results in ion frictional heating as indicated in the 3 panel of Figure 4. This increase in ion temperature implies an increase rate of recombination in the ionosphere leading to the reduction in the electron density observed (Figure 4, top panel). Careful examination of the comparative timing of the parameters observed by EISCAT reveals that the enhanced ion velocity feature at ~00:30 UT leads the observation of faint electron temperatures enhancement slightly.

These observations are consistent with the relative motion of an auroral arc into the beam of the EISCAT radar (Fox *et al.*, 2000). The observations of strong flows at the boundary are indicative of the strong electric fields often observed at the boundary of an auroral arc (Opgenoorth *et al.*, 1990). This is followed by an observation of enhanced electron temperature, suggesting of electron precipitation occurring inside the arc.

The observations presented are similar to those of Milan *et al.* (1997) although summer conditions implied that no optical observations were available during the interval presented here. Milan and co-authors suggested that the arc was similar to either horse-collar or theta aurora both of which are common in B_Z positive conditions (e.g. Hones *et al.*, 1989).

In order to confidently determine the absolute motion of the proposed arc structure it will be necessary to study the additional 15 beams of the CUTLASS Finland radar as well as the remaining EISCAT beams and make a comparative timing study of the observed motion of the feature in each beam. Examination of auroral imager data from space based instruments will also yield a clearer interpretation of the spatial and spatial evolution of this arc structure.

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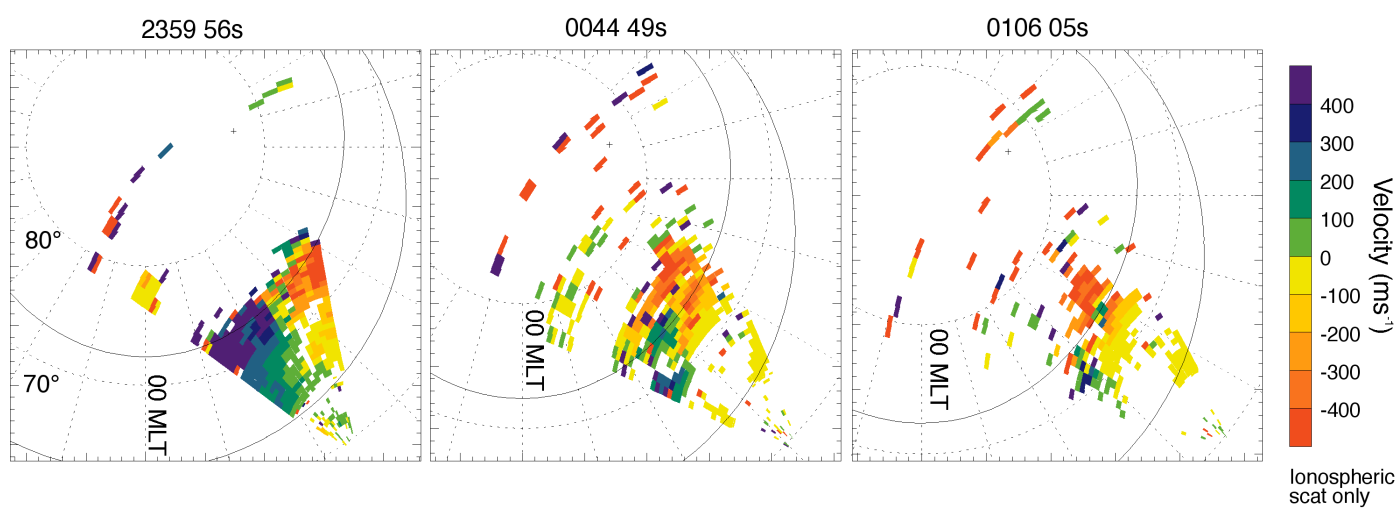

Figure 5. Scans of line-of-sight Doppler velocity observations made by the CUTLASS Finland radar. All panels are presented in a common polar format, *dashed lines* indicate lines of magnetic latitude and MLT. The location of the geographic pole is indicated by a *black cross.* The *solid curves* show the statistical position of the auroral oval for K_P=3 (Feldstein and Starkov, 1967).

References

Cowley, S. W. H., and M. Lockwood, Excitation and delay of solar wind-driven flows in the magnetosphere-ionosphere system, *Ann. Geophysicae,* **10**, 103, 1992.

Feldstein, Y. I., and G. V. Starkov, Dynamics of auroral belt and polar geomagnetic disturbances, *Planet. Space. Sci.*, **15**, 209, 1967.

Fox, N. J., S. W. H. Cowley, J. A. Davies, R. A. Greenwald, M. Lester, M. Lockwood, and H Lühr, Ionospheric ion and electron heating at the poleward boundary of a poleward-expanding substorm-disturbed region, *J. Geophys. Res.*, in press, 2000.

Greenwald, R. A., K. B. Baker, J. R. Dudeney, M. Pinnock, T. B. Jones, E. C. Thomas, J.-P. Villain, J. –C. Cerisier, C. Senior, C. Hanuise, R. D. Hunsucker, G. Sofko, J. Koehler, E. Nielsen, R. Pellinen, A. D. M. Walker, N. Sato, and H. Yamagishi, Darn/SuperDARN: a global view of the dynamics of high-latitude convection, *Space Sci. Rev*, **71,** 761, 1995.

Hones, E. W., J. D. Craven, L. A. Frank, D. S. Evans, and P. T. Newell, The horse-collar aurora – a frequent pattern of the aurora in quiet times, *Geophys. Res. Lett.*, **16**, 37, 1989.

Lepping, R. P., M. H. Acuna, L. F. Burlaga, W. M. Farrell, J. A. Slavin, K. H. Schatten, F. Mariani, N. F. Ness, F. M. Neubaur, Y. C. Whang, J. Byrnes, R. S. Kennon, P. V. Panetta, J. Scheifele, and E. M. Worley, The Wind magnetic field investigation, *Space. Sci. Rev.*, **71**, 207, 1995.

Lewis, R. V., M. P. Freeman, A. S. Rodger, G. D. Reeves, and D. K. Milling, The electric field response to the growth phase and expansion phase onset of a small substorm, *Ann. Geophysicae*, **15**, 289, 1997.

Milan, S. E., T. B. Jones, M. Lester, E. M. Warrington, and G. D. Reeves, Substorm correlated absorption on a 3200 km trans-auroral path HF propagation path, *Ann. Geophysicae,* **14**, 182, 1996

Milan, S. E., M. Lester, and J. Moen, A comparison of optical and coherent HF radar backscatter observations of a post-midnight aurora, *Ann. Geophysicae.*, **15** 1388, 1997.

Milan, S. E., J. A. Davies, and M. Lester, Coherent HF radar backscatter characteristics associated with auroral forms identified by incoherent radar techniques: A comparison of CUTLASS and EISCAT observations, *J. Geophys. Res.*, **104,** 22,591, 1999.

Opgenoorth, H. J., I. Häggström, P. J. S. Williams, and G. O. L. Jones, Regions of strongly enhanced perpendicular electric fields adjacent to auroral arcs, *J. Atmos. Terr. Phys.*, **52**, 449, 1990.

Opgenoorth, H. J., M. A. L. Persson, T. I. Pulkkinen, and R. J. Pellinen, Recovery phases of magnetospheric substorms and its association with morning sector aurora, *J. Geophys. Res*, **99**, 4115, 1994.

Rishbeth, H., and P. J. S. Williams, The EISCAT Ionospheric radar: the system and its early results, *Q. Jl. R. astr. Soc*, **26**, 478, 1985.

Rostoker, G., S. –I. Akasofu, J. Foster, R. A. Greenwald, Y. Kamide, K. Kawasaki, A. T. Y. Lui, R. L. McPherron, and C. T. Russell, Magnetospheric substorms – definitions and signatures, *J. Geophys. Res.*, **85**, 1663, 1980.

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

Ruohoniemi, J. M., R. A. Greenwald, K. B. Baker, J. –P. Villain, C. Hanuise, and J. Kelly, Mapping High-Latitude Plasma Convection with Coherent HF radars, *J. Geophys. Res.*, **94**, 13,463, 1989.

Villain, J. –P., R. A. Greenwald, K. B. Baker, and J. M. Ruohoniemi, HF Radar Observations of *E* Region Plasma Irregularities Produced by Oblique Electron Streaming, *J. Geophys. Res.*, **92**, 12,327, 1987.

Wild, J. A., T. K. Yeoman, P. Eglitis, and H. J. Opgenoorth, Multi-instrument observations of the electric and magnetic field structure of omega bands, *Ann. Geophysicae*, **18**, 99, 2000.

Yeoman, T. K., J. A. Davies, N. M. Wade, G. Provan, and S. E. Milan, Combined CUTLASS, EISCAT, and ESR observations of an isolated substorm, *Ann. Geophysicae,* in press 2000.