RAPID GLOBAL RECONFIGURATION OF THE HIGH-LATITUDE IONOSPHERE ON 24 NOVEMBER 1996: AN OBJECTIVE METHOD FOR DETERMINING CONVECTION CHANGE

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ABSTRACT

Whether the high-latitude ionosphere responds gradually (~10 min) or "instantaneously" (<2 min), or both, to changes in the coupling between the solar wind and magnetosphere is an outstanding problem. It can be difficult determining exactly when a significant convection change has occurred, if at all, in measurements which are essentially non-stationary time series data with an additional random (noise) component. Here we present an independent, objective method of determining if, and when, significant changes have occurred in ionospheric measurements. The method is applied to the HF backscatter radar data recorded on 24 November, 1996 [1], and confirms a coherent large-scale convection change occurred nearly "instantaneously" (2–4 min) over at least 11 hours of local time. Our simple analysis method can also be applied to similar problems when there is uncertainty about whether time series data has undergone a significant change.

INTRODUCTION

Numerous observations (e.g., [2] to [6]) have suggested that reconfiguration of the large-scale high-latitude ionospheric convection pattern occurs gradually (~10 min), propagating away from the noon sector cusp at phase speeds in the order of ~1–10 km s^{-1}. More recent observations (e.g., [7], [8]) also suggest the same, in accordance with important theoretical concepts [9], [10].

However, some other recent observations ([1], [11] to [16]) suggest the global-scale reconfiguration of the high-latitude convection pattern can occur far more rapidly than previously thought (2–4 min). This has led to the suggestion that convection changes are communicated throughout the high-latitude ionosphere by fast-mode Alfvén waves [1], or electromagnetic waves ducted in the Earth-ionosphere waveguide [17].

The scientific debate has become polarised [18], [19], but we need to remain open-minded about all of the possible frequency-dependent response times that might occur in the coupled ionosphere-magnetosphere system. Table 1 summarises four conceivable mechanisms for communicating high-latitude convection changes. They include the "very slow mechanism" (i.e., convection & neutral wind speeds), the "slow mechanism" (i.e., the Cowley-Lockwood picture) [9], [10], the "fast mechanism" (i.e., Alfvénic speeds) [1], and the "ultra fast mechanism" (sub-light speeds) [17].

Fig. 1 is a cartoon representing the broad spectrum of possible response times. The time scale is logarithmic and commences at t=0. System responses are considered to be perturbations in the convection electric fields, $\Delta E_{\perp}$, and velocities, $\Delta v_{\perp}$. The initial response is "zero order" in that t=0 corresponds to the instant when the response commences, yet no detectable perturbation exists. The response becomes observable when it has risen above some threshold corresponding to the envelope of "measurement noise" (defined later). In this case, dayside reconnection was considered to be the system driver; hence the initial zero-order response commenced in the ionospheric cusp near 14 MLT. However, when nightside reconnection is the driver, the initial response might occur near 24 MLT.

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Table 1. Possible mechanisms communicating high-latitude convection changes.

"VERY SLOW MECHANISM"
(1) "Ionospheric convection:" Transport of changing electrodynamic conditions at *F*-region convection speeds of ~200 m s^{-1} to 2 km s^{-1} (typically ~500 m s^{-1}).
"SLOW MECAHNISM"
(2) "The Cowley-Lockwood mechanism:" Propagation of reconnection signature at magnetosheath speeds (~100 km s^{-1}) mapping to propagation around the ionospheric open-closed boundary at phase speeds of ~2 km s^{-1} to 10 km s^{-1} (typically ~6 km s^{-1}).
"FAST MECHANISM"
(3) "Magnetosonic propagation:" Transport of large-scale electric field changes (not transient perturbations) at Alfvénic speeds in the topside *F*-region and inner magnetosphere, e.g., $V_A = B_0/(\mu_0 \rho_0)^{1/2}$ >820 km s^{-1} [1].
"ULTRA FAST MECHANISM"
(4) "Earth-ionosphere wave guide:" Redistribution of large-scale electric potential at sub-light (<300,000 km s^{-1}) via spatially and temporally variable wave guides formed by the conducting Earth and ionosphere [17]. Analogous to spherical capacitor plates.

Fig. 1 presents a variety of curves specifying the linear growth of electric field perturbations at 14 MLT (brown). Whilst only four curves are shown, conceivably an infinite number of curves and growth rates may exist depending on the communication mechanism (Table 1), and variability in the particular geophysical conditions which modify the time constants (e.g., variability in ionospheric conductivity). Fig. 1 also presents a variety of curves specifying the linear growth of electric field perturbations at 24 MLT (green). Again, a complete spectrum of response times may occur. However, we might expect these responses to be more dispersed, and weaker, than in the noon-sector ionosphere, thus explaining the diverse observations.

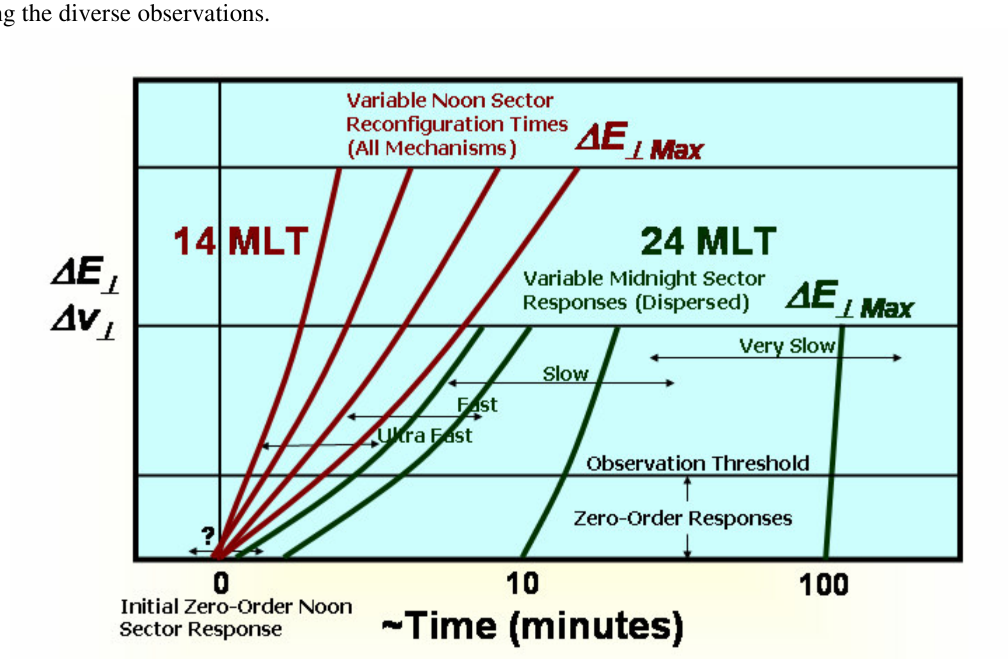

Fig. 1. Pluralistic view of response times for changes in the large-scale ionospheric convection. The linear growth of electric field perturbations at 14 MLT are shown in brown, and the delayed, linear growth of electric field perturbations at 24 MLT are shown in green.

Anyone of the mechanisms listed in Table 1 and illustrated in Fig. 1 might become especially important depending on the particular state of the system. Also, we need to consider the possibility of highly non-linear responses for the coupled ionosphere-magnetosphere system. Modellers are presently attempting to reconcile the two basic regimes of response time [10], [20], but radical new insights are required.

As well as considering all of the theoretical possibilities, it is important to question the interpretation of different observations, if only to establish whether they represent special cases. For example, time series of measurements recorded with networks of ionospheric and magnetospheric probes can be thought of as complex, multi-dimensional, and non-stationary random data. It is important to develop and apply objective, independent analysis methods to identify if, and when, significant changes have occurred. Here we develop just such a method, and exercise it on the multi-dimensional HF backscatter radar observations recorded on 24 November 1996 [1]. Our simple method confirms that a coherent large-scale convection change occurred nearly "instantaneously" (2–4 min) during this particular event.

INSTRUMENTS

The HF backscatter radar observations analysed here were recorded with elements of the Super Dual Auroral Radar Network (SuperDARN) [21], [22]. All radars within this network have uniform design, operation, and data archiving procedures, thereby facilitating co-ordinated studies of the high-latitude ionosphere on global scales. Descriptions of the SuperDARN radars are given in [21], [22], and literally hundreds of other papers. We only provide a brief description of radar operations during the chosen study interval.

During 24 November 1996, the SuperDARN radars were operating in the routine "common mode" of operation. The radars integrated for 7 s on each of 16 beams, sequentially scanning from beam 0 (the western-most beam) to beam 15 (the eastern-most beam). New scans occurred on the minute boundary every two minutes. The radar beams were separated by 3.24°, thereby providing an azimuthal scan of ~52°. Echoes were recorded on each beam at 75 ranges starting at 180 km and separated by 45 km (i.e. 180 to 3510 km). The FITACF algorithm [23] analysed the echoes to provide estimates of the backscatter power expressed as a signal-to-noise ratio (dB), the line-of-sight (LOS) Doppler velocity (m s^{-1}), and the Doppler velocity spread, or "spectral width" (m s^{-1}).

The SuperDARN radars which were operating and providing potentially useful data are listed in Table 2. Their location in the altitude adjusted corrected geomagnetic (AACGM) coordinate system [24] is also given.

ANALYSIS METHOD

Consider any non-stationary time series data with an additional random (noise) component superimposed. For example, Fig. 2 shows a time series of LOS Doppler velocity (fluctuating black curve) recorded on beam 0 of the Saskatoon (SAS) radar at range 2340 km during 20:00 to 22:00 UT on 24 November 1996. Common sense might indicate the most significant long-term change commenced somewhere near 21:12 UT. Whether significant changes occurred at other times is not so clear. Our aim is to determine whether any of the changes, in particular the change at 21:12 UT, were statistically significant.

Table 2. SuperDARN radars recording useful ionospheric scatter on 24 November 1996

Name(s)	Abbreviation	Geographic Coordinates	AACGM Coordinates
Saskatoon	SAS	106.5°W, 52.2°N	45.3°W, 61.3°N
Kapuskasing	KAP	82.3°W, 49.4°N	9.22°W, 60.1°N
Goose Bay	GOS	60.5°W, 53.2°N	23.0°E, 61.9°N
Halley Station	HAL	26.6°W, 75.5°S	28.9°E, 61.7°S
Stokkseyri (Iceland West)	STK	22.0°W, 63.9°N	67.3°E, 65.0°N
Þykkvybær (Iceland East)	PYK	19.2°W, 63.9°N	69.7°E, 64.6°N
Hankasalmi	HAN	26.6°E, 62.3°N	105.5°E, 59.8°N

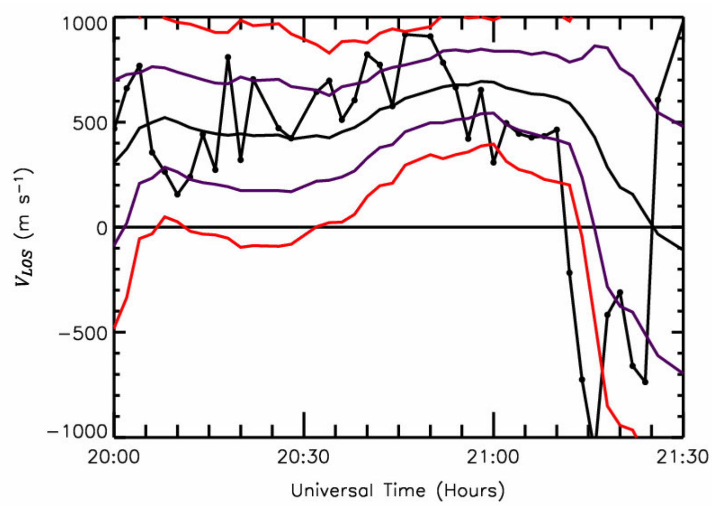

Fig. 2. Time series of line-of-sight Doppler velocities recorded on beam 0 of the Saskatoon (SAS) radar at range 2340 km during 20:00 to 21:30 UT on 24 November 1996. The fluctuating black curve connecting the solid black dots represent the actual measurements, whereas the smoother continuous black curve represents the running mean of the preceding 30 min of observations. The purple curves represent ±one standard deviation of the noise fluctuations about the running mean, and the red curve is the same except for ±two standard deviations. Notice these curves do not closely follow the upswing in measurements at the end of the record because it is defined by a single preceding data point.

The numerous fluctuations superimposed on the long-term trends constitute high frequency "measurement noise." This noise is the independent superposition of two components: (1) "instrumental noise" associated with poor signal-to-noise ratio combined with limitations of the pulse set and FITACF algorithm, and (2) "geophysical noise." The latter is a novel concept in which we admit to our ignorance about the specific causes of countless fluctuations in the state of the system being measured (in this instance, the ionosphere). Complete elimination of instrumental and geophysical noise might require deployment of a prohibitive number of scientific instruments with unlimited time resolution, as well as a perfect understanding of the causal mechanisms, an unattainable goal.

We begin by defining the time interval over which the system driver is thought to be stationary, ΔT. If fluctuations in the system driver are effective in changing the state of the system on time scales comparable to the sampling interval of measurements, t_s, then every change in one time series element, x_{i-1}, to the next, x_i, might be significant. However, usually we take measurements at a much faster rate than changes in the system driver, and the high frequency fluctuations constitute measurement noise. To determine whether individual data points have undergone a statistically significant change, we calculate the average, $<x_{i\Delta T}>$ and standard deviation, $\sigma_{i\Delta T}$, of the measurements over the preceding interval ΔT. That is, we calculate an average and standard deviation for all x_i using samples in the range $i-\Delta T/t_s$ to $i-1$. We then calculate the difference between x_i and $<x_{i\Delta T}>$, and finally normalise it with respect to $\sigma_{i\Delta T}$.

Hence the amplitude of the difference between the current data point and the average of the preceding data points is normalised with respect to the standard deviation of the preceding data points. The preceding data points are chosen from some plausible, predefined time interval consistent with the physical behaviour of the system driver. Thus we have a continuous test for the significance of a fluctuation in the time series. Keeping the predefined time interval constant with respect to all subsequent data points would test for the significance of changes with respect to that fixed epoch. By necessity, the former approach was adopted in this study.

If the fluctuations belong to a Gaussian distribution, and the change is only one standard deviation, it is probably not statistically significant. This is because ~68% of all samples lie within ±one standard deviation. On the other hand, ~95% of all samples lie within ±two standard deviations; hence if the magnitude of the change exceeds $2\sigma_{i\Delta T}$, a statistically significant change may have occurred. Strictly, the data should be tested to see if it approximates to a Gaussian distribution, otherwise the threshold of significance will change. In fact, we know the velocity fluctuations observed by SuperDARN radars are not Gaussian [25], and this has implications for complexity science beyond the scope of this paper. However, the principle of the method is the same, and no doubt larger normalised differences imply more significant changes.

For convenience, hereafter we will refer to the normalised differences as the “change” measured in standard deviations. We will also refer to the calculation method and closely related variants as the “change method.”

RESULTS

In this example, variability in the interplanetary magnetic field (IMF) is considered to be the system driver. Major changes affecting the behaviour of the coupled ionosphere-magnetosphere are assumed to re-occur on time scales >30 min; hence we use ΔT=30 min. Whilst numerous high frequency fluctuations in the IMF do occur, major transitions between the IMF pointing northward and southward usually re-occur on time scales >30 min. These major IMF transitions are well known to regulate the magnetic reconnection rate, and thus produce major changes in the high-latitude convection pattern. Nevertheless, keep in mind that from the point of other convection drivers, many of the lesser fluctuations which occur on shorter time scales may represent significant changes.

Fig. 3 shows the IMF data recorded on board the Wind spacecraft during 19:00 to 22:00 UT on 24 November 1996. This 3-sec resolution data reveals a major, sudden transition in B_z from +6 to –7 nT commenced near 20:43 UT. Variations in the B_z component are well known to drive the greatest changes in high-latitude convection. Transitions in the B_y component, which influences the symmetry of the convection pattern via the Svalgaard-Mansurov effect, are also important, but here the variations in the B_y component were relatively minor and gradual. Variations in the B_x component drive relatively minor changes in the convection pattern.

Note that the earliest preceding switch in the direction of B_z finished near 19:20 UT, well over an hour before the transition at 20:43 UT, thus supporting the choice of ΔT=30 min. Significant but relatively minor changes in the high-latitude convection were probably influenced by IMF variations on time scales <30 min, but our 30-min running averages will reduce the significance of these changes in the final results.

The Wind spacecraft was located ~73 Earth radii up stream of the Earth at the time of the major B_z southward turning. Using the representative solar wind speed of 450 km s^{-1}, and a basic method of advecting transitions in the solar wind, the ionospheric arrival time should have been shortly after 21:00 UT, and not 21:12 UT as was observed. However, the errors involved in estimating the advection time for a solar wind probe located so far upstream are sometimes ~10 min or more.

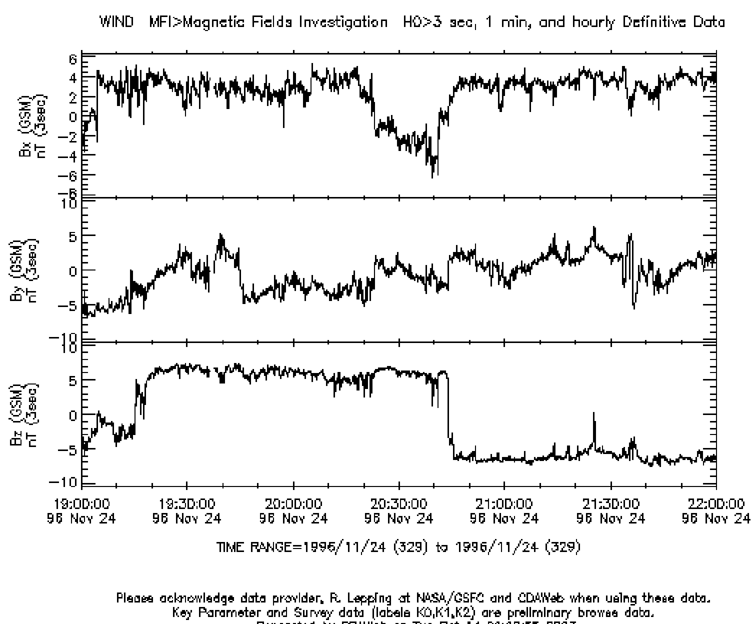

Fig. 3. Wind spacecraft measurements of the IMF B_x, B_y, and B_z components recorded at 3 sec resolution during 19:00 to 22:00 UT on 24 November 1996.

Fig. 4 shows the results of applying the change method to all the SuperDARN radar data recorded during the full-scans commencing 21:10 UT on 24 November 1996. The radars measure the LOS Doppler velocity (and other parameters) in up to 1200 pixels per full scan (16 beams × 75 ranges). Hence there are potentially 1200 time series per radar field-of-view (FOV). However, continuous ionospheric scatter is usually observed in a fraction of the pixels. The present implementation of the change method estimates an average and standard deviation as long as two or more valid samples were recorded during the preceding pre-defined time window, ΔT=30 min. Thus a lack of continuity in the ionospheric scatter may produce "edge effects," namely anomalous changes whenever scatter commences. Also, isolated values of change $>2\sigma_{i\Delta T}$ should not be considered. On the other hand, regions of change $>2\sigma_{i\Delta T}$ persisting over several beams, range gates, and scans should be considered.

In Fig. 4, the radar FOVs have been mapped within a standard polar plot format consisting of magnetic local time (MLT) and AACGM latitude. The results for SAS (13 MLT), GOS (18 MLT), and PYK (21 MLT) are shown in the top panel, and the results for KAP (16 MLT), HAL (18 MLT), and STK (21 MLT) are shown in the bottom panel. The MLT in brackets gives the location of the radar to the nearest hour of MLT. By design, some of the radar FOVs cross over each other (e.g., SAS and KAP), or are magnetically conjugate (GOS and HAL). Hence the radar FOVs have been separated into two groups to minimise the number of overlapping pixels. Lastly, the results for HAN are not shown because we felt the small amount of scatter detected was of limited use.

The results shown in Fig. 4 were for the full scans commencing at 21:10 UT, one scan period prior to when the major, sudden transition in B_z began to affect the ionosphere. Fig. 4 results are also representative of results recorded during other full scans prior to 21:10 UT. Note that the pixels are dominated by green colours ($-1.2\sigma_{i\Delta T}$ < change $\leq 1.2\sigma_{i\Delta T}$), implying most of the fluctuations were typical of those occurring during the previous 30 min. However, there are a few regions where the colour of the pixels represent change $>2.0\sigma_{i\Delta T}$ (grey-blue, purple, and black) and change $<-2.0\sigma_{i\Delta T}$ (orange, crimson, brown). Whilst most of the isolated pixels are due to measurement noise, there are a few spatially continuous regions in the SAS (13 MLT) and HAL (16 MLT) radar FOVs which suggest a significant change might have commenced.

Fig. 5 shows the change results for the full scan commencing at 21:12 UT. They reveal a large, sudden noon-sector response to the southward turning of B_z. A spatially extended region with change $< -3.6\sigma_{i\Delta T}$ (brown) occurred on SAS beams 0 and 1 (12–13 MLT and ~81°Λ). The negative sign means that the LOS Doppler velocities became more negative, or more away from the radar; hence the velocities became more anti-sunward. On the other hand, an extended region with change $>1.2\sigma_{i\Delta T}$ (blue) developed to the east of this region, on SAS beams 4 to 12. There were also regions of large change throughout the FOV of KAP, on the eastern beams of GOS (18–19 MLT, ~68°Λ), and even the magnetically conjugate eastern beams of HAL in the Southern Hemisphere. As reported in [1] there is evidence that significant velocity change occurred in the western beams of PYK (22 MLT, ~72°Λ). The least evidence of change was observed in the nearest range gates of STK, possibly because any velocity change was orthogonal to the radar beams.

Fig. 6 shows the change results for the full scan commencing at 21:14 UT. They reveal a consolidation of most of the changes which began during the previous two-minute interval. However, some of the changes became slightly weaker (KAP) or stronger (HAL). The changes occurring in the nightside ionosphere, as observed on the western beams of PYK, were now especially strong ($>3.6\sigma_{i\Delta T}$). This suggests an additional two-minute delay for the nightside ionosphere.

The significance of the changes generally decreased in a gradual way throughout the radar FOVs in subsequent two-minute intervals. This is confirmed by Fig. 7 which shows the change results for the full scan commencing at 21:20 UT. Significant change was ongoing, but most of it had subsided to well below the $3.6\sigma_{i\Delta T}$ level. This is 8 min after the first two-minute interval revealing unambiguous evidence of large-scale convection change. Hence 8 min is an estimate of the time scale required to consolidate the final convection pattern.

Finally, the number of pixels with ionospheric scatter generally increased throughout the time sequence, Figs. 4 to 7. Enhanced electric fields associated with the convection change may have stimulated ionospheric irregularity production [16], [26].

The change method can also be applied to the backscatter power, spectral widths, and elevation angles measured by the radars to reveal further aspects of the electrodynamics.

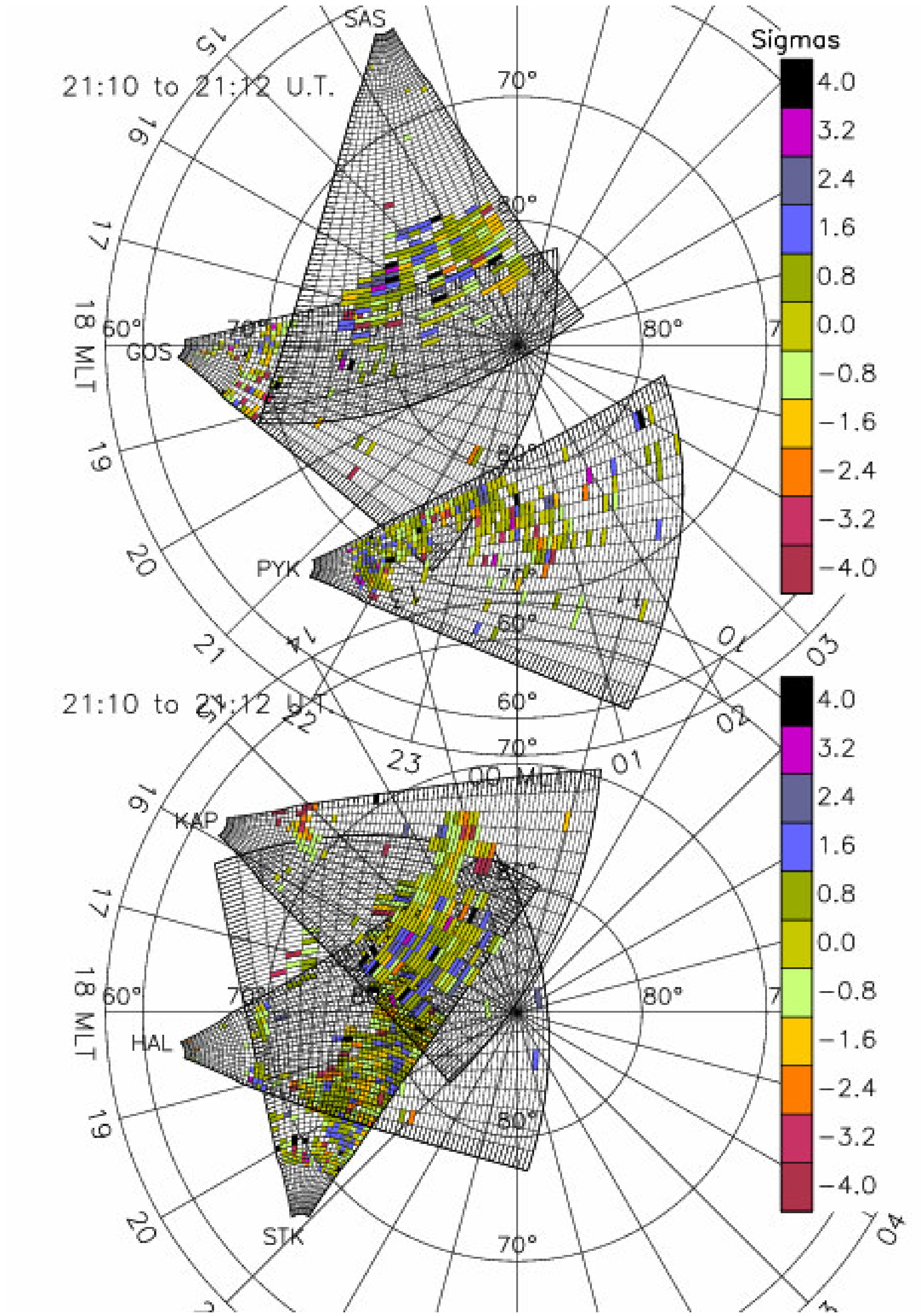

Fig. 4. Statistical significance of changes in the LOS Doppler velocity for full scans commencing at 21:10 UT on 24 November 1996. The results are shown for six SuperDARN radars (top panel: SAS, GOS, PYK; and bottom panel: KAP, HAL, STK). The colour scale represents Doppler velocity changes normalised by the standard deviation of fluctuations about the running mean, $\sigma_{i\Delta T}$. For example, blue-grey pixels ($2.4\sigma_{i\Delta T}$) actually include all changes >2.0 and $\leq 2.8\sigma_{i\Delta T}$.

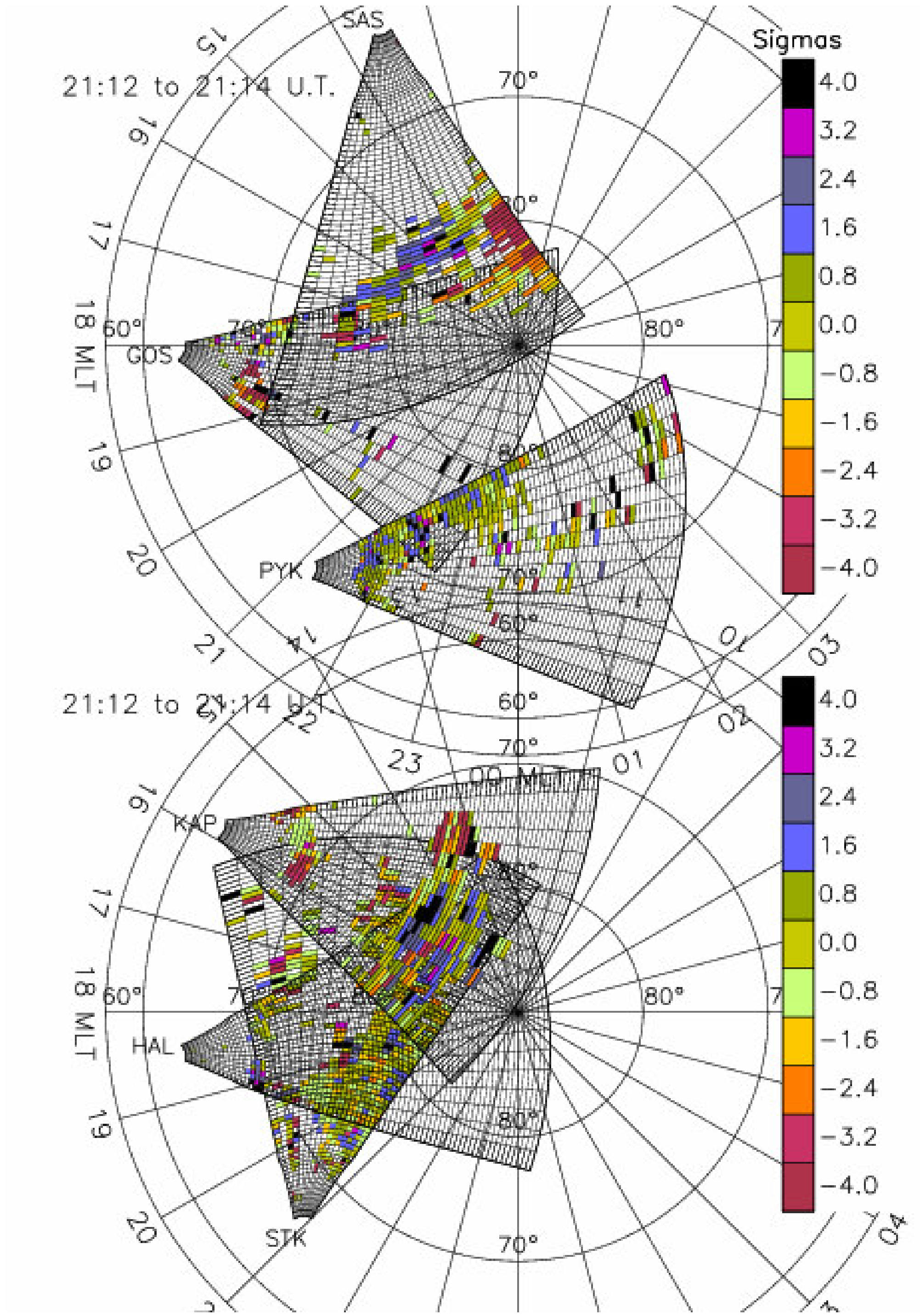

Fig. 5. Statistical significance of changes in the LOS Doppler velocity for full scans commencing at 21:12 UT on 24 November 1996.

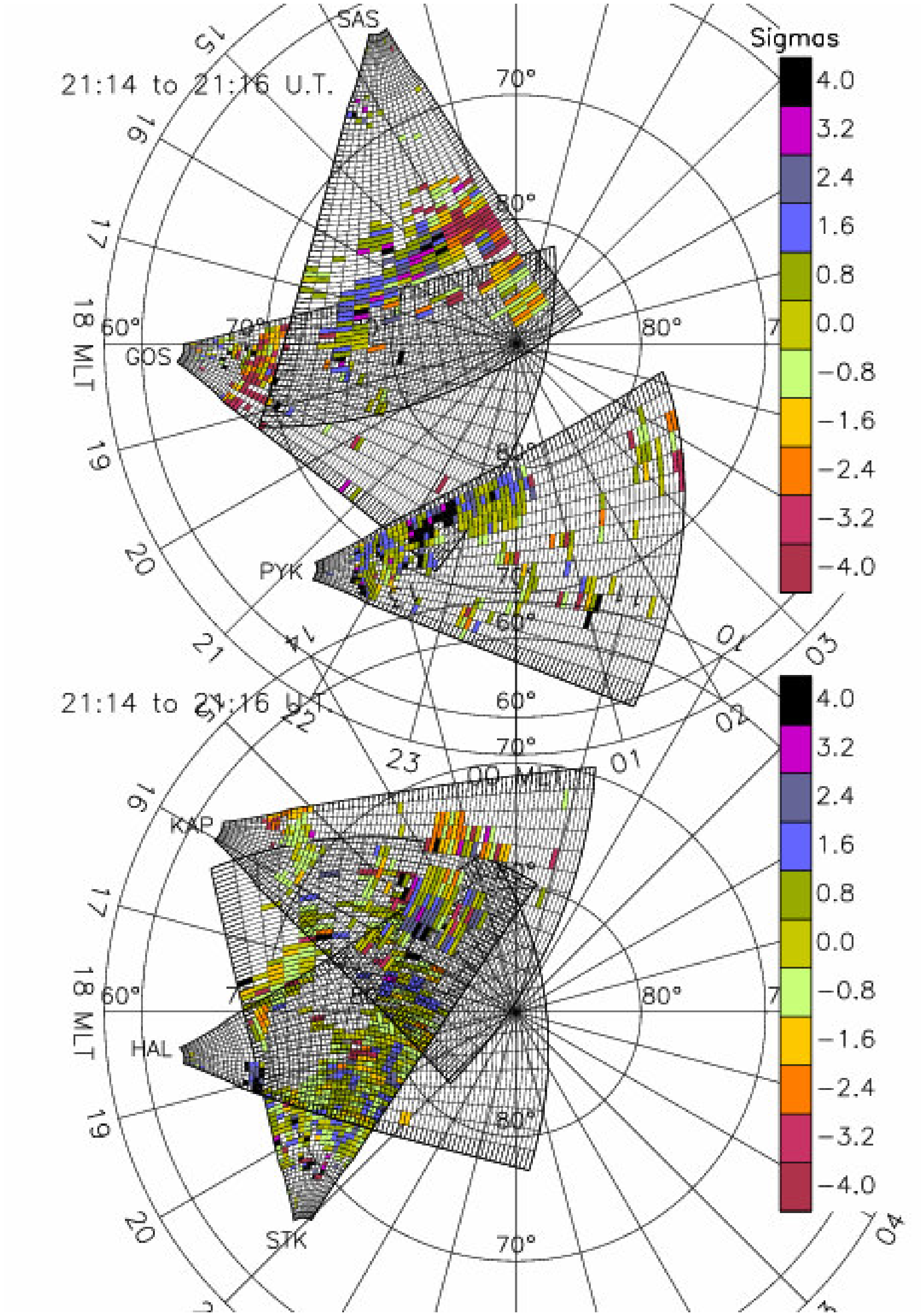

Fig. 6. Statistical significance of changes in the LOS Doppler velocity for full scans commencing at 21:14 UT on 24 November 1996.

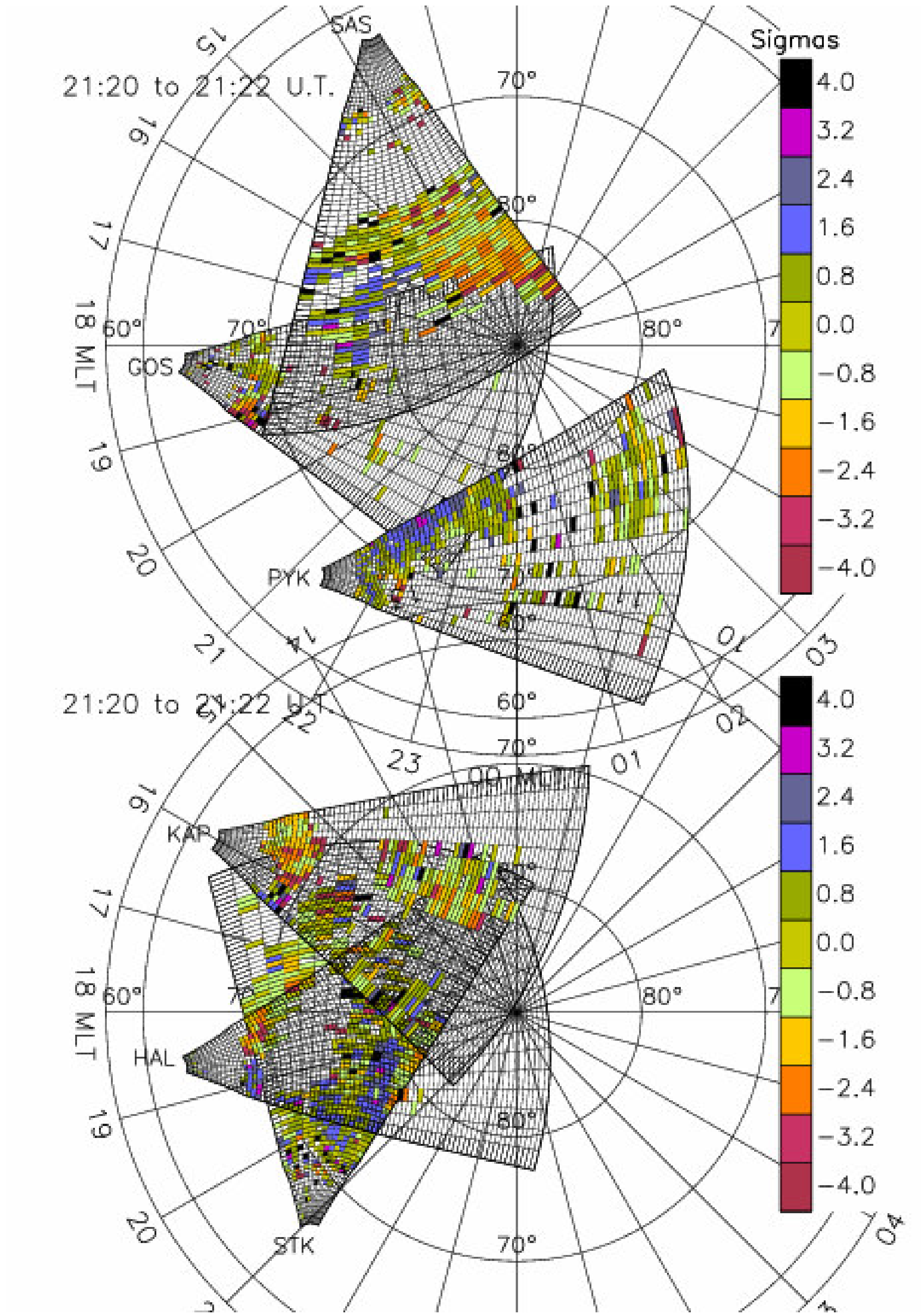

Fig. 7. Statistical significance of changes in the LOS Doppler velocity for full scans commencing at 21:20 UT on 24 November 1996.

DISCUSSION AND CONCLUSIONS

An independent, objective method of identifying if, and when, a significant change has occurred in non-stationary random time series data has been developed and tested. In the "change method," any change is quoted as a multiple of the standard deviations of ongoing fluctuations; the actual behaviour and physical meaning of the data is almost irrelevant. The change method reduces theoretical biases which may influence the interpretation of traditional line or colour contour plots of time series data. For example, subtle changes in the gradient of a line plot, or merely the choice of colour scale in a contour plot, may lead to the misinterpretation of the data.

We tested the change method on the large-scale convection change observed by the SuperDARN network on 24 November 1996 [1]. The two-minute resolution data permitted us to conclude a fast (cf. Table 1 and Fig. 1), globally coherent convection change occurred near to 21:12 UT. This change took <2 min to establish over much of the noon to dusk ionosphere, and <4 min between dusk and 23 MLT. The 24 November 1996 event was chosen to test our method because of the clarity of the response, and, as expected, our results support the original interpretation [1]. However, application of the change method to other events [8] confirm that only slow responses were statistically significant on large scales.

An objection to the interpretation of this particular event may be that the concurrent minor and gradual change in the IMF B_y component has been ignored. However, even if the ionospheric changes were influenced by the change in B_y, they were still observed to occur on fast time scales. Note that our event analysis was actually based upon a detailed examination of enlarged versions of the full-scan plots for every two-minute interval throughout the study interval, and not just the limited selection of representative results reproduced here. However, there is a possibility that the ionospheric response was actually a slow change because, for example, magnetic field-line draping meant reconnection actually commenced simultaneously over an extended region of the dusk magnetopause [13]. It is also important to keep in mind the ionospheric response may have been influenced by the solar-wind dynamic pressure and its direction with respect to the geomagnetic field, the dipole tilt angle, the state of magnetotail and ring currents, etc.

Whilst it is interesting and valuable to imagine the convection changes and patterns implied by the changes in the sign of the LOS Doppler velocities, ultimately the point of this analysis was to eliminate the influence any preconceptions about how the convection pattern should behave. The aim was to apply an objective, independent algorithm to the "raw" velocity data to determine if, and when, a change occurred. This approach contrasts with other methods whereby the evolution of convection patterns are inferred from spherical harmonic fits to a limited set of observations (e.g., [11], [12]). A danger with the latter approach is the globalisation of localised fluctuations which are subsequently misinterpreted as an instantaneous response. That is, the global responses may be artefacts of the fitting technique.

Whilst this study has not solved the greater problem of reconciling theory with the different time delays observed, it has established a methodology to objectively analyse complex observations. The interpretation of the observations should no longer be a source of vexation in addressing the greater problem. We recommend the application of the change method to space physics time series data for determining if, and when, significant changes have occurred. Determining the correct time sequence of events occurring in the coupled ionosphere-magnetosphere system is crucial to the formulation of plausible theory.

FUTURE INVESTIGATIONS

A synthesis of the very slow, slow, fast, and ultra fast mechanisms (cf. Table 1) may ultimately be required to explain the diversity of observations. Different mechanisms may operate concurrently, with their relative importance changing with geophysical conditions. For example, field-line draping [13], and the relative extent and location of the reconnection *X*-line [27], may explain some of the observations of nearly simultaneous dayside responses. The ultra fast redistribution of ionospheric electric potential [17] might be confined to continuous regions of large ionospheric conductivity. The slow, dominant ionospheric responses might be explained by the classic Cowley-Lockwood mechanism [9], [10], especially in nightside regions with low ionospheric conductivity. All of these processes are highly variable, and there may also be relevant ideas we are yet to discover.

The following questions are aimed to provoke further investigation. They illustrate just how little we really know about the behaviour of the coupled magnetosphere-ionosphere system:

(1) Do different mechanisms play a role in communicating large-scale convection changes, and to what extent and under what conditions?
(2) What are the relative occurrence rates and relative amplitudes of convection changes associated with different mechanisms, and how do they change with geophysical conditions?
(3) Can the observed response times be sorted according to solar-wind conditions including the IMF, and especially according to ionospheric conductivity and its spatial continuity?
(4) Do the contributions from different mechanisms add "in phase?"
(5) Does the magnetospheric convection always drive the ionospheric convection, or can the ionospheric convection drive the magnetospheric convection?
(6) Do convection changes occur on the dayside after changes occur on the nightside (i.e., when dayside merging relaxes, and reconnection in the tail dominates)?
(7) Can measurements made with the four Cluster II spacecraft reveal the passage of step-like changes in magnetospheric electric fields propagating at Alfvénic or sub-light speed?
(8) Can we devise experiments to negate any of the proposed mechanisms for communicating convection changes?

Fortunately, the answer to the last question is probably no.

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REFERENCES

[1] J. M. Ruohoniemi and R. A. Greenwald, "The response of the high-latitude convection to a sudden southward IMF turning," *Geophys. Res. Lett.,* vol. 25, pp. 2,913–2,916, 1998.
[2] M. Lockwood, A. P. van Eyken, B. J. I. Bromage, and D. M. Willis, "Eastward propagation of a plasma convection enhancement following a southward turning of the interplanetary magnetic field," *Geophys. Res. Lett.,* vol. 13, pp. 72–75, 1986.
[3] A. Etemadi, S. W. H. Cowley, M. Lockwood, B. J. I. Bromage, and D. M. Willis, "The dependence of high-latitude dayside ionospheric flows on the north-south component of the IMF: A high time resolution correlation analysis using EISCAT "POLAR" and *AMPTE UKS* and *IRM* data," *Planet. Space Sci.,* vol. 36, pp. 471–498, 1988.
[4] H. Todd, S. W. H. Cowley, M. Lockwood, and D. M. Willis, "Response time of the high-latitude dayside ionosphere to sudden changes in the north-south component of the IMF," *Planet. Space Sci.,* vol. 36, pp. 1,415-1,428, 1988.
[5] M. A. Saunders, M. P. Freeman, D. J. Southwood, S. W. H. Cowley, M. Lockwood, J. C. Samson, C. J. Farrugia, and T. J. Hughes, "Dayside ionospheric convection changes in response to long-period interplanetary magnetic field oscillations: determination of the ionospheric phase velocity," *J. Geophys. Res.,* vol. 97, pp. 19,373–19,380, 1992.
[6] M. Lester, O. de la Beaujardière, J. C. Foster, M. P. Freeman, H. Lühr, J. M. Ruohoniemi, and W. Swider, "The response of the large scale ionospheric convection pattern to changes in the IMF and substorms: results from the SUNDIAL 1987 campaign," *Ann. Geophysicae,* vol. 11, pp. 556–571, 1993.
[7] H. Khan and S. W. H. Cowley, "Observations of the response time of high-latitude ionospheric convection to variations in the interplanetary magnetic field using EISCAT and IMP-8 data," *Ann. Geophysicae*, vol. 17, pp. 1,306–1,335, 1999.
[8] M. L. Parkinson, M. Pinnock, P. L. Dyson, J. C. Devlin, C. L. Waters, P. R. Smith, and A. M. Breed, "Multiple time delays between IMF-driven convection changes at cross polar locations in the high-latitude ionosphere," *Space Physics Research Group Internal Report*, 6th February, 2002.
[9] S. W. H. Cowley and M. Lockwood, "Excitation and decay of solar wind-driven flows in the magnetosphere-ionosphere system," *Ann. Geophysicae*, vol. 10, pp. 103–115, 1992.
[10] M. Lockwood and S. K. Morley, "A numerical model of the ionospheric signatures of time-varying magnetic reconnection: I. ionospheric convection," unpublished.
[11] A. J. Ridley, L. Gang, C. R. Clauer, and V. O. Papitashvili, "Ionospheric convection during nonsteady interplanetary magnetic field conditions," *J. Geophys. Res.,* vol. 102, pp. 14,563–14,579, 1997.

[12] A. J. Ridley, L. Gang, C. R. Clauer, and V. O. Papitashvili, “A statistical study of the ionospheric convection response to changing interplanetary magnetic field conditions using the assimilative mapping of ionospheric electrodynamics technique,” *J. Geophys. Res.,* vol. 103, pp. 4,023–4,039, 1998.
[13] S. G. Shepherd, R. A. Greenwald, and J. M. Ruoheniemi, “A possible explanation for rapid, large-scale ionospheric responses to southward turnings of the IMF,” *Geophys. Res. Lett.,* vol. 26, pp. 3,197–3,200, 1999.
[14] M. Watanabe, N. Sato, R. A. Greenwald, M. Pinnock, M. R. Hairston, R. L. Rairden, and D. J. McEwen, “The ionospheric response to interplanetary magnetic field variations: Evidence for rapid global change and the role of preconditioning in the magnetosphere,” *J. Geophys. Res.,* vol. 105, pp. 22,955–22,977, 2000.
[15] D. L. Murr and W. J. Hughes, “Reconfiguration timescales of ionospheric convection,” *Geophys. Res. Lett.,* vol. 28, pp. 2,145–2,148, 2001.
[16] J. M. Ruohoniemi, S. G. Shepherd, and R. A. Greenwald, “The response of the high-latitude ionosphere to IMF variations,” *J. Atmos. Solar-Terr. Phys.,* vol. 64, pp. 159–171, 2002.
[17] T. Kikuchi, H. Lühr, T. Kitamura, O. Saka, and K. Schlegel, “Direct penetration of the polar electric field to the equator during a *DP 2* event as detected by the auroral and equatorial magnetometer chains and the EISCAT radar,” *J. Geophys. Res.,* vol. 101, pp. 17,161–17,173, 1996.
[18] M. Lockwood and S. W. H. Cowley, “Comment on “A statistical study of the ionospheric convection response to changing interplanetary magnetic field conditions using the assimilative mapping of ionospheric electrodynamics technique” by A. J. Ridley et al.,” *J. Geophys. Res.,* vol. 104, pp. 4,387–4,391, 1999.
[19] A. J. Ridley, L. Gang, C. R. Clauer, and V. O. Papitashvili, “Reply,” *J. Geophys. Res.,* vol. 104, pp. 4,393–4,396, 1999.
[20] M. P. Freeman, “A unified model of the response of ionospheric convection to changes in the interplanetary magnetic field,” unpublished.
[21] R. A. Greenwald, K. B. Baker, R. A. Hutchins, and C. Hanuise, “An HF phased-array radar for studying small-scale structure in the high-latitude ionosphere,” *Radio Sci.*, vol. 20, pp. 63–79, 1985.
[22] R. A. Greenwald, et. al., “DARN/SuperDARN: A global view of the dynamics of high-latitude convection,” *Space Sci. Rev.*, vol. 71, pp. 761–796, 1995.
[23] K. B. Baker, et. al.: “HF radar signatures of the cusp and low-latitude boundary layer,” *J. Geophys. Res.,* vol. 100, pp. 7,671–7,695, 1995.
[24] K. B. Baker and S. Wing, “A new magnetic coordinate system for conjugate studies of high latitudes,” *J. Geophys. Res.,* vol. 94, pp. 9,139–9,143, 1989.
[25] G. A. Abel and M. P. Freeman: “A statistical analysis ofionospheric velocity and magnetic field power spectra at the time of pulsed ionospheric flows,” *J. Geophys. Res.*, vol. 107 (A12), doi: 10.1029/2002JA009402, 2002.
[26] S. E. Milan, 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.*, vol. 104, pp. 22,591–22,604, 1999.
[27] G. Chisham, M. Pinnock, A. S. Rodger, J.-P. Villain, “High-time resolution conjugate SuperDARN radar observations of the dayside convection response to changes in IMF B_y,” *Ann. Geophysicae*, vol.18, pp. 191–201, 2000.