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The response of the high-latitude ionosphere to IMF variations

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Abstract

The convection of plasma in the high-latitude ionosphere is strongly affected by the interplanetary magnetic field (IMF) carried by the solar wind. From numerous statistical studies, it is known that the plasma circulation conforms to patterns that are characteristic of particular IMF states. Following a change in the IMF, the convection responds by reconfiguring into a pattern that is more consistent with the new IMF. Some early studies reported that the convection first begins to change near noon while on the dawn and dusk flanks and on the nightside it remains relatively unaffected for tens of minutes. Work by Ridley et al. (J. Geophys. Res. 103 (1998) 4023–4039) and Ruohoniemi and Greenwald (Geophys. Res. Lett. 25 (1998) 2913–2916) that was based on measurements with more global sets of instruments challenged this view. A debate ensued as to the true nature of the convection response. We follow the arguments of Lockwood and Cowley (J. Geophys. Res. 104 (1999) 4387–4391) and Ridley et al. (J. Geophys. Res. 104 (1999) 4393–4396) by reviewing recent results on the timing of the onset of the convection response to the changed IMF. We discuss the timing problem from the perspectives of observations and modeling. In our view, the onset of the ionospheric response to changed IMF is globally simultaneous on time scales of a few minutes. A physical basis for the rapid communication of effects in the dayside convection to the nightside has been demonstrated in magnetohydrodynamic simulations. We also offer some cautionary notes on the timing of convection changes and the use of global assimilative techniques to study local behavior.

Keywords: Convection; Ionosphere; Solar wind; Magnetosphere interactions

1. Introduction

The plasma of the earth's ionosphere at high latitudes is usually observed to be in motion. Because of the incompressibility of the plasma, a displacement or acceleration within a localized region will generally give rise to compensatory drifts over a much larger area. A number of statistical studies have shown that the global circulation of plasma conforms to patterns that are characteristic of the interplanetary magnetic field (IMF) carried by the solar wind. Indeed, the most recent statistical models essentially prescribe the pattern of convection based solely on the magnitude and orientation of the IMF (e.g., Rich and Hairston, 1994; Weimer, 1995; Ruohoniemi and Greenwald, 1996).

The preeminence of the IMF factor is most easily explained by the dominant role played by magnetic reconnection on the dayside magnetopause (Cowley, 1982). Where the magnetic field imposed by the solar wind encounters the geomagnetic field in a favorable orientation, energy and momentum may be transferred across the magnetopause (Dungey, 1961). For a southward IMF, reconnection may proceed at points equatorward of the high-latitude cusp leading to an antisunward flow of plasma into the polar cap. The plasma eventually returns to the dayside along the dawn and dusk flanks of the auroral zone resulting in a two-cell pattern of plasma circulation. Tubes of geomagnetic flux are 'opened' into the solar wind at the dayside reconnection site and returned to dipolar form at a reconnection site in the magnetotail. The azimuthal component of the IMF strongly influences the reconnection geometry and hence the orientation of the dayside flows and the shape of the overall convection pattern (Cowley et al., 1991).

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The newer statistical models cited above largely agree on the basic IMF dependencies of high-latitude convection. The patterns they generate are remarkably similar given the very different sources of measurements, namely, ion drift measurements from DMSP satellites (Rich and Hairston, 1994), electric field measurements from the DE 2 satellite (Weimer, 1995), and backscatter from ground-based HF radar (Ruohoniemi and Greenwald, 1996). It could be said that a consensus has emerged in the community regarding the statistical characterization of the pattern for stable IMF conditions. The statistical patterns certainly cannot reproduce the variability in the convection described by Codrescu et al. (1995) and the parameterization by IMF must be inadequate when the other causes of convection (substorm reconnection, viscous interaction, neutral wind coupling) are comparable in their effects. Nonetheless, a paradigm has been established for the basic dependence of the convection on the IMF for quasi-static conditions.

It has been more difficult to agree on the manner in which the high-latitude convection pattern reconfigures in response to a change in the IMF. In part, this can be attributed to the difficulties in making observations on spatial and temporal scales sufficient to resolve the evolving pattern. Only within the last 10 years, the observational and analytical techniques have progressed to the point where the instantaneous pattern can be mapped on a global scale. Certain key questions can now be addressed. These include:

- Is the onset of the convection response to changed IMF localized or global?
- What are the time scales for the pattern to reconfigure?
- Is the onset of a response conditioned by the existence of thresholds?
- To what extent is variability in the convection not due to variation in the IMF?

Important progress on all of these points can be expected within the next 5 years.

In this review, our focus is on the first question as this has generated the most controversy to date. We encourage the reader to become familiar with the exchange of views contained in the comment by Lockwood and Cowley (1999) and the reply by Ridley et al. (1999). In the next section,

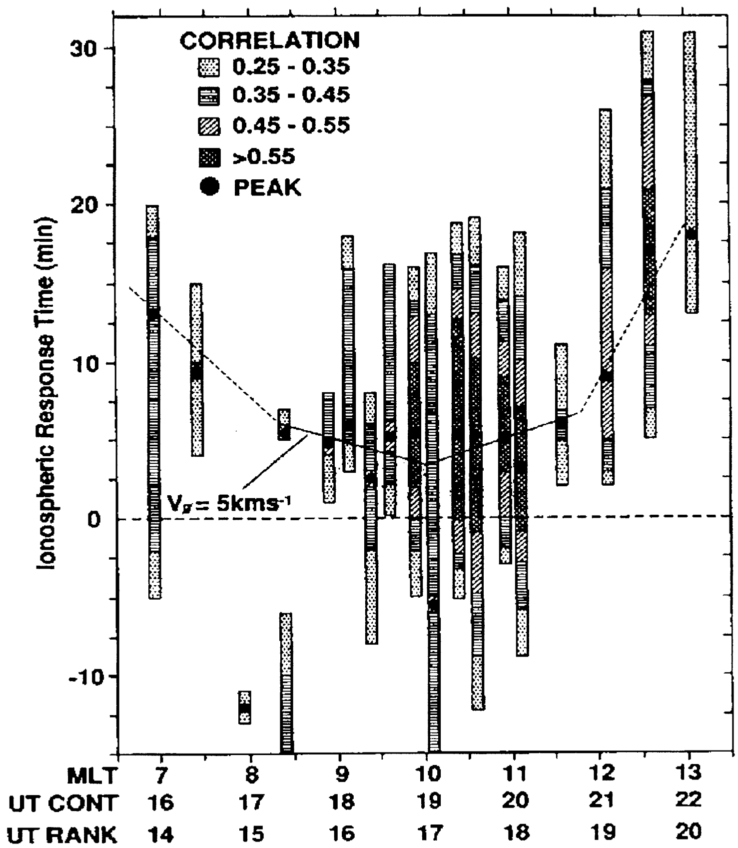

Fig. 1. MLT dependence of the ionospheric response time deduced by cross-correlating an event of fluctuating B_z with CANOPUS ground magnetometer data (after Saunders et al., 1992).

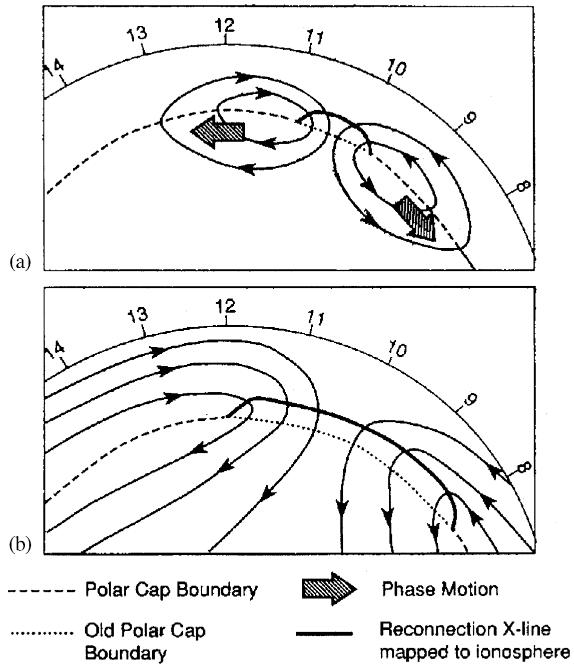

Fig. 2. The Cowley–Lockwood model of the excitation and expansion of flows in the dayside ionosphere following the commencement of magnetic reconnection at the dayside magnetopause (after Saunders et al., 1992).

we will briefly review the background of the controversy. Then we summarize recent developments in observations and modeling studies. We believe that this research narrows some of the disagreement.

2. Background

The first attempt to time the propagation of a convection response was made by Lockwood et al. (1986). They observed effects in the ionosphere that followed a southward turning of the IMF with the EISCAT radar. They concluded that the response propagated away from noon with a phase velocity of 2.6 km/s. This corresponds to a delay on the dusk (midnight) meridian relative to noon of about 15 min (30 min) at 72° invariant latitude. (Here and in the following, for ease of comparison, we characterize all results on propagation in terms of time delay). This work was followed by others that found comparable delays (Etemadi et al., 1988; Todd et al., 1988; Saunders et al., 1992). Fig. 1 shows a plot of the local time dependence of the response time from Saunders et al. (1992). These authors correlated a case of fluctuations in the z-component of the IMF with deflections in magnetograms collected with the CANOPUS magnetometers. Relative to the time of earliest onset (9–11 MLT), the delays approaching the dawn and dusk meridians climb to values greater than 10 min. These results were interpreted in terms of the Cowley and Lockwood (1992) model of the excitation of plasma flows for changed IMF conditions. As shown for a southward IMF turning in Fig. 2, the Cowley–Lockwood model posits an initial perturbation that is confined to the area of the ionospheric footprint of the cusp. This is followed by a gradual expansion to earlier and later MLTs as more open flux is added to the polar cap.

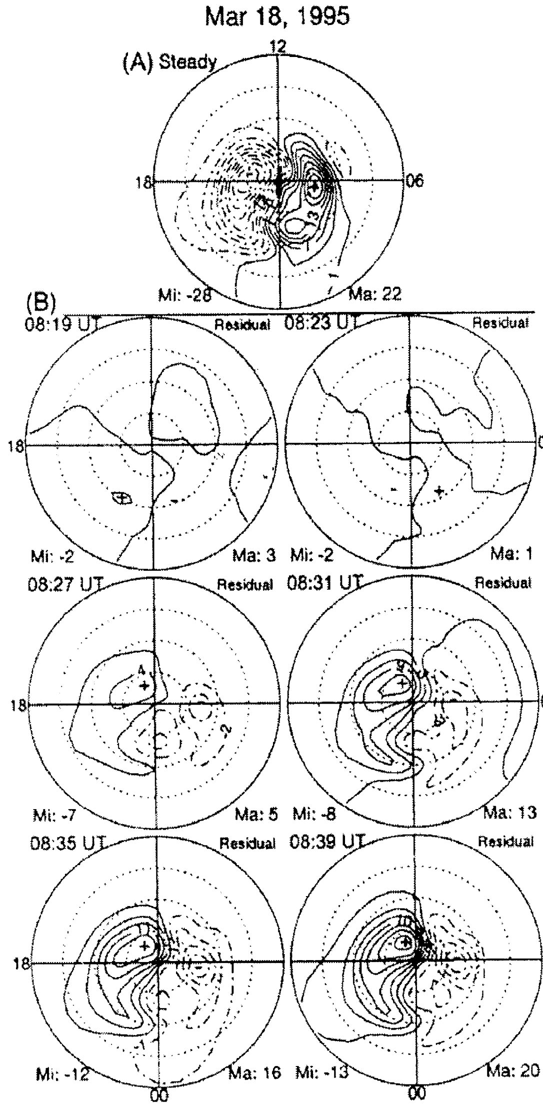

Fig. 3. Analysis of the reconfiguration of the convection pattern for a northward turning of the IMF as performed by Ridley et al. (1998). The upper plot shows the base potential pattern before the convection change. The subsequent series of plots shows contours of residual electric potential obtained by subtracting the base potential pattern from the patterns realized during the period of reconfiguration.

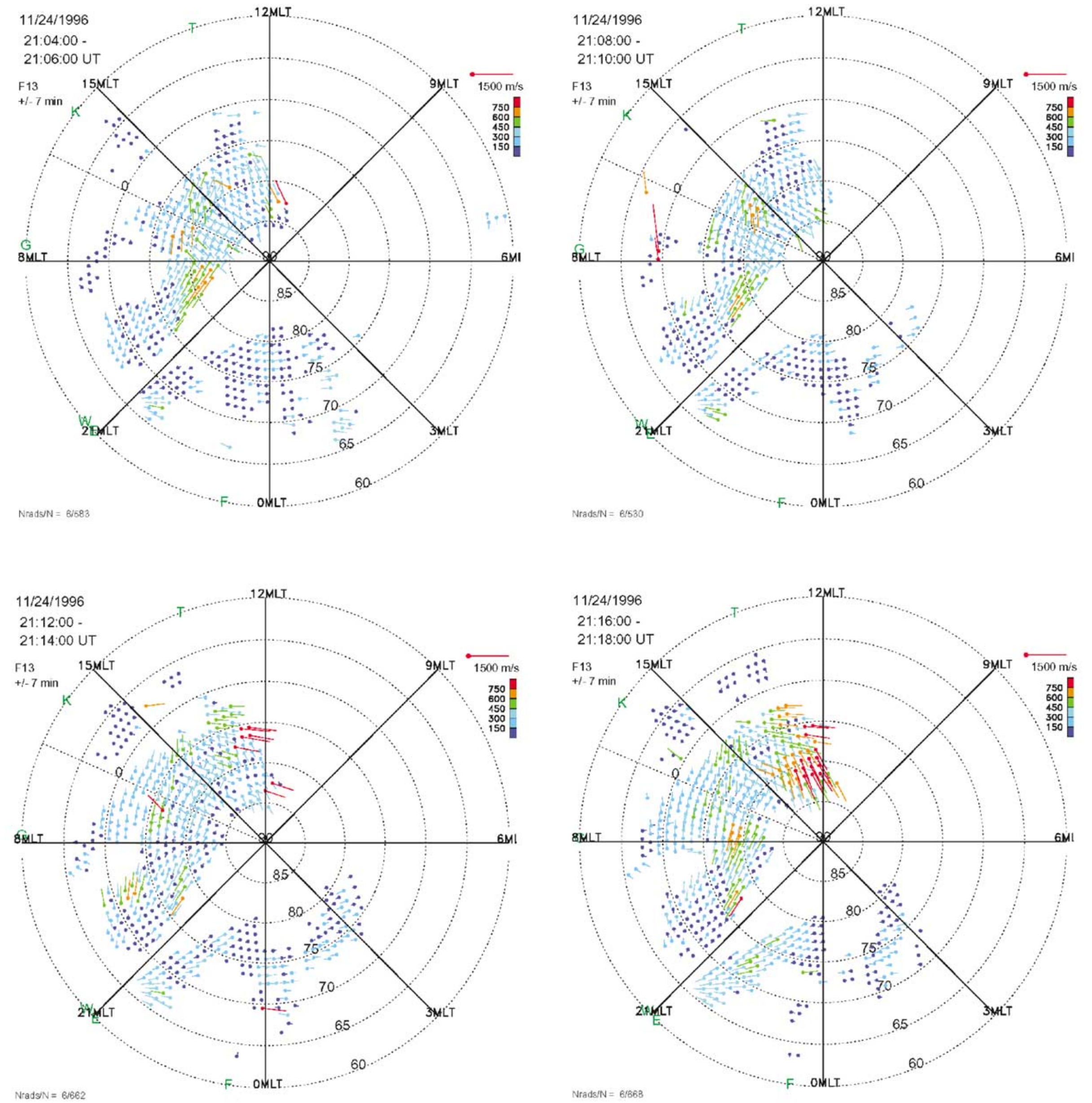

Fig. 4. Sequence of maps of the line-of-sight velocities measured by the SuperDARN HF radars during the southward turning of the IMF recorded on November 24, 1996 and discussed by Ruohoniemi and Greenwald (1998). The sources of the measurements are indicated by the letters identifying the approximate locations of the radars (T: Saskatoon, K: Kapuskasing, G: Goose Bay, W: Stokkseyri, E: Pykkkvibaer, F: Finland).

The time scales for the expansion are taken to be consistent with the observations of tens of minutes of delay from noon to the nightside.

This picture was challenged by Ridley et al. (1998), who built on the earlier work of Ridley et al. (1997). These researchers used the AMIE technique applied to magnetometer data to map patterns of electrostatic potential through periods of changing IMF. This approach had previously been used by Knipp et al. (1993) to study the reconfiguration of the pattern during a northward turning of the IMF. The particular innovation introduced by Ridley et al. (1997, 1998) was the use of residual potential patterns whereby an initial pattern is subtracted from subsequent patterns to highlight the manner in which the reconfiguration progresses. An example is shown in Fig. 3 for a south-to-north turning of the IMF. The initial perturbation (seen in the map for 08:27 UT) is clearly global. This is seemingly inconsistent with the Cowley–Lockwood depiction of the response onset for which the initial perturbation is confined to a small area on the dayside. Ridley et al. (1998) concluded that their results implied that the onset of change in the convection pattern following an IMF turning occurs simultaneously on all MLTs on time scales of less than about 1 min (or perhaps 2 min, allowing for the sampling rate of the magnetometers). Ridley et al. (1998) do not challenge the validity of the Cowley–Lockwood model on smaller time scales than this.

Ruohoniemi and Greenwald (1998) presented a case study of the response of convection to a sudden southward turning of the IMF. The velocity data measured directly by the HF radars of the SuperDARN network (Greenwald et al., 1995) were examined for evidence of the onset of a response over the MLT sector stretching from noon to almost midnight. This approach avoids complications that result from the inversion of magnetometer data for electric field and the application of global assimilation techniques (see below). Ruohoniemi and Greenwald (1998) described an onset that was very nearly simultaneous on the 2-min resolution of the SuperDARN observations. Fig. 4 shows a sequence of maps of the line-of-light velocity obtained from the radars for a time interval that includes the onset of new IMF effects in the convection. The data are plotted in the magnetic coordinate system described by Baker and Wing (1989). For each velocity determination, an arrow is drawn that extends from a dot at the point of measurement in the direction of the flow. The arrow is both color-coded and scaled in length in accordance with the velocity magnitude. The step between plots is 4 min in order to show the evolution from northward to southward IMF conditions. Noon MLT is toward the top of each plot. The changes in the velocities near noon were very dramatic, with the flows reversing from sunward (characteristic of strong B_z+) to antisunward. The velocities also changed in the other MLT sectors, generally becoming larger in magnitude. These authors concluded that the pattern reconfigured very quickly and globally following the arrival of the southward IMF turning. These results were more consistent with the findings of Ridley et al. (1998) concerning the nature of the initial response.

The interpretation of the results of Ridley et al. (1998) was argued in the exchange between Lockwood and Cowley (1999) and Ridley et al. (1999). Lockwood and Cowley (1999) showed that a day-to-night progression could be discerned in the plots of residual potential by tracking the individual contours. Ridley et al. (1999) accepted this but responded that this motion did not invalidate their conclusion that the initial effects were globally simultaneous and hence still inconsistent with the earlier reports of MLT dependence in the time of onset. We remark that the day-to-night progression cited by Lockwood and Cowley (1999) is obviously consistent with a faster rate of reconfiguration on the dayside. This tendency is apparent in the plots of Fig. 4 and does not conflict with the fact of a global onset.

The controversy then hinges on whether there is a significant simultaneous response in the convection at MLTs that are distant from those directly affected by the changed conditions of dayside reconnection. This issue can be addressed with observations, or, more indirectly, by appealing to magnetohydrodynamic (MHD) models or through consideration of theoretical concepts. In the next section, we discuss some of the complications encountered in addressing this issue using measurements and global assimilation techniques. Then we discuss the recent findings from observational and modeling studies.

3. Some complications

It is worth reviewing some of the difficulties that are encountered in studying the timing of changes in the convection that follow IMF changes. Some concerns have already been expressed in the literature (e.g., Lockwood and Cowley, 1999). Here we develop some different concerns that we feel should be recognized.

Timing issues: In most studies of the response of convection to IMF variations, an effort is made to estimate the time of arrival of the IMF change at the magnetopause. This typically involves estimating the orientation of IMF ‘phase fronts’ in the solar wind and the positions of the bow shock and magnetopause and some modeling of the propagation within the magnetosheath. Several approaches are possible and, in general, these render results that vary considerably (e.g., Ridley et al., 1998). From the presumed arrival at the magnetopause some additional time, usually 1–2 min, is then applied to account for propagation into the high-latitude ionosphere. Confusion sometimes arises in discussions of response times from the several choices that can serve as the reference point for timing the delays:

(i) the moment of presumed arrival of the new IMF at the magnetopause,
(ii) the moment of presumed arrival of the new IMF in the high-latitude ionosphere,
(iii) the moment of the first response of the high-latitude ionosphere to the change in IMF.

The third choice, the one that we have preferred, is feasible only when a large portion of the high-latitude ionosphere is under observation. If the specific interest is the manner in which the ionosphere reconfigures, the details of the propagation of the new IMF are largely irrelevant. In fact, it can be misleading if errors in the modeling of the IMF propagation contribute to the determination of delays in the ionosphere.

We have then to agree on when a response is apparent in the convection that can be reasonably attributed to a change in the IMF observed at the position of an upstream satellite monitor. Several difficulties arise in this regard. First of all, variability in the IMF and structure in the solar wind cast doubt on whether every variation seen by the satellite in fact reaches the magnetopause (e.g., Collier et al., 1998). Less well appreciated is the impact of variability in the ionosphere on the identification of a response. Even for reasonably stable IMF conditions, we find that the point-to-point and sample-to-sample variability in the ionospheric convection velocity is pronounced, as first discussed by Codrescu et al. (1995). The cause of this variability is unknown. As a practical matter, it complicates the task of identifying unambiguously the onset of a response to an IMF change. We might expect that very marked changes in the IMF, such as sudden north-to-south turnings, would stand out clearly in the observational records. Indeed, as shown by Ruohoniemi and Greenwald (1998), the main effect of such a change is large-scale and dramatic, but even here the possibility that more localized perturbations precede the large response cannot be ruled out.

Shortcomings of potential maps: In their comment, Lockwood and Cowley (1999) proposed an alternative interpretation of the potential maps that had been generated by Ridley et al. (1998). We have some more basic concerns. One is the use of global assimilative techniques to characterize local behavior. Procedures such as AMIE (Richmond and Kamide, 1988) and the APL potential fitter (Ruohoniemi and Baker, 1998) ingest distributed measurements and output a global pattern that is a 'best-fit' in the sense of reproducing as nearly as possible the individual measurements while preserving global behavior that is physical and reasonable. An example of a physical constraint is the requirement that the fitted velocity field be consistent with a potential electric field, $\mathbf{E} = -\text{grad}\,\Phi$, even if the individual measurements are not. An example of a 'reasonableness' constraint is the use of statistical model data to fill in areas where measurements are lacking. The essential point is this: in a global optimization procedure, there is a tendency to 'globalize' local behavior. Consider the sudden appearance of a localized high velocity feature in a subset of the available measurements. If the coverage of the surrounding area is sparse, the solution for the global potential pattern will likely adjust itself to accommodate the need for greater inflow to and outflow from the high-velocity area. The degree to which this occurs depends on certain weightings and tradeoffs that affect the balance between reproduction of local behavior and reasonableness of the overall map. The cautionary note that we sound here is that the globalizing tendency of the fitting procedures compels us to check our results for consistency with the local measurements.

A related problem arises in the interpretation of the maps of residual potential as defined Ridley et al. (1998). A finite residual potential results from differencing global quantities, namely, the potential distributions obtained by fitting measurements from two periods. It is possible to have a significant residual potential emerge over an area with no change in the local measurements. One then has to question whether a convection response has really occurred. That this can come about is easily seen: the fitting procedure may faithfully reproduce the potential gradients associated with the (unchanged) local convection while assigning new potential values to the local contours because of changes recorded elsewhere. One then obtains a finite residual potential and infers the onset of a local response that was not apparent in any of the local measurements. Differences in the characterization of the convection response may sometimes arise between the global and local approaches from this cause.

4. Recent work: observations and modeling

In this section, we review recent experimental and modeling results that bear on the question of how the high-latitude ionosphere begins to respond to the arrival of changed IMF. Some of this material was presented and discussed at the S5 Symposium of the 2000 S-RAMP meeting held at Sapporo, Japan. We conclude with our view of how matters currently stand.

Findings on the response of convection to IMF changes were recently presented by Khan and Cowley (1999). These authors argue that there is a significant MLT dependence in the time of response onset. They performed a correlation analysis on IMF data from the IMP-8 satellite and convection velocity measurements from the EISCAT facility. A large number of individual events were consolidated into a database for reduction by statistical methods. Fig. 5 summarizes their results. Here, the response time is reckoned from the presumed time of arrival of the IMF change at the magnetopause. For each MLT hour, the smaller of the response times determined separately for the meridional and zonal components of the convection velocity is plotted. A best-fit line is overlaid as a solid trace. It is interesting to note that the minimum delay is found at 14 MLT rather than at noon. Although the scatter is considerable, the distribution is consistent with somewhat longer delay away from this meridian. The maximum response delay is about 6 min, calculated roughly as 8 min (0 MLT) −2 min (14 MLT). That is, on average, the nightside begins to respond within 6 min of the first sign of a response on the dayside. This is a longer delay than the 1 min claimed by Ridley et al. (1998) but not very different from the 2–4 min cited by Ruohoniemi and Greenwald (1998). Thus the disagreement regarding the degree of simultaneity is reduced to minutes.

Lu et al. (2001), following the example of Ruohoniemi et al. (1998) used a stackplot presentation to analyze the response of the southward IMF turning of November 24, 1996 in magnetometer data. Their result is shown in Fig. 6. Four meridional chains of magnetometers provided

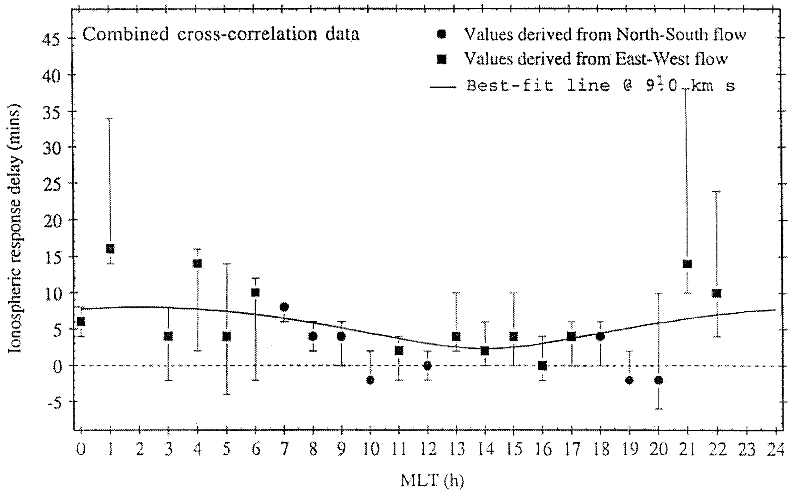

Fig. 5. MLT dependence of the onset of the convection response to IMF change as determined from cross-correlation analysis of EISCAT and IMP8 data (after Khan and Cowley, 1999).

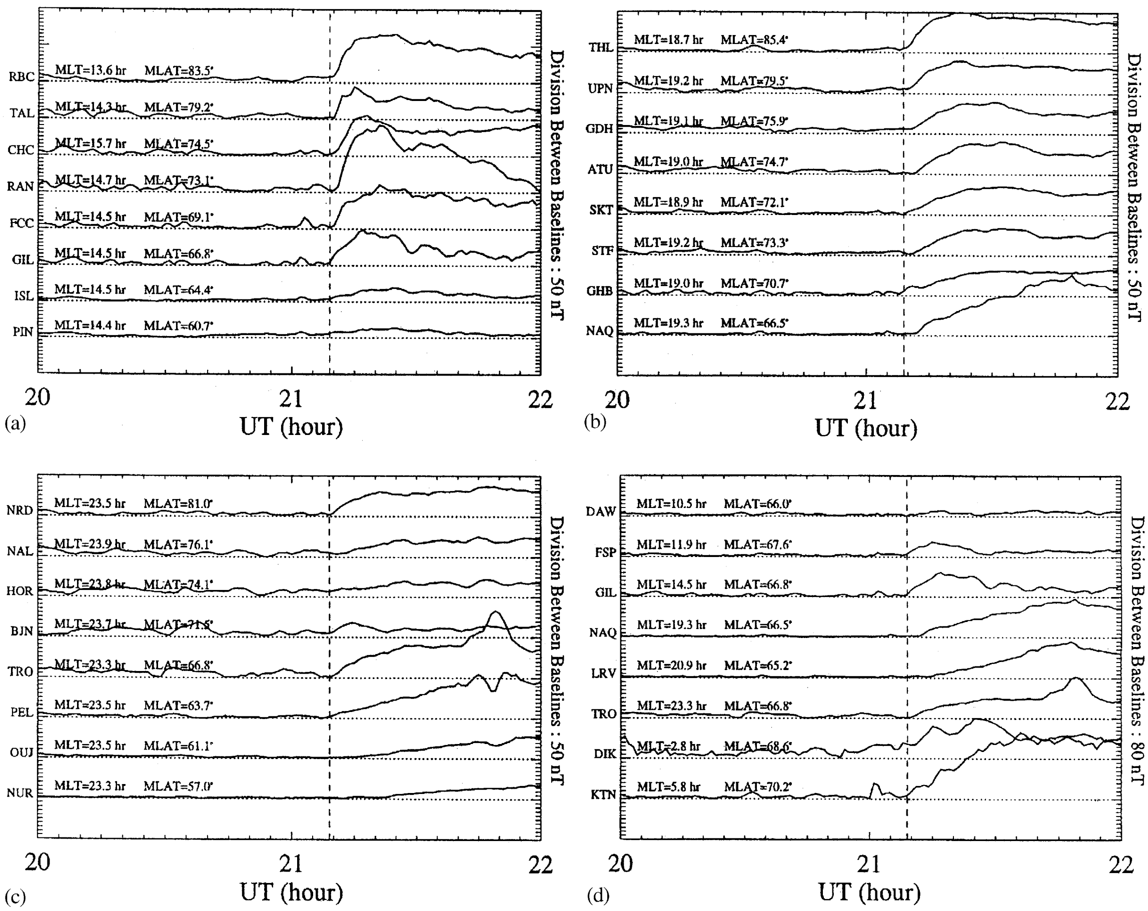

Fig. 6. Stackplots showing the horizontal magnetic perturbations that followed the southward IMF turning of November 24, 1996. The coverage provided by the chains of magnetometers extended from near noon to midnight MLT (after Lu et al., 2001).

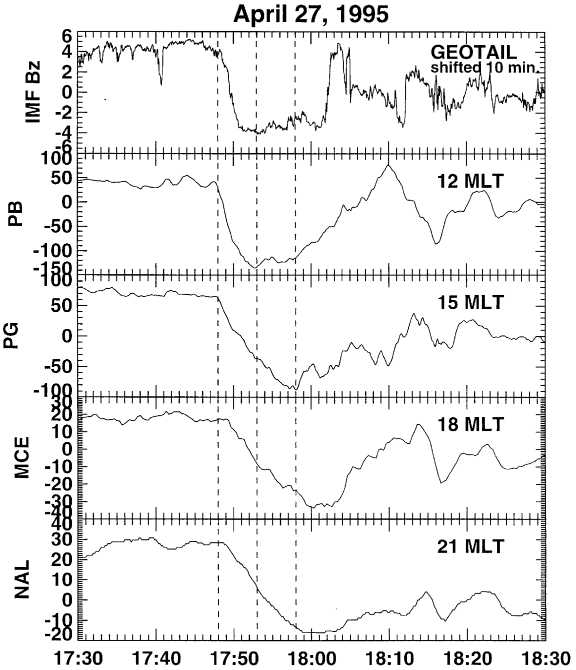

Fig. 7. Stackplot showing the effect of a southward IMF turning recorded by the Geotail satellite on equivalent flows deduced from ground-based magnetograms. The upper panel shows the IMF z-component at Geotail time delayed by 10 min. The next four panels show the changes in the equivalent flows in the direction of maximum flow change at each station. The approximate MLT of each station is indicated. The time shifting of the IMF data aligns the southward turning with the onset of significant effects in the equivalent flows. The vertical dashed lines at 5-min spacing highlight the increase in reconfiguration time away from noon (from Murr and Hughes, 2001).

observations that extended from near noon to midnight MLT. In all sectors, strong effects were recorded within a few minutes of 2110 UT. This agrees with the conclusion of Ruohoniemi and Greenwald (1998) on the near-simultaneity of the IMF response measured on time scales of a few minutes. This is also the most complete presentation to date of the effects of an IMF turning on magnetometer data and tends to confirm the findings of Ridley et al. (1998).

Magnetometer data have also been analyzed by the group at Boston University lead by J. Hughes. Their results have been presented at several venues by D. Murr, including the S5 Symposium of the 2000 S-RAMP meeting. Although confined mainly to the dayside by conductivity considerations, their results also show nearly simultaneous response onsets at all MLTs. Fig. 7 shows an example of effects in magnetograms that followed the passage of a southward IMF turning at the Geotail satellite. The onset of reconfiguration was observed nearly simultaneously across the 12–21 MLT sector. The total spread in the times of response onset was no more than 1–2 min. It was pointed out by D. Murr at the S-RAMP meeting that while the onsets occur at virtually the same time for all the magnetometers, the maximum perturbations do not. Rather, the magnetometers at MLTs away from noon tend to change more slowly. In the example of Fig. 7, the reconfiguration clearly proceeded most rapidly near noon. If one were to cross-correlate the magnetograms, the best correlations with the noon data would be obtained for somewhat later times on the dusk flank. The lengthening of the reconfiguration. time away from noon might help explain the MLT dependence of the onset time reported in some of the correlation studies, such as that of Saunders et al. (1992).

The effects of strong IMF turnings are readily apparent in the observations carried out with the SuperDARN HF radars (Ruohoniemi et al., 2001). The onsets are generally global on the 2-min time scale of the radar observations. Fig. 8 presents an example of the arrival of a southward IMF turning. The maps span the time of response onset in the ionosphere. The map for 1312–1314 UT shows dramatic effects at all the MLTs under observation. These include an increase in the number of velocity estimates, which is due to an increase in the amount and intensity of HF backscattering. The backscatter is also seen to extend to lower latitudes at all MLTs, consistent with an expansion of the auroral zone. Where velocities can be compared in a before-and-after sense, the magnitudes have generally increased from the 1304–1306 UT. The perturbations in the velocity show definitively the onset of a response in the high-latitude convection. We see that ionospheric responses are apparent both in the velocities and in the general conditions of HF backscattering and that the onsets are globally simultaneous.

We can combine time series of the various IMF and ionospheric measureables to examine the timing problem more closely. Fig. 9 shows a stackplot that illustrates the magnitude of the change in the ionosphere that follows the arrival of the southward IMF turning. From this, we infer that an effective delay of 34 min from observations of the IMF at the position of the Wind satellite to significant effects in the ionosphere. We may carry this analysis further to the individual MLT sectors. Fig. 10 shows the results for the number of velocity estimates and the maximum line-of-sight velocity. Within each 3-h MLT sector, a dramatic change was recorded in one or the other parameter within a few minutes of 1310 UT. We conclude from consideration of numerous examples of this kind that the onset of dramatic effects in the high-latitude ionosphere following IMF changes is globally simultaneous on time scales of a few minutes.

The new results have stimulated several efforts to understand the timing of the convection response from the perspective of modeling. Shepherd et al. (1999) analyzed the propagation of IMF phase fronts from the bow shock to the magnetopause using data from upstream satellites

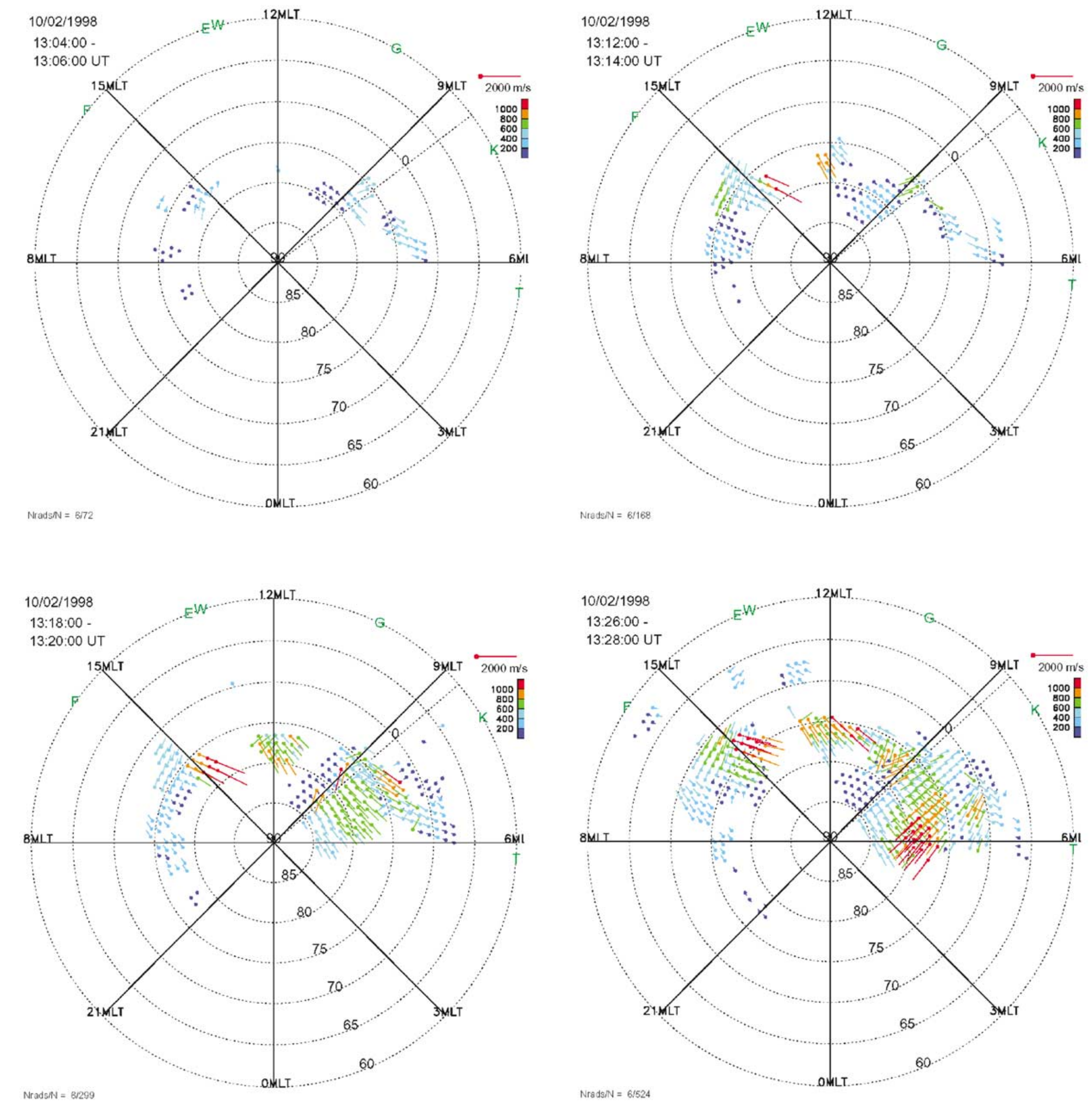

Fig. 8. An example of the effects of the arrival of a southward IMF turning in the observations of the SuperDARN HF radars. The first clear response was seen in the 2-min scan beginning at 1310 UT.

while Geotail was positioned near the subsolar magnetopause. Fig. 11 shows an example. The propagation within the magnetosheath was based on the gas dynamic model of Spreiter and Stahara (1980). Because of the variation in propagation speed with distance off the sun–earth line, new IMF comes into contact with a large portion of the magnetopause nearly simultaneously. The draping that results greatly reduces the time needed to communicate information about the new IMF throughout the high-latitude ionosphere.

A study has been performed with the MHD global simulation code of Fedder et al. (1995) to help elucidate the physics of the convection response. Slinker et al. (2000) modeled the southward IMF turning of November 24, 1996.

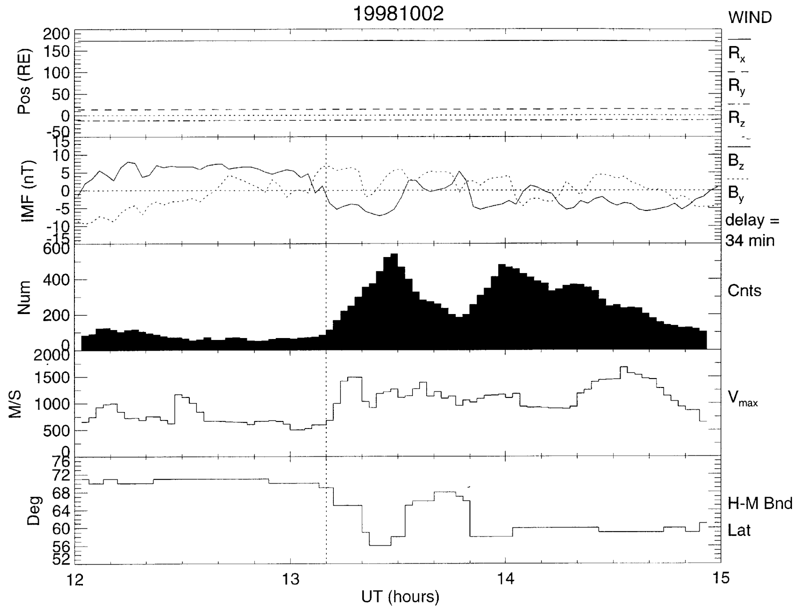

Fig. 9. Stackplot of data from the Wind satellite and the SuperDARN HF radars for an extended interval on October 2, 1998. The frames show (i) the position of the Wind satellite in GSE coordinates, (ii) the IMF z- and y-components delayed by 34 min, (iii) the number of velocity measurements available from the radars within the grid cells defined by Ruohoniemi and Baker (1998), (iv) the largest line-of-sight velocity magnitude seen by any of the radars, and (v) the latitude of the equatorward boundary of the HF backscatter as defined by Shepherd and Ruohoniemi (2000). The delay applied to the IMF data aligns the southward IMF turning with the onset of dramatic effects at 1310 UT in all three parameters (vertical dotted line).

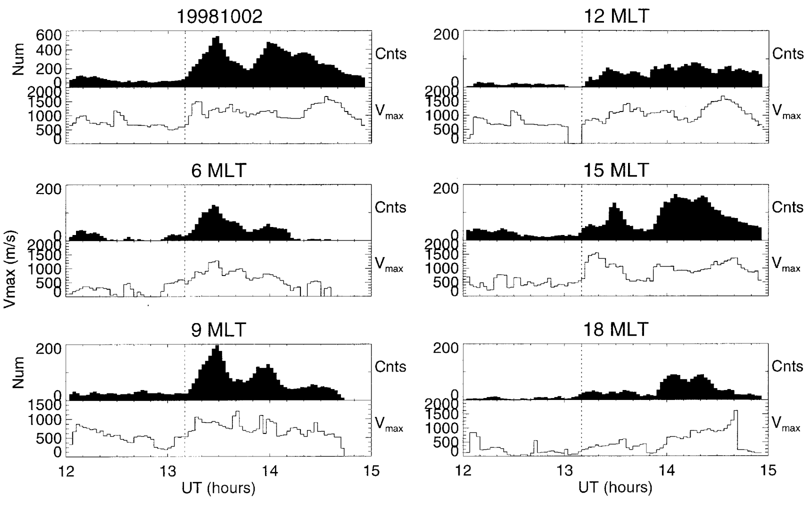

Fig. 10. Stackplots of SuperDARN data for the October 2, 1998 interval. The first plot repeats the time series of counts and maximum velocity magnitude from Fig. 8; the remaining plots show the behavior of these parameters within distinct 3-h MLT intervals. Dramatic effects were seen in all sectors within 2 min of the nominal onset time of 1310 UT.

Some of their results are shown in Fig. 12. Simulated convection patterns are plotted for a sequence of times that span the time of arrival of the IMF turning in the high-latitude ionosphere. The figure also shows plasma convection velocities projected into the dusk quadrant of the magnetic equatorial plane and velocities perpendicular to the

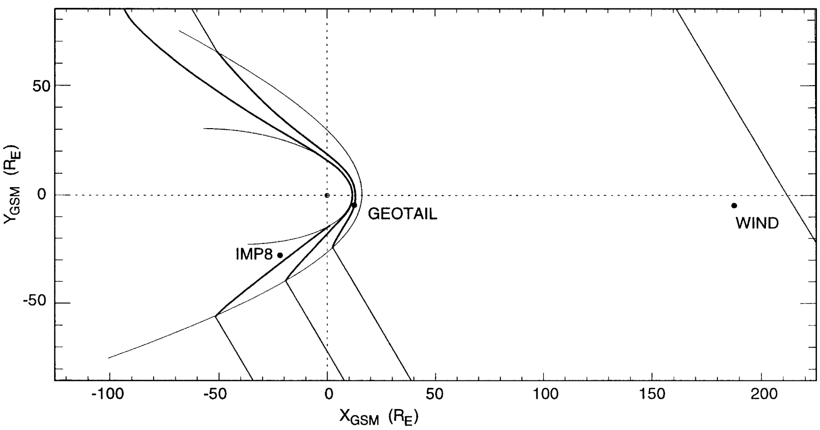

Fig. 11. Draping of IMF field lines over the dayside magnetopause as modeled by Shepherd et al. (1999). The thicker lines show the intersection of the, X–Y_{GSM} plane with planes containing the IMF at four distinct times (1551, 1652, 1701, and 1713 UT). When the first effects of the IMF transition were observed in the ionosphere at 1703 UT, field lines of the new IMF were draped over most of the dayside magnetopause.

magnetic field in the noon-meridian plane. There is good consistency between the patterns and those derived by fitting the SuperDARN line-of-sight velocity measurements. In particular, the convection through the preceding interval of northward IMF was characterized by reverse two-cell convection on the dayside with sunward flows on the noon meridian. Following the arrival of the southward turning, the convection quickly reconfigured into the more conventional global two-cell pattern with strong antisunward flows in the noon sector. Slinker et al. (2000) found that perturbations in the convection on the nightside followed the onset of perturbations on the dayside by less than 5 min. Physically, this could be understood in terms of the propagation of a rarefaction wave on closed field lines with flow toward the subsolar region needed to supply the magnetic flux to the reconnection site. The simulation also reproduced the suddenness and simultaneity of the velocity changes observed with the SuperDARN radars by Ruohoniemi and Greenwald (1998). Thus, reasonable agreement has been found between observations of the global response and MHD modeling results.

5. Conclusion

In our view, the onset of effects in the ionospheric convection at high latitudes due to changed IMF is globally simultaneous on time scales of a few minutes. Numerous observations by radars and magnetometers support this conclusion. Taking a somewhat contrary view, Khan and Cowley (1999) argued that there is a discernible spread in onset times but found that it is typically only about 6 min. Following southward IMF turnings, in particular, the SuperDARN radars detect dramatic changes in the intensity and extent of HF backscattering that are consistent with a global ionospheric response. The global aspect of the response is reproduced in MHD simulations.

One caveat is in order. Workers in the field have naturally focussed on the large effects in their data sets that follow IMF changes. These have been found to have global onsets. The possibility that smaller, more localized perturbations precede the onset of the global transformation cannot be ruled out.

There remains the task of reconciling this conclusion with the earlier findings. One suggestion, made by D. Murr, allows that correlation analyses of perturbation amplitudes distributed in MLT might not properly associate the perturbation onset times. There might also be some sensitivity to local effects, as would occur when observations restricted to a certain latitude failed to detect the onset of a change in an MLT sector until an expansion of auroral effects brought a change within view. This sensitivity was in fact discussed by Todd et al. (1988) and Etemadi et al. (1988) but perhaps was not fully resolved. When the exact nature of the evolution of the high-latitude ionosphere is determined with the aid of the more comprehensive observational networks that are now operating, it may be possible to simulate the earlier results and explain the differences.

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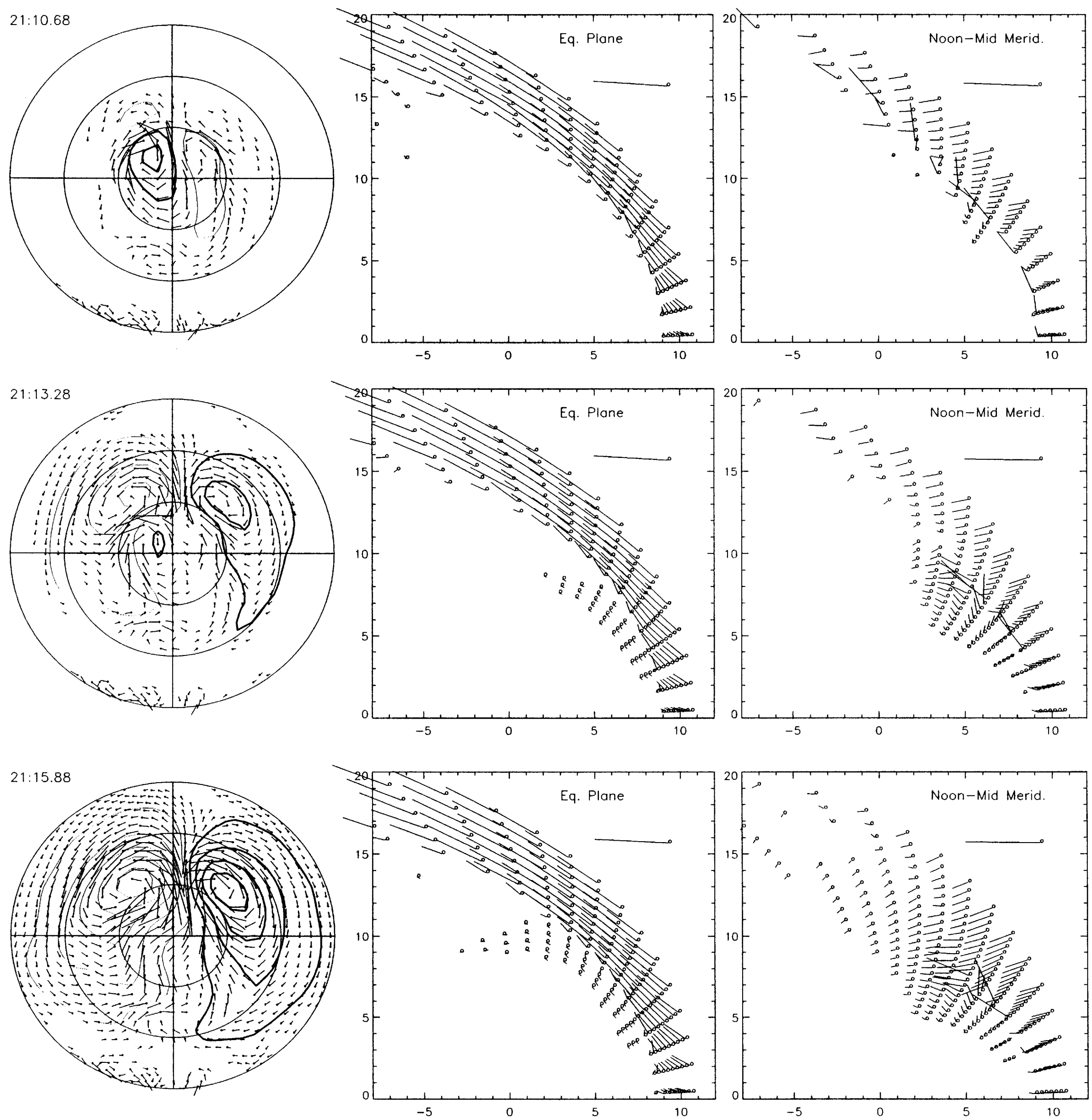

Fig. 12. MHD simulation of the effects of the arrival of the southward IMF turning of November 24, 1996. The first column shows maps of the global potential pattern and includes flow vectors where the velocity is greater than 100 m/s. The second column shows flow vectors in the equatorial plane where velocity magnitude is greater than 30 km/s. The third column shows the component of the flow velocity perpendicular to the magnetic field in the noon–midnight meridional plane where the magnitude is greater than 30 km/s (after Slinker et al., 2000).

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