

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.

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1. Introduction

Ridley et al. [1998] have presented some very interesting maps of ionospheric potential and discussed how they change in response to changes in the orientation of the interplanetary magnetic field (IMF). Their results on propagation delays and the response of the transpolar voltage are very valuable, particularly as they have studied a relatively large number of cases. However, there is one important point of interpretation that we believe needs clarification. The authors employ a valuable new technique of subtracting the background potential distribution, prior to the IMF change, to highlight the convection changes. They term these difference patterns the "residual" convection pattern. In their discussion (p. 4032), they state "In almost all the events that we examine the residual potential pattern shows very little motion. The lack of motion in the residual potential patterns implies that there is no propagation of the change from the dayside to the nightside". They later state (p. 4037) "This finding is different from that of past studies, which show convection changes spreading out from the cusp [e.g. Saunders et al., 1992] but is consistent with the intensification of localized field aligned currents, as described by Banks et al. [1984] and Clauer and Banks [1986]."

In this comment, we wish to point out that the examples they give do show an expansion of the convection change away from the cusp and that the propagation speeds are consistent with those observed in previous studies. Furthermore, the above statements imply that such an expansion of a convection change is inconsistent with an intensification of the field-aligned currents. This is not so. We also wish to point out that the incompressibility of the ionosphere has been incorrectly invoked as a reason why there cannot be an expansion of the convection pattern.

2. Previous Studies

Short time scale responses of ionospheric convection to the reconnection rate changes induced by IMF orientation changes were first inferred from magnetometer data by Nishida [1968a, b]. The propagation of the convection change was first reported

by Lockwood et al. [1986], who observed an increase in ion temperatures caused by a convection enhancement resulting from a southward turning of the IMF. This increase was shown to have propagated eastward over two radar beams in the afternoon sector auroral oval (i.e., away from noon), a cross-correlation analysis showing that the rise was seen first in the beam closer to noon. The lag between the change seen in the two beams gave a propagation speed of 2.6 km s^{-1} in the eastward direction. The same technique was used to make direct observations of similar propagation of convection enhancements associated with transient cusp/cleft auroral events thought to be caused by pulses of magnetopause reconnection [Lockwood et al., 1993].

This propagation has also been found in surveys of the response time of the convection change, as a function of position. The response time was found to increase with distance from noon, using EISCAT (European Incoherent Scatter) radar observations of the flow in combination with AMPTE-UKS (Active Magnetospheric Particle Tracer Explorer) observations of the IMF close to the subsolar point of the bow shock. Etemadi et al. [1988] employed a statistical correlation analysis, whereas Todd et al. [1988] made a survey of event studies. A similar result was found by Saunders et al. [1992] by comparing oscillations in the B_z component of the IMF to those seen by the CANOPUS (Canadian Auroral Network for the Open Program Unified Study) magnetometer network and, more recently, by Cowley et al. [1998] using a dataset of tristatic EISCAT flow measurements. There are undoubtedly uncertainties in the response times, introduced by the uncertainty in the propagation delay from the IMF monitor to the magnetopause, even for observations close to the subsolar bow shock. However, these will not depend on the location of the radar observing the ionospheric flows. Therefore these uncertainties cannot explain the consistent rise in responses time toward the nightside, as observed in both the dawn and dusk convection cell. Lockwood and Cowley [1991] pointed out that the response to a northward turning, as deduced by Knipp et al. [1991] from global radar and magnetometer data using the AIME (Assimilative Mapping of Ionospheric Electrodynamics) method, also showed this expansion. Recently, we note that Ruchoniemi and Greenwald [1998] have reported SuperDARN (Dual Auroral Radar Network) HF radar measurements of the dusk cell, which they interpret as showing a near-instantaneous global change of the convection pattern from a northward IMF lobe-circulation cell to a southward IMF pattern, i.e., with no expansion. This interpretation will be the subject of a separate publication.

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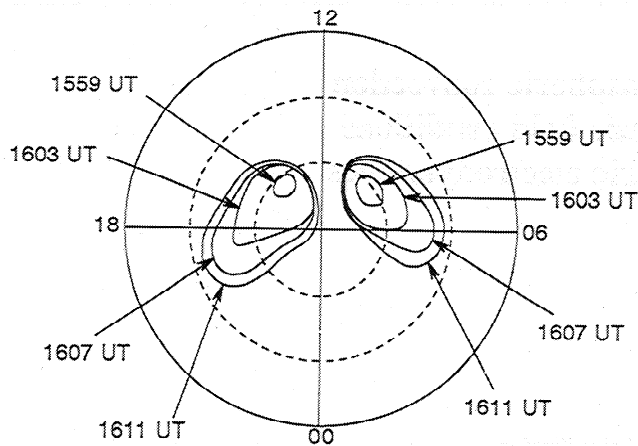


Figure 1. The +12 kV and -12 kV "residual" disturbance potential contours (part of the dawn and dusk cells, respectively) for 1559, 1603, 1607 and 1611 UT on March 17, 1995 on an invariant latitude (Λ), magnetic local time (MLT) plot. The outer circle is $\Lambda = 60^\circ$, and 12 MLT is at the top. Taken from Figure 8 of *Ridley et al.* [1998].

3. The Results of Ridley et al.

We believe that the data presented by *Ridley et al.* [1998] clearly show expansion of the convection pattern. This is demonstrated here in Figure 1, which is taken from their Figure 8, showing the response of the residual potential contours following a southward turning of the IMF seen by Wind at 1455 UT on March 17, 1995. However, instead of plotting the convection patterns (all contour levels) at different times, we here show just two contour levels at different times. Figure 1 shows the +12 kV residual potential contour (part of the dawn cell) and the -12 kV value of the dusk cell. The expansion away from noon outside of the inferred merging gap (9.1-14.4

Magnetic Local Time, MLT) is clear. The example of the northward turning shown by *Ridley et al.* (their Figure 5) also shows exactly the same general features but is harder to discuss in detail as different potential contour levels were used at different times.

Figure 2 shows the extent to which the results of *Ridley et al.* are consistent with the previous studies. In Figure 1, we take the points where the +12 kV and -12 kV contours have expanded farthest as at each time, we find they have reached the locations given in Table 1. The solid points in Figure 2 give the lag since the estimated time that the southward turning reached the magnetopause (adopting the same estimate for the propagation delay between Wind and the magnetopause as *Ridley et al.*) as a function of the MLT of those points. Also plotted in Figure 2 are the results of the surveys by *Etemadi et al.* [1988] and *Todd et al.* [1988] (histogram and open squares, respectively). There are some differences (for example, shorter response times in the mid morning sector), but the overall agreement is apparent. Furthermore, if we use great-circle geometry we find that the distances between the points given in Table 1 are 558, 567, and 222 km for the dawn cell and 1075, 1625, and 214 km for the dusk cell. Given that the points are for times 240 s apart, this gives expansion speeds of 2.3, 2.4, and 0.9 km s⁻¹ for the dawn cell and 4.5, 6.8, and 0.9 km s⁻¹ for the dusk cell. These are consistent with the expansion speed of 2.6 km s⁻¹ observed by *Lockwood et al.* [1986] in the mid afternoon sector and the speeds of about 10 km s⁻¹ (near noon) to 2 km s⁻¹ (near dawn and dusk) inferred from the response times.

We also note that this consistency between the results of *Ridley et al.* (using the AIME technique) and *Cowley et al.* [1998] (using the tristatic EISCAT UHF system) with the previous studies (as discussed above) disproves the speculation by *Greenwald et al.* [1996] that *Etemadi et al.* [1988] misinterpreted observed mesoscale vortices (of the kind in fact studied by *Lockwood et al.* [1993]) because they employed the beam-swinging technique to derive vector flows. This possibility was also incorrectly applied to the work of *Lockwood et al.*

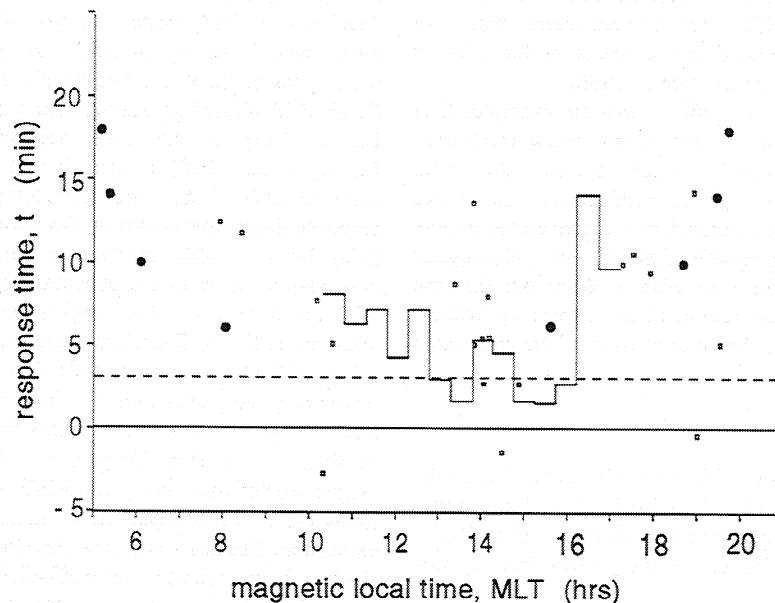


Figure 2. The ionospheric response time for a convection change as a function of MLT. The histogram is the result of the statistical study of EISCAT-AMPTE data by *Etemadi et al.* [1988], and the open squares are the individual case studies by *Todd et al.* [1988]. The solid circles are for the 12 kV residual potentials from *Ridley et al.* [1998] (taken from Figure 1).

Table 1.

time, UT	lag, min	Dawn Cell		Dusk Cell		V_m , kV	V_{pc} , kV	(V_{pc}/V_m)
		Λ , deg	MLT, hours	Λ , deg	MLT, hours			
1559	6	80.2	7.5	81.5	15.7	25	15	0.60
1603	10	77.3	6.1	77.1	18.7	41	27	0.66
1607	14	73.3	5.4	73.5	19.5	52	36	0.69
1611	18	72.1	5.1	72.1	19.7	55	44	0.80

[1986] and *Todd et al.* [1988], who used scalar data (the ion temperature and the line-of-sight velocities, respectively) which are not subject to the beam-swinging uncertainties which Greenwald et al. invoke.

In part, the confusion appears to have arisen because Ridley et al. do not make the important distinction between the convection change and what they term the "pattern" (we presume meaning the shape of the potential contours). *Cowley and Lockwood* [1992] note that for a circular expanding polar cap in the absence of tail reconnection, the region 1 field-aligned currents are a maximum at the ends of the dayside merging gap and decrease linearly to zero near midnight. In all our schematics of the growth phase flows the center of the flow cells (and the associated peak field aligned current) remained at the end of the dayside merging gap at all times [see, e.g., *Cowley and Lockwood*, 1992, 1997; *Lockwood et al.*, 1993; *Cowley et al.*, 1998]. Only when tail reconnection starts to destroy open flux in the expansion phase of a substorm would the center of the convection cells and the peak field-aligned current shift to the nightside. If the strength of the field-aligned currents increases, without altering their distribution with MLT (i.e., without changing the convection pattern), there will be a propagation of a point of given current density from the dayside toward the nightside. Similarly, convection speeds exceeding some threshold will propagate from the dayside toward the nightside. Thus the "pattern" of convection equipotentials could remain constant, but if the associated field aligned currents increased in magnitude, the convection change and the individual contours of the residual potential would propagate away from noon, as observed here and in all the papers cited above. In their reply, *Ridley et al.* [this issue] arrive at precisely the same conclusion with their thought experiment. Thus the intensification of dayside field-aligned currents discussed by *Banks et al.* [1984] and *Clauer and Banks* [1986] is fully consistent with the expansion of the convection change from dayside to nightside, as reported by *Lockwood et al.* [1986], *Etemadi et al.* [1988], *Todd et al.* [1988], and *Saunders et al.* [1992]. The only way that intensifying field-aligned currents could not give the expansion of the convection pattern is if there is no local time variation of their intensity: the convection patterns presented by *Ridley et al.* clearly show that this is not the case. Therefore the statements by *Ridley et al.*, that their results are consistent with the concepts by *Banks et al.* [1984] and *Clauer and Banks* [1986] but inconsistent with those by *Lockwood et al.* [1986], *Etemadi et al.* [1988], *Todd et al.* [1988], and *Saunders et al.* [1992] are contradictions.

However, Figure 8 of *Ridley et al.* also contains clear evidence for an antisunward propagating evolution in the shape of the patterns, as postulated by *Cowley and Lockwood* [1992], as well as the change associated with intensification of the flow. Table 1 also gives the voltage appearing across the dayside merging gap (V_m), the peak voltage seen along the 6-18 MLT

meridian (V_{pc}), and the ratio (V_{pc}/V_m). This ratio consistently increases from 0.60 at 1559 UT (the first plot in which the change can be seen) to 0.82 at 1615 UT. We also know that this ratio was zero at the instant the dayside merging gap voltage changed (near 1555 UT). Therefore the shape of the pattern had indeed evolved with time, with a larger fraction of the dayside reconnection voltage appearing on the nightside. This is exactly the behavior predicted by *Cowley and Lockwood* [1992].

4. Use of Magnetometer Data

We note that the initial work of *Nishida* [1968a, b] showed magnetometer responses to IMF changes on the dayside that were more gradual than the flow and electric field responses seen in the later radar observations. A magnetometer is an integrating device: it records the effect of all currents, the Biot-Savat law showing that the biggest response is to currents closest to the magnetometer. A current enhancement anywhere in the ionosphere would cause a change in the magnetic field at any magnetometer. Thus a magnetometer away from noon will, if it is sufficiently sensitive, respond to currents and electric fields that are localized to around noon. In addition, the effect of a given electric field distribution (convection pattern) on the magnetometer depends on the spatial distribution of ionospheric conductivities. For these reasons, *Saunders et al.* [1992] detected the antisunward expansion of both enhancements and decays of the convection pattern (due to southward and northward IMF turnings, respectively), only when they cross-correlated magnetometer data, rather than when they looked for the onsets of the changes in the data series. An inversion technique for magnetometer data accounts for both the Biot-Savat law and the spatial variation of conductivities. To look for onset times in individual magnetometer traces is to neglect these considerations. If *Ridley et al.* cross-correlated the data from different magnetometer sites, or if they looked at the time for a perturbation to rise over fixed and significant thresholds (for example, 10 nT or above), they would find the delays associated with the expansion of the convection pattern. As discussed above, the inverted patterns given by *Ridley et al.* do reveal an expanding convection pattern.

5. Effect of Ionospheric Incompressibility

Ridley et al. [1998, p.4032] state: "We conclude that the electric field of the IMF, which is mapped down to the cusp regions, is communicated to the entire polar cap ionosphere in less than 1 min. (our temporal resolution). This rapid communication, via a magnetosonic wave travelling at the Alfvén velocity, would allow the entire ionosphere to change as a whole and would show no propagation of the changes on the timescale we are observing." This statement is uniquely identical to invoking ionospheric incompressibility as the reason

why convection speeds are forced to increase everywhere in the polar ionosphere simultaneously (i.e., with no expansion of the convection pattern). Indeed, the speed of the magnetosonic wave quantifies how incompressible the ionosphere is (rising to infinity for the case of complete incompressibility). By invoking communication via the very fast magnetosonic wave, Ridley et al. are invoking ionospheric incompressibility.

It is worth considering the physical implications of the flow pattern expansion not being present, as Ridley et al. [1997, 1998] claim. At the onset of dayside flows driven by magnetopause reconnection a flow increase of the same fractional magnitude would have to be simultaneously excited everywhere in the polar cap and auroral oval. This means that nightside flux tubes would be moving in the ionosphere despite the fact that in the magnetosphere they are stationary (information on the change taking 10-15 min to spread through the relevant parts of the magnetosphere). There is no reason in principle why this should not happen because changes in the magnetic field can give a curl of the electric field (i.e., induction effects). For example, Lockwood et al. [1990] invoked such induction effects, with a magnetospheric voltage in substorm growth phases exceeding that across its ionospheric footprint because of the growth phase rise in the lobe magnetic flux that threads the Faraday loop connecting the two. However, Ridley et al. require the opposite situation, with ionospheric nightside voltages exceeding the corresponding magnetospheric ones. This is equivalent to a fall in the lobe flux threading the Faraday loops, even though this is during a substorm growth phase following a southward turning. There is no reason for this to happen. Because of collisions with the neutral thermospheric particles, there is always resistance to setting the ionosphere in motion. The tail magnetosphere cannot be driving the enhanced ionospheric flows as it does not yet know about the change.

Figure 3 explains why invoking ionospheric incompressibility (i.e. communication by a fast magnetosonic wave) is not a valid argument. Figure 3a shows the flow predicted by the flow excitation model of Cowley and Lockwood [1992], shortly (~ 5 min) after the onset of magnetopause reconnection. By definition, this reconnection transfers open flux across the merging gap (the dashed line M) from the region of closed field lines to the open field line (polar cap) region. The arrows show the antisunward expansion of the potential contours and the motion of the segments of the polar cap boundary that are expanding equatorward most rapidly. The peak potentials and the peak field-aligned currents of both the dawn and dusk cells remain at the ends of the dayside merging gap at all times in the growth phase.

Figure 3b shows the flow that would have to be present (for the same time and the same magnetopause reconnection voltage as Figure 3a), according to Ridley et al. Because they claim that there is no expansion of the flow pattern, this is the same in form as the final flow pattern (~ 20 min after the onset of reconnection) with all points of the polar cap expanding equatorward at the same speed at all times. It should be noted that both flow patterns in Figure 3 are fully consistent with ionospheric incompressibility (in neither case are there flow streamlines that are not closed loops nor do they cross each other). Therefore the argument of Ridley et al. that incompressibility of the ionosphere supports Figure 3b in favor of Figure 3a is not valid.

Magnetopause reconnection converts closed flux to open flux. In both cases shown in Figure 3, ionospheric incompressibility means that the open field line polar cap is expanding (there being no way that the reconnection rate in the cross-tail current

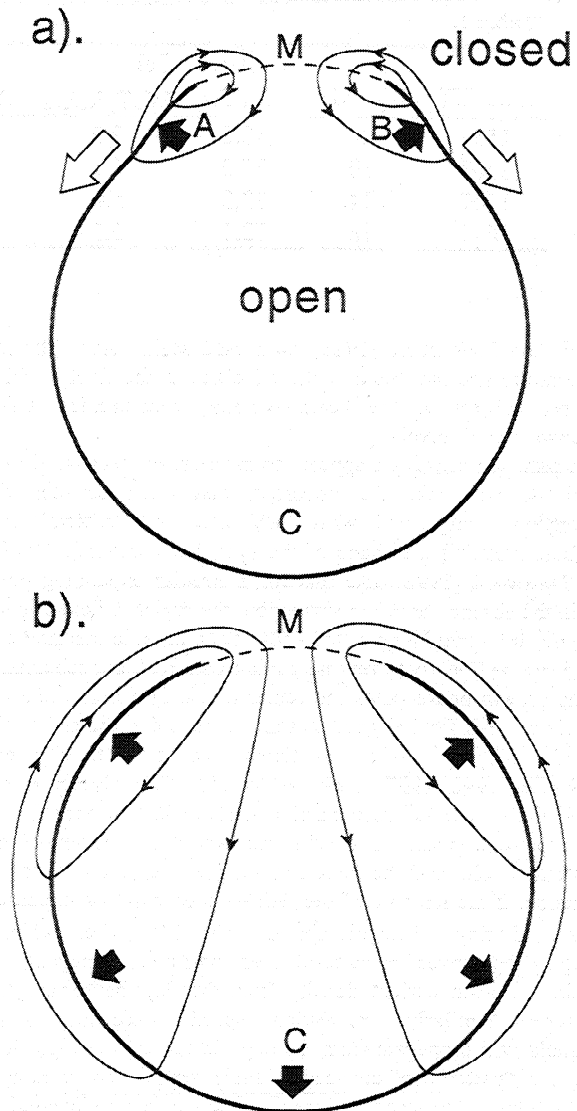


Figure 3. Convection patterns a few (~ 2) minutes after the onset of magnetopause reconnection (a) according to Cowley and Lockwood [1992] and (b) according to the arguments of Ridley et al. [1997; 1998]. In both cases, the magnetopause reconnection voltage is applied along the merging gap (dashed line, M), causing the polar cap to expand. In Figure 3a the polar cap is expanding most rapidly around A and B and these points propagate toward the nightside. In Figure 3b the polar cap expansion is the same at all local times (including at C in the midnight sector) so that the pattern of flow does not vary with time. Flow streamlines (thin lines) are closed loops in both cases and so ionospheric incompressibility is obeyed in both cases. Thick lines are nonreconnecting ("adiarctic") segments of the boundary between open and closed field lines. In Figure 3a the ratio of the voltage across dawn-dusk meridian to that across the dayside merging gap, (V_p/V_m), increases as the polar cap expansion moves toward the nightside. In Figure 3b it remains the same at all times. Table 1 shows that the results of Ridley et al. yield a rise in (V_p/V_m), as in Figure 3a.

sheet can have gained any information about the onset of enhanced magnetopause reconnection in a few minutes, let alone have responded to match it). The total region of closed flux in that hemisphere is decreasing in size at the same rate: applying

Faraday's law to the open/closed field line boundary, the magnitude of the rate of change of the area, for both closed and open regions, is equal to the excess magnetopause reconnection voltage divided by the ionospheric magnetic field. In our model the initial polar cap expansion is taking place most rapidly around A and B, the flow streamlines crossing the boundary there because the nonreconnecting ("adiarctic") boundary segments there are moving equatorward with the same speed as the local plasma and its frozen-in magnetic flux. Note that the incompressibility of the ionosphere means that the point C in the midnight polar cap will have, very quickly, gained information via the magnetosonic wave about the onset of dayside reconnection. Of that there is no question, but this is not a reason for C to be set into bulk motion at this early stage.

Ridley et al. claim that incompressibility means that points like C are set into full motion immediately. To give a final form of the convection, with no evolution of the pattern as they suggest, the initial flow speed at points like C would have to have the same ratio to the flow speed across the dayside merging gap M as it has at all other times, and the boundary expansion near C would have to be the same as at all other local times. However, the new open flux is generated on the dayside, and the closed flux is also lost from the dayside. Ridley et al. do not offer an explanation as to why incompressibility means that the midnight polar cap boundary near C would move immediately to accommodate the polar cap expansion (as in Figure 3b), as well as the dayside boundary segments A and B in Figure 3a.

The expansion of the convection pattern that we observed, and that present in the data given by Ridley et al., simply means that the points of the fastest polar cap expansion move from the dayside to the nightside. We predicted that this would be the case because the newly opened flux is progressively appended to the tail lobe. As the polar cap expansion migrates from the dayside to the nightside, the flow will evolve from that shown in Figure 3a to that in Figure 3b over a period of about 10-15 min. Both the region 1 and region 2 current sheets, which close the Pedersen currents associated with the ionospheric convective flow, will also show an enhancement that spreads from the dayside to the nightside. Note that there is no "expanding boundary" confining the flow in Figure 3a, most of the equipotentials remain on the dayside only because that is where the polar cap is expanding most rapidly at this time.

In summary, our model of the expansion of the polar cap [Cowley and Lockwood, 1992] certainly does not violate ionospheric incompressibility. The results of Ridley et al. show precisely the expansion predicted by this model and as found by earlier studies of the response of ionospheric flows to IMF orientation changes.

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