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Interactive comment on "On the convection of ionospheric density features" *by* John D. de Boer et al.

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1 Reply

The points raised are addressed below first, and following are several amended/added paragraphs for the manuscript. We have also prepared a revised manuscript with changes highlighted in red if it would be better to view the changes in that context

1.1 Minor changes:

We have corrected our terminology to ‘polar region’ and ‘auroral oval.’ We have added the word ‘sharp’ to the title and content of Sec. 1.1, however the idea applies to density steps of any value, and since we are not modeling but arguing generally we would like to avoid specific density values.

In Sec. 3.1, the E-region was named because the effect we are arguing comes about because of conductivity. Any structuring of the electric field will affect both the E- and F-regions equally, and if the E-region is uniformly weak, then it will be the F-region structure that determines the structuring of the electric field. The time required for the ionosphere to reach steady state will still be on the order of seconds, since the underside F-region, say below 200 km, still has reasonably high momentum transfer collision frequency. But then the ratio of integrated Pedersen to Hall conductivity will be very high, leading only to a simple case of the more general result we obtain for arbitrary κ. That explains our focus on the E-region. Our discussion has been expanded to explain why the results also apply to F-region patches.

A diagramme has been added to help explain the argument in Sec. 4.1 (now 4.2) about steepening gradient scale lengths.

The assumption of a vertical magnetic field has been mentioned, and also explained in the discussion.

1.2 Major changes:

The assumption of vertical magnetic field has been addressed in a new Sec. 4.1. The papers that the reviewer mentioned have been addressed, and indeed we think that they even offer evidence of the negative correlation we propose between plasma density and $\mathbf{E}$ field strength. A few other papers we mention also offer support. We address modeling, citing the paper mentioned. We have not delved further into a review of modeling because a prescribed electric potential, or a fixed boundary condition for electric potential, is so common in those fields. We hope that the changes address the major concerns.

1.3 Technical comments:

By ‘FAC’s’ we had intended ‘FACs’; that has been changed. Several sentences beginning with ‘And’ have been reworked, and the remaining few we think are permissible.

2 Amended/added paragraphs in the discussion:

2.1 Addressing some idealisations

If we are considering F-region structure, our results are still applicable. We presented the analysis in the context of the E-region because we are treating the Hall current, whereas the F-region alone, with negligible Hall current, would constitute a narrower problem. Also any E-region structure is weighted much more highly than the F-region’s in determining electric field structure, due to its stronger contribution to Σ_P.

We assumed a vertical $\mathbf{B}$ field. In the polar region this is not a large approximation, but the $\mathbf{E} \times \mathbf{B}$ drift acts perpendicular to $\mathbf{B}$ so it can have a vertical component. In the polar cap, between the dayside open-close boundary (OCB) and the line across 06-18 MLT, the convection adds an upward component to the plasma’s vertical momentum balance, while on the midnight side of the cap it is driving the plasma downwards. This adds a layer of complexity, but also ensures that even initially purely F-region patches should create some conductivity structure by the time the plasma reaches the nightside OCB.

There is an open question which requires further research: how non-ideal is the electric potential source along a given flux tube? Our research began with modelling closed field lines in the dawn- or dusk-side auroral oval, and these are in a situation which is most directly addressed in our Introduction and in App. B. A Neumann upper boundary condition is more appropriate for electric potential. An old open flux tube in the cap, especially as it approaches the nightside OCB, should also display density-driven potential structuring. A new open field line will behave the most like an ideal power source, i.e. one which can provide currents as required to maintain the potential that is initially mapped down. Here a Dirichlet boundary condition may be more appropriate. However the opportunity to observe and measure also progresses in the same sequence, with dayside polar cap patches being the largest and most prominent phenomena available for quantitative study. So our discussion in [new Sec.] will necessarily focus on a region where the effect we have put forth may not be dominant.

2.2 Implications for gradient scale lengths

[Fig. concentric.png] Equipotential contours that satisfy $\nabla \cdot \mathbf{J} = 0$ for two concentric patches of density $2\times$ and $5\times$ the background density, and a uniform $\kappa = 1$. Although the $\mathbf{E}$ field and the boundary shapes will become quite complicated as the inner patch approaches the boundary of the outer one, we can appreciate that the step boundaries will approach each other around their 10 o'clock position, while growing farther apart around 4 o'clock.

2.3 Search for observational support

There are however two ways that the effect we argue could bias patch motion statistically. Fig. 7 shows that a patch in the boreal polar cap *might* be expected to drift somewhat to the left (towards post-midnight) relative to the average convection, and that it should travel more *slowly* than the mean drift. But if it is a predominantly F-region feature, then the leftward deviation may be negligible.

Moen et al. (2007) did a statistical study of patch exit times and found a high degree of symmetry around midnight. There was a small bias toward pre-midnight exits, the distribution being centred on 23:25 MLT, which might only reflect the small bias of IMF By in their sample. This offset is the opposite of what we are positing, albeit in a region where convection is expected to be the least structured by conductivity. Moen et al. (2015) examined the statistical variation of patch exit times with IMF By and Bz more closely, and found that the pre-midnight shift for By positive is mirrored by a post-midnight shift for By negative. So this test is inconclusive.

Next we look at drift speed. Oksavik et al. (2010) studied two particular polar cap patch events in 2001, of which we examine no. 2. Their Fig. 3.e) is interesting because it shows that this patch's velocity was distinctly lower than the plasma ahead and behind it. The SuperDARN flow plotted in their Fig. 2.d) shows a speed of approximately 470 m/s on the patch's right (east) side and 620 m/s on its left. (The patch undergoes a clockwise rotation of 90°.) The SuperDARN *maps* for that day show electric field strengths of about 40 and 30 mV/m at 08 and 09 UT, respectively, or roughly 700 m/s at 0830. Yet the patch progressed through the east and west beams of the radar at 226 and 566 m/s, respectively. So there is some evidence that patches convect more slowly than the average convective flow around them.

Hosokawa et al. (2010) looked at an event where two patches were pulled away from each other by a shear in the convection. It is curious that in their Fig. 6 the highest speed shown is inferred from the SuperDARN convection map, and is clearly higher than the patch's speed measured by radar backscatter. Also Gillies et al. (2009) have examined the factor of about 0.75 by which SuperDARN Doppler velocities are lower than those obtained for convection from the DMSP satellites. Their work shows that about a third of the discrepancy is accounted for by taking the index of refraction into account. But it is intriguing to speculate that the remaining factor may arise because the

DMSP data yield *mean* convection, while the Doppler speeds may be biased towards plasma with higher density and therefore stronger radar return. Perhaps the remaining systematic difference is due to an inverse correlation between plasma density and *local* electric field strength.

In some convection maps, it seems like it might even be possible to see the effect we posit. For example in Fig. 2 in Zhang et al., looking around the terminator in the polar cap in panels C, D & E, and in the return flow in panel G, it appears that the contours of potential are slightly spread out (weaker $\mathbf{E}$) around the stronger TEC structures.

2.4 Modeling

We should address how our work is relevant to ionospheric modeling. Our result shows that the electric field cannot be simply prescribed for some region, but that it will have structure implicitly determined by the plasma density structure. Most models, including our own cited work, assume an $\mathbf{E}$ or potential field that is prescribed in some way. For example Schunk and Sojka (1987) used an $\mathbf{E}$ field that remained fixed despite the introduction of very strong density features.

A numerical model intended to address $\mathbf{E}$ field structuring might begin with an initial electric potential map, but the actual Pedersen and Hall currents will generate FACs wherever they converge or diverge in the ionosphere. These FACs cannot be driven immediately or indefinitely by magnetospheric processes. Charge accumulations will then force a structuring of the ionospheric and magnetospheric potential towards a situation where FACs are no longer required to maintain current closure, i.e. exactly the sort of structure we have identified. Where the plasma density is higher, the field will be lower, and *vice versa*. In the limit of closed field lines, this will amount to solving the Laplace equation in 2-D.

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3 Additional references:

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Please also note the supplement to this comment:
https://www.ann-geophys-discuss.net/angeo-2018-13/angeo-2018-13-AC2-supplement.pdf

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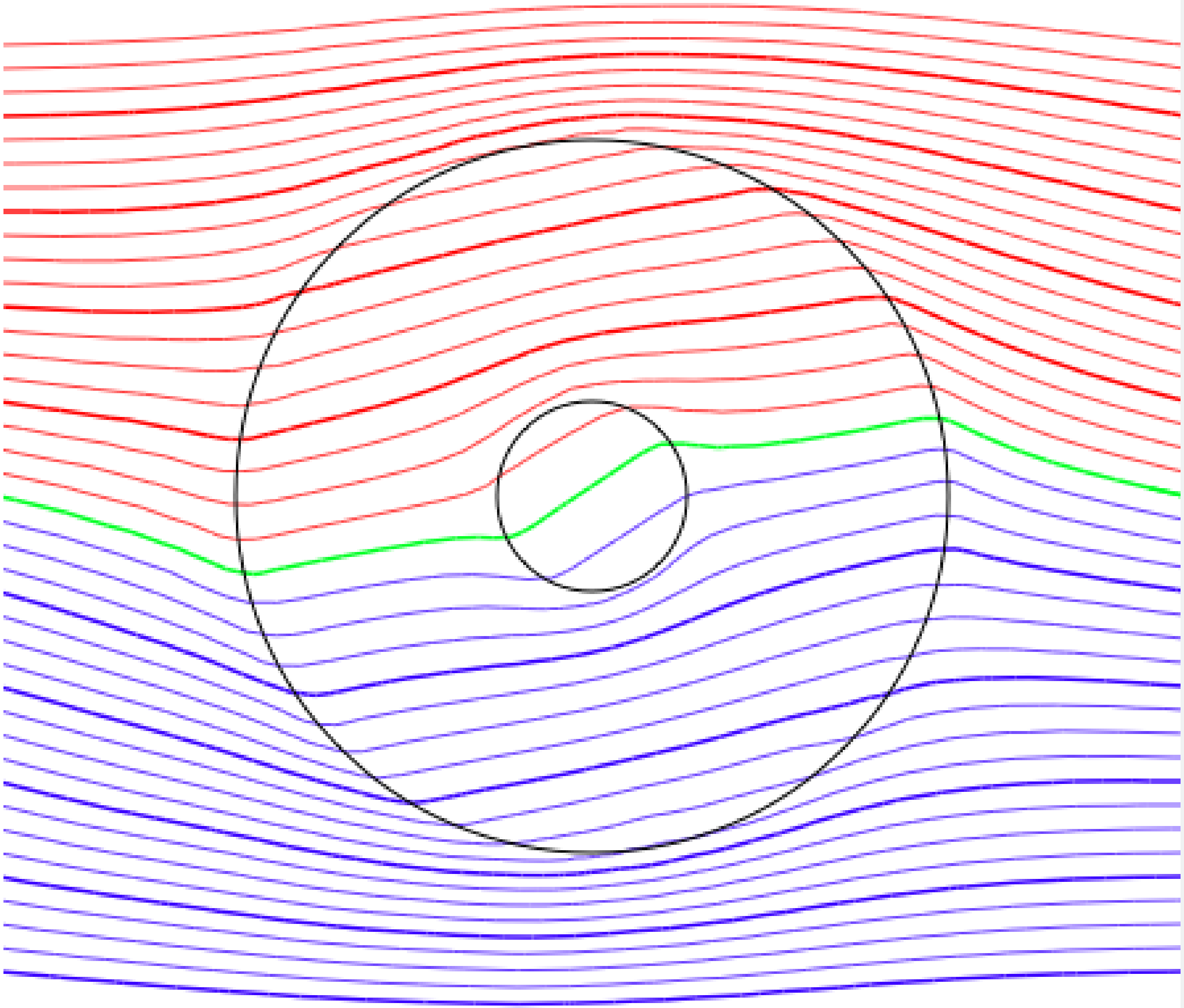

Fig. 1. Equipotential contours that satisfy [divJ=0] for two concentric patches of density 2x and 5x the background density, and a uniform [kappa]=1 Although the E field and the boundary

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