GEOPHYSICAL RESEARCH LETTERS, VOL. 20, NO. 17, PAGES 1783-1786, SEPTEMBER 3, 1993

MODELING POLAR CAP *F*-REGION PATCHES USING TIME VARYING CONVECTION

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Abstract. Creation of polar cap *F*-region patches are simulated for the first time using two independent physical models of the high latitude ionosphere. The patch formation is achieved by temporally varying the magnetospheric electric field (ionospheric convection) input to the models. The imposed convection variations are comparable to changes in the convection that result from changes in the B_y IMF component for southward interplanetary magnetic field (IMF). Solar maximum-winter simulations show that simple changes in the convection pattern lead to significant changes in the polar cap plasma structuring. Specifically, in winter, as enhanced dayside plasma convects into the polar cap to form the classic tongue-of-ionization (TOI) the convection changes produce density structures that are indistinguishable from the observed patches.

1. Introduction

Over the last decade, observations have established that, during periods of southward IMF, patches of enhanced ionization drift across the polar cap in an antisunward direction [*Buchau et al.*, 1983; *Weber et al.*, 1984]. These patches, although strongest in winter, occur at all seasons and levels of solar and geomagnetic activity. Their horizontal dimensions range from hundreds to several thousand kilometers. Patches also possess small scale structuring from meters to tens of kilometers. As they convect across the polar cap, the patch shape can change [*Robinson et al.*, 1985]. Several models of convection dynamics have been proposed to explain patch formation. *Anderson et al.* [1988] proposed that polar cap expansion in response to *Kp* changes brings high density plasma into the cusp region while *Lockwood and Carlson* [1992] argued that flux transfer event (FTE) signatures in the cusp cause short-lived enhanced flows that transport plasma into the polar cap. Indeed, *Pinnock et al.* [1993] have presented an example of one such event. In this study, two physical models of the high-latitude ionosphere were used to simulate patch formation caused by time varying convection that responds to IMF B_y changes.

2. TDIM and PL Ionospheric Models

The Utah State University Time-Dependent Ionospheric Model (TDIM) and the Phillips Laboratory (PL) *F*-region model were used in independent studies of polar cap *F*-region patch formation. Both simulations used the same patch formation scenario and discovered the same consequences of "realistically" varying the magnetospheric electric field on the polar cap electron density distribution.

The USU TDIM is a multi-species (O_2^+, N_2^+, NO^+, O^+, N^+, and He^+) global model of the ionosphere that is based upon solutions of the continuity, momentum, and energy equations in the collision-dominated 13-moment transport formulation. The development of this model is described by *Schunk* [1988], while the model predictions and comparisons with observations are described by *Sojka* [1989]. The PL *F*-region model is a single species (O^+) global model of the ionosphere that is based upon solutions of the continuity and momentum equations. Its development involved generalizing the theoretical low latitude *F*-region model of *Anderson* [1973].

3. Patch Simulation

Two sets of results are presented to highlight the sensitivity of the polar cap plasma to the structuring that results from the time varying convection electric fields; in particular, a time dependence driven by a time varying B_y IMF component. In the PL simulation, the semi-empirical convection model of *Hairston and Heelis* [1990] is used to simulate time varying southward IMF patterns. The TDIM simulation used two *Heppner and Maynard* [1987] convection patterns to do likewise.

3.1. PL F-Region Patch Simulation.

Figure 1 shows the plasma drift trajectories for the two IMF conditions used in the PL simulations. Both convection patterns are for southward IMF and a cross-polar cap potential of 80 kV. They differ in that the left and right patterns

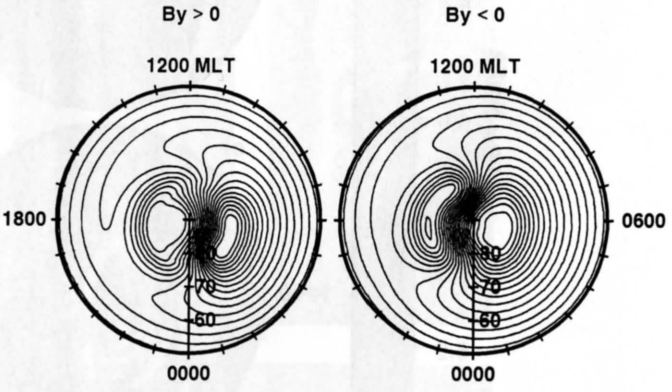

Fig. 1. Hairston and Heelis [1990] convection patterns with corotation added for southward IMF, where IMF B_y = 8 gamma (left panel) and IMF B_y = -8 gamma (right panel). The cross polar cap potential is 80 kV and the polar cap radius is 12 degrees.

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Paper number 93GL01347
0094-8534/93/93GL-01347$03.00

correspond to IMF B_y values of 8 and -8 gamma, respectively. The patterns are from the *Hairston and Heelis* [1990] semi-empirical electric field model with a corotational potential field added. Note that the plasma enters the polar cap in the vicinity of the cusp region, pre-noon, and then convects antisunward across the polar cap. For B_y negative, the flow is across the dusk-side of the polar cap (right panel, Figure 1), while for B_y positive this flow is on the dawn-side (left panel, Figure 1). This IMF B_y control of the ionospheric polar cap plasma convection is well known [*Heppner and Maynard*, 1987] but its full significance in the formation of polar cap patches has not been recognized. Since the details of how a given ionospheric convection pattern changes into a new pattern are largely unknown at this time, we adopted a rather simplistic procedure for changing from one convection pattern to the next. For this simulation, the convection pattern is maintained for 17 hours and then, at 1700 UT, is changed to the pattern in the right panel, and again at 1830 UT, is changed back to the first pattern.

For this simulation and that of the TDIM, winter solstice and solar maximum conditions were adopted with an F10.7 of 190 and a *Kp* of 4. The auroral precipitation model of *Hardy et al.* [1985] for a *Kp* of 4 was used, and was kept constant during the entire simulation. O^+ profiles were generated at 5-minute time steps for the 17 hours prior to the 1700 UT first convection change and through to 2100 UT. Snapshots of the $F2$ peak density (N_mF2) at 1700, 1830, 2000, and 2100 UT are shown in Plate 1. At 1700 UT, a well-defined TOI feature in the polar cap shows how the plasma transport associated with the Figure 1 left-panel convection brings high-density plasma into the dawn-side of the polar cap. The peak density in the TOI is around 1 x 10^6 cm^{-3}. In the remainder of the polar cap, the density drops to values as low as 1 x 10^5 cm^{-3}.

The effect of changing the convection pattern at 1700 UT can be seen in the N_mF2 snapshot at 1830 UT. A new TOI begins to form on the dusk-side of the polar cap and structuring of the high-latitude plasma also begins as the old dawn-side tongue is caught up in the circulation of the dawn convection cell. At 1830 UT, the convection changes back to its initial pattern and further structuring occurs in the high-latitude plasma at 2000 and 2100 UT (see Plate 1). In particular, after 2000 UT a TOI forms back in the dawn-side of the polar cap. It is the remnants of what was the dusk-side TOI, which are deformed and striated due to differing trajectories of the dusk convection cell. In the next section, results of a TDIM simulation will illustrate further details of how plasma structuring occurs.

3.2. *TDIM F-Region Patch Simulation*

The TDIM simulation followed the same methodology described for the PL simulation. The *Heppner and Maynard* [1987] empirical convection model was used. Specifically, the A and DE patterns, which correspond to southward IMF for B_y slightly negative and B_y strongly negative, respectively, were used. Plate 2 shows these two convection patterns within the TDIM simulation region. This region is centered on the magnetic pole and extends from 70° invariant latitude on the noon meridian to 70° invariant latitude on the midnight meridian, with noon at the top. The dawn-dusk latitudinal extent is somewhat smaller, i.e., from 76° invariant latitude at dawn to 76° invariant latitude at dusk. Each trajectory was followed for 24 hours prior to the snapshot. Each arrow in the convection patterns represents a 20-minute trajectory taken from within the simulation region. The A pattern convection is fairly uniform over the polar region at about 500 m/s. In contrast, the DE pattern has a dusk sector flow speed of 1000 m/s and a slow dawn sector flow of < 200 m/s.

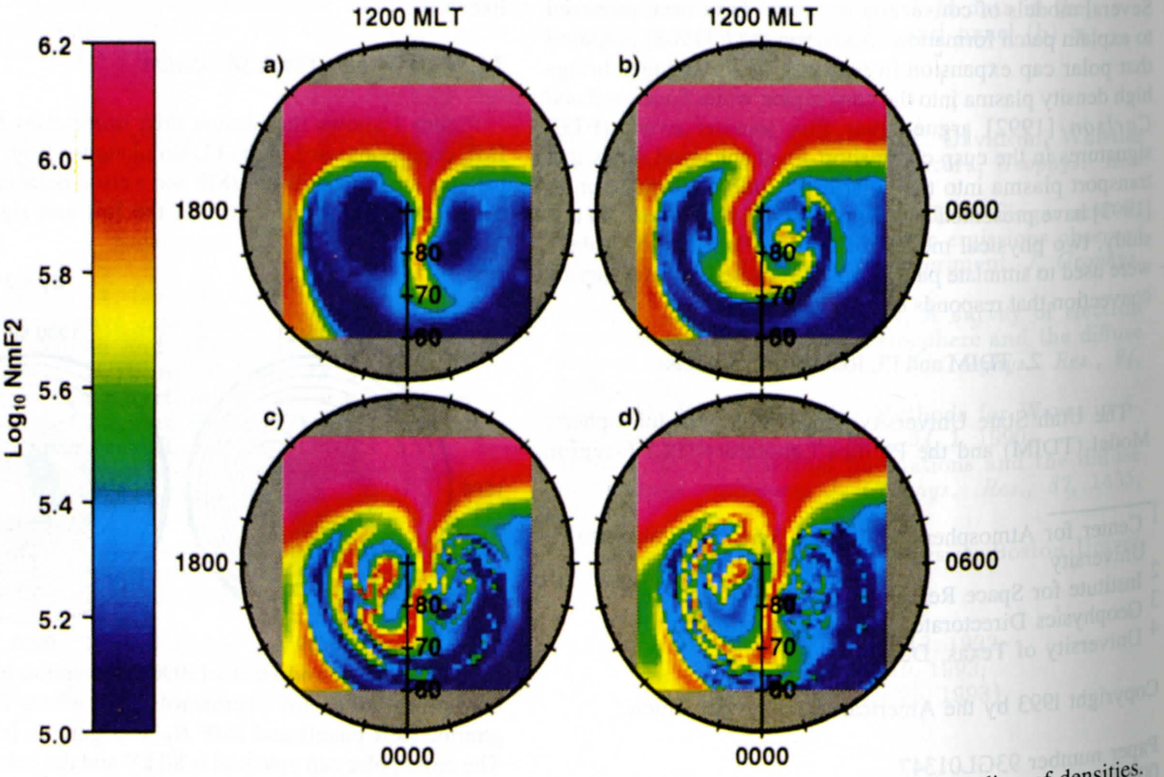

Plate 1. Four color-coded N_mF2 snapshots from the PL simulation. Each snapshot uses the same color coding of densities. The UT of each snapshot is as follows: (a) 1700 UT; (b) 1830 UT; (c) 2000 UT; and (d) 2100 UT.

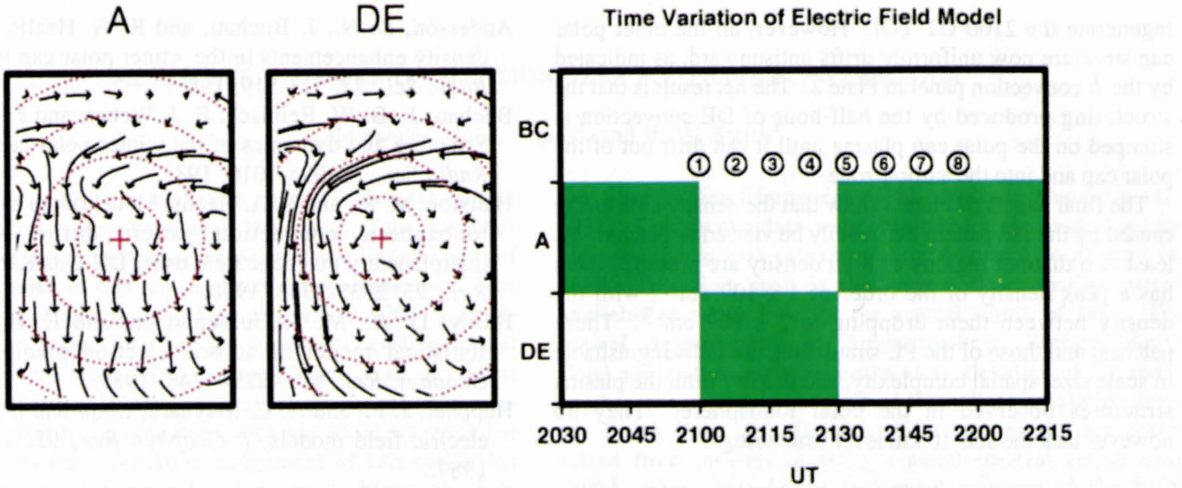

Plate 2. The A and DE convection patterns within the TDIM simulation region (left panels). The dotted red circles represent constant invariant latitudes at 5° intervals from the magnetic pole (red cross). Noon is at the top. The right panel shows the time history of the TDIM simulation as well as times of density snapshots (circled numbers) shown below.

The TDIM simulation is schematically shown in Plate 2 as a time-line plot at the top next to the two convection panels. Numbers are circled and placed along the time axis. These numbers identify the times of the TDIM N_mF2 snapshots shown in Plate 3. These are at eight minute time intervals beginning at 2100 UT when the first change in the convection pattern occurs. A well defined TOI is present in the first snapshot. Panel 3, sixteen minutes after the change to DE, already shows well defined changes in the TOI. However, this only occurs near the throat; everywhere else the convection associated with the TOI has slowed down, but maintains the same flow direction. This differential flow trend is maintained until 2130 UT. Each panel up to this time shows that the distortion of the tongue increases. Indeed, by 2130 UT, Panel 5, the density structuring is too complex to be referred to as a single TOI. At 2130 UT, the convection reverts back to the A pattern and the ensuing snapshots show how the plasma entering the polar cap at the cusp begins to

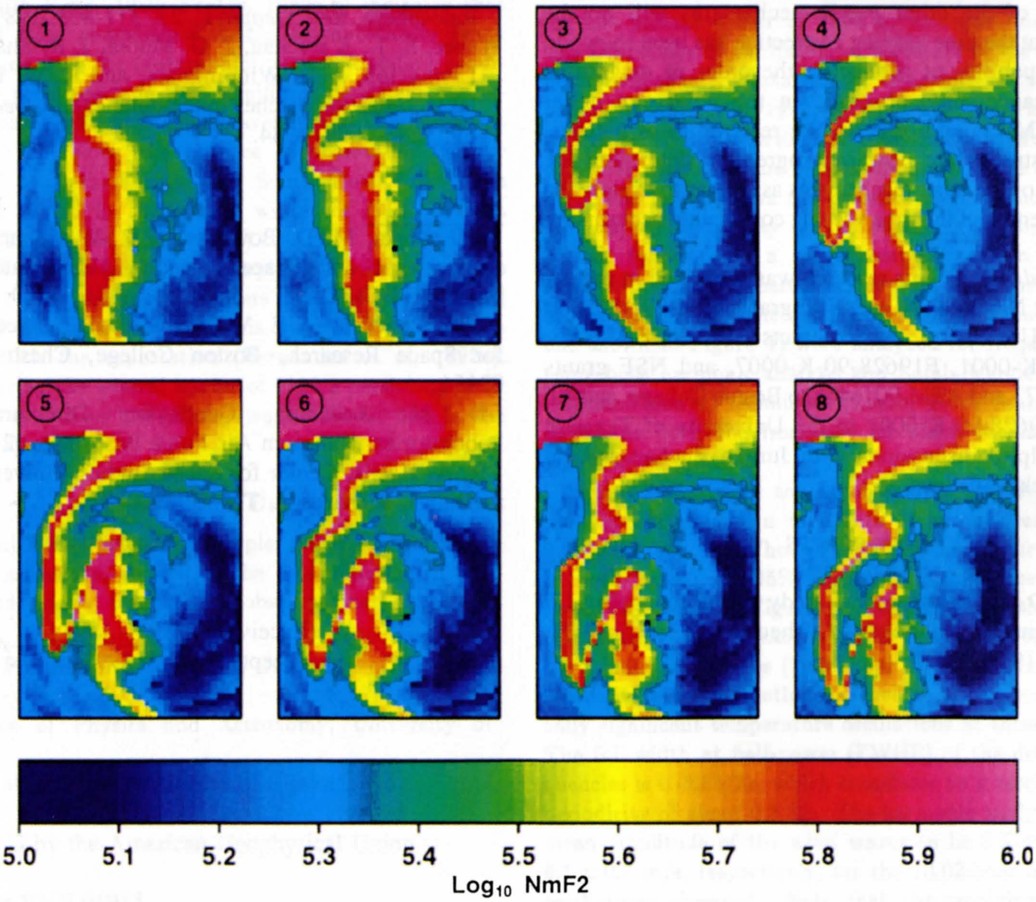

Plate 3. A series of eight color-coded N_mF2 snapshots from the TDIM simulation. Each snapshot uses the same color coding of densities. The snapshots are labeled with the numbers given in the time history plot of Plate 2.

regenerate the 2100 UT TOI. However, all the other polar cap structure now uniformly drifts antisunward, as indicated by the A convection panel in Plate 2. The net result is that the structuring produced by the half-hour of DE convection is stamped on the polar cap plasma until it can drift out of the polar cap and into the auroral zone.

The final panels of Plate 3 show that the density structuring caused by the DE pattern can readily be viewed as patches. At least two distinct regions of high density are present. Each has a peak density of the order of 1×10^6 cm^{-3}, with the density between them dropping to 2×10^5 cm^{-3}. These patches, and those of the PL simulation, are indistinguishable in scale size, spatial complexity, and density from the plasma structures observed in the polar ionosphere. They do however lack the sub-10 km level structuring.

4. Conclusions

The PL and TDIM simulations show that the shape and extent of polar cap patches are determined by the plasma flow changes that occur while the plasma is in the cusp and polar cap. Qualitatively, the PL and TDIM simulations show, for the first time, that given the variability we know exists in the IMF and, hence, the magnetospheric convection, patches occur naturally without complex plasma source and sink mechanisms. Both models show that, under constant southward IMF conditions, a TOI extends from the cusp into the polar cap. It is this flow of dayside high-density plasma that becomes the source of patches as the convection undergoes time variations.

The role of the other patch mechanisms will not be irrelevant, but the time varying convection has been shown to have the capability of producing the order of magnitude density enhancements observed in the polar cap under southward IMF conditions that are referred to as patches. Follow-on studies are now in progress to determine the contribution of the other mechanisms as well as to explore the full consequences of the time varying convection mechanism.

Acknowledgment. This research was supported in part by NASA grant NAG5-1484 and NSF grant ATM-89-13230 to Utah State University; AF contracts F19628-88-K-0008, F19628-89-K-0001, F19628-90-K-0007, and NSF grants ATM-9000273 and ATM-9016465 to Boston College; and AF contract F19628-90-K-0001 to the University of Texas at Dallas. Helpful discussions with Jurgen Buchau and Ed Weber are acknowledged.

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(Received April 11, 1993;
accepted May 5, 1993.)