Field-aligned currents during northward interplanetary magnetic field: Morphology and causes

S. Vennerstrom
Danish National Space Center, Copenhagen, Denmark

T. Moretto and L. Rastätter
NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

J. Raeder
Institute for the Study of Earth, Oceans and Space, University of New Hampshire, Durham, New Hampshire, USA

Received 24 September 2004; revised 18 January 2005; accepted 10 February 2005; published 9 June 2005.

[1] We present the results of a global MHD simulation of solar wind magnetosphere interaction during northward IMF. In particular, we emphasize the effect of the IMF B_y component on the reconnection geometry and the mapping along field lines to the polar ionosphere, through field-aligned currents. We find that the existence and geometry of the polar cap is closely connected to the IMF B_y component. During strictly northward IMF the simulated magnetosphere can remain essentially closed because the solar wind field lines reconnect in both hemispheres, thereby creating newly reconnected closed dayside field lines. The existence of a small nonzero IMF B_y component, however, effectively acts to open up the magnetosphere. When $|B_y| < B_z$ the position of the polar cap is strongly asymmetric with respect to the noon-midnight meridian, depending on the sign of B_y. In the northern hemisphere for B_y positive(negative) the polar cap is then located mainly in the dawnside (duskside), in close accordance with what have been observed using particle precipitation data or auroral observations. The simulated NBZ currents map to major portions of the magnetopause: the flanks and the mantle. They can exist both on open and closed field lines and are created by the shear of the newly reconnected field lines against the mantle field as they are convected tailward by the solar wind. When the IMF rotates from northward toward east, the magnetospheric mapping regions of the NBZ currents likewise rotates. However, the idea that the NBZ currents rotate to form the two sheets of FACs sandwiching the ionospheric DPY current is only partly confirmed by the simulation.

Citation: Vennerstrom, S., T. Moretto, L. Rastätter, and J. Raeder (2005), Field-aligned currents during northward interplanetary magnetic field: Morphology and causes, *J. Geophys. Res.*, *110*, A06205, doi:10.1029/2004JA010802.

1. Introduction

[2] There is a long tradition for investigating solar wind-magnetosphere interaction processes by observing their effect on the high-latitude ionosphere. Because of the huge extent of the dayside magnetopause, this method remains the only way to obtain a global view of the interaction processes at any given time. Several ionospheric signatures are used, ranging from the pattern of ionospheric electric fields and currents to the pattern of aurora and particle precipitation. Field-aligned currents (FAC) flowing along the field lines from the magnetosphere to the ionosphere, although not the most frequently observed signature, are of special importance because they constitute a direct link between the magnetospheric processes and the ionospheric signatures.

[3] During northward interplanetary magnetic field (IMF) conditions, strong field-aligned currents (FACs) and ionospheric convection are known to exist in the polar cap and cusp region. The origin of these currents as well as their detailed morphology, however, are still not completely understood. In particular, the effect of a nonzero IMF B_y component in addition to the positive B_z component, is poorly understood.

[4] When the interplanetary magnetic field (IMF) is predominantly northward, sunward convection associated with two so-called reversed convection cells are found at very high latitudes [e.g., *Maezawa*, 1976; *Burke et al.*, 1979; *Huang et al.*, 2000]. The convection cells have been found to be accompanied by a set of two oppositely directed field-aligned currents, the so-called NBZ currents [e.g.,

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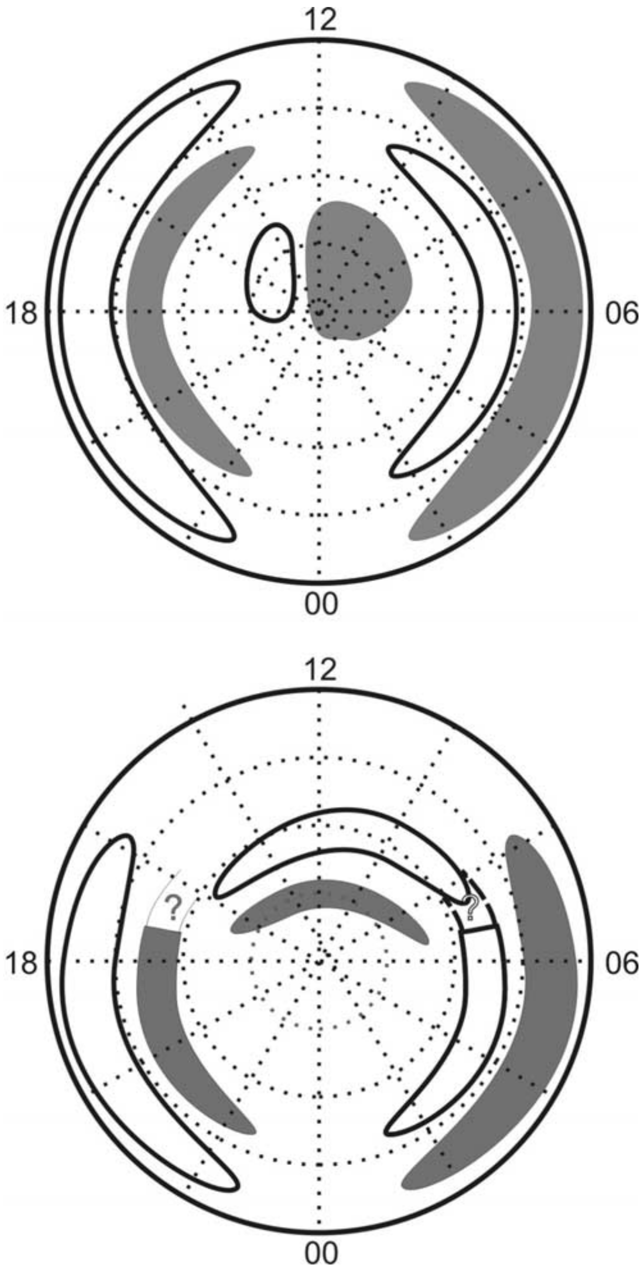

Figure 1. Cartoon showing different views of the pattern of field-aligned currents for positive B_z and positive B_y. White currents are downward, and gray currents are upward. (top) Interpretation of the data from Magsat [*Iijima et al.*, 1984]. (bottom) Interpretation of groundbased magnetic measurements [*Wilhjelm et al.*, 1978; *Friis-Christensen et al.*, 1985].

Iijima et al., 1984; *Friis-Christensen et al.*, 1985]. Very early these signatures were taken as evidence for the occurrence of magnetic merging between the IMF and the magnetosphere poleward of the cusp [*Maezawa*, 1976], and subsequent mapping of the dusk-to-dawn directed solar wind electric field to the polar ionosphere. This idea has later been developed further in several studies [e.g., *Cowley*, 1983; *Lyons*, 1985; *Song and Russell*, 1992; *Crooker*, 1992] but has also been disputed theoretically [*Vasyliunas*, 1989; *Hill*, 1994].

[5] The existence of a substantial IMF B_y component in addition to the northward component, causes asymmetry of the field-aligned currents and convection cells. As the magnitude of B_y increases, one of the cells in the reversed system will grow while the other cell will contract [*Reiff and Burch*, 1985]. As regards the FACs, different patterns have been suggested. From the magnetic measurements of the Magsat satellite, a low-altitude polar orbiting satellite flying in a dusk-dawn orbit, it was inferred that when the IMF rotated from northward toward east (west) the dawnside (duskside) NBZ current would spread out over the polar cap while the duskside (dawnside) NBZ current would decrease in area and intensify (An eastward component of the IMF corresponds to $B_y > 0$ and a westward to $B_y < 0$). The resulting pattern of FAC for $B_y > 0$ is illustrated in Figure 1 (top). On the other hand, the existence of an east-west flowing ionospheric current associated with IMF B_y, the so-called DPY current, has been inferred from ground-based measurements. The DPY current has been observed to be sandwiched between two sheets of roughly east-west aligned FACs [*Wilhjelm et al.*, 1978; *Friis-Christensen et al.*, 1985] as illustrated in Figure 1 (bottom). The association between the most equatorward of these two currents and the dayside region 1 current has also been discussed [e.g., *Friis-Christensen et al.*, 1985; *Iijima*, 2000]. On the basis of magnetic measurements from noon-midnight passes of the polar orbiting satellite Ørsted *Vennerstrom et al.* [2002] suggested that when the IMF rotates from northward toward east or west, the two NBZ currents rotate to form the two sheets of FACs sandwiching the ionospheric DPY currents.

[6] Interpreting the changing patterns of FACs and ionospheric convection in terms of different reconnection scenarios at the magnetopause is a very indirect way to investigate solar wind-magnetosphere interaction and requires extensive theoretical support. Here we present the results of a global MHD simulation of solar wind magnetosphere interaction, in which the IMF is rotated slowly from strictly northward to eastward, while all other parameters are kept constant. We use this to investigate how the field-aligned currents in the high-latitude ionosphere develop in response to the changing reconnection scenario at the dayside magnetospheric boundary. Because of the extensive use of ionospheric signatures as indicators of magnetopause merging, and also due to the complicated field line geometry, the emphasis of our analysis is the mapping along field lines from the ionosphere to the magnetosphere.

2. Model

[7] The used model is the so-called open Geospace General Circulation Model (GGCM), which was originally developed as a MHD model of Earth's magnetosphere at UCLA in the early 1990s [*Raeder et al.*, 1995, 1998; *Raeder*, 2003]. The model solves the ideal MHD equations in the magnetosphere. Numerical effects like diffusion, viscosity, and resistivity are necessarily introduced by the numerical method [*Raeder*, 1999; *Raeder et al.*, 2001]. These permits viscous interaction and also magnetic field reconnection to a limited extent. The only explicit diffusive term is the anomalous resistivity that is included in Ohms law. The model includes a magnetosphere-ionosphere cou-

pling module that not only maps the field-aligned currents into the ionosphere and the potential back into the magnetosphere, but also computes electron precipitation parameters and the ionospheric Hall and Pedersen conductances using empirical relations in a self-consistent manner [*Raeder et al.*, 1998; *Raeder*, 2003].

[8] The magnetospheric part solves the MHD equations on a stretched Cartesian grid using second-order explicit time integration with conservative and flux-limited spatial finite differences [*Raeder*, 2003]. A Yee grid is used to preserve the magnetic field divergence to roundoff error. The simulation results used for this study are from the implementation of the code run at the Community Coordinated Modeling Center (CCMC) at NASA Goddard Space Flight Center. The run was performed as a so-called run on request, and the modeling results are available at http://ccmc.gsfc.nasa.gov/ under run number Susanne_Vennerstrom_102402_1.2. The code has been run on a grid $160 \times 60 \times 60$ in size, spanning from $-255\ R_E$ to $33\ R_E$ in the GSE X direction and from $-48\ R_E$ to $48\ R_E$ in the GSE Y and Z directions. The grid has finest resolution of $0.4\ R_E$ close to the inner magnetospheric boundary.

[9] Field-aligned currents are calculated close to the inner boundary of the magnetospheric part of the simulation (at $3.7\ R_E$) and are used as input to solve the ionospheric potential equation. The field-aligned currents are mapped from the inner boundary of the magnetospheric part of the simulation into points in the ionosphere along dipole field lines.

[10] The ionospheric Hall and Pedersen conductances play a large role in determining the ionospheric electrodynamics of the model. In the implementation of the model used for this study, they are computed from empirical formulas. The conductances are proportional to the ionospheric number energy density (mostly dominated by the E region), which is mainly determined by solar EUV irradiance and precipitation of magnetospheric electrons. The contribution to the conductance from the former is reliably parameterized by the solar radio flux parameter, $F_{10.7}$, together with the solar zenith angle [*Moen and Brekke*, 1993]. The contributions to the conductance from magnetospheric electron precipitation are parameterized by the energy flux and mean energy of the precipitating electrons [*Robinson et al.*, 1987]. For the diffuse precipitation (from pitch angle scattering of hot magnetospheric electrons) these are parameterized, in turn, by the magnetospheric electron temperature and density, which are approximated by the density and temperature values from the magnetospheric part of the simulation. Additional discrete electron precipitation (auroral electrons accelerated by field-aligned potential drops) is parameterized by the field-aligned current density through the Knight relation [*Knight*, 1972].

3. Simulation Results and Discussion

[11] The solar wind input parameters specified for the run are the following: solar wind speed $v = 400$ km/s, number density $n = 7\ \mathrm{cm}^{-3}$, and IMF intensity $B = 10$ nT. All these are kept constant throughout the run, only the direction of the IMF is changed. At the beginning of the run the IMF is strictly northward ($B_z = 10$ nT, $B_y = 0$ nT). The IMF then rotates eastward at a constant rate until it, two hours later, is strictly eastward ($B_z = 0$ nT, $B_y = 10$ nT). The IMF B_x component is zero throughout the run.

[12] The initial conditions for the magnetic field are constructed from the superposition of the Earth's dipole over an equally strong mirror dipole, such that B_x vanishes at $x = 16\ R_E$. Sunward of the plane of symmetry at $16\ R_E$ the field is replaced by the initial solar wind field. The simulation is started with a 2 hour run where all the solar wind parameters are kept constant at their initial values, i.e., with a 2 hour run of strictly northward IMF. Only after this the simulation described below starts, and this time instant is therefore in the following referred to as $t = 0$. The result of this procedure is, as will be seen below, that the magnetosphere is completely closed at $t = 0$.

3.1. Ionosphere: The Changing FACs

[13] The evolution of the ionospheric convection pattern and the pattern of FACs flowing into and out of the ionosphere as the IMF slowly rotates from strictly northward toward east is illustrated in Figure 2. The diagrams show the simulated electric potential and the intensity of FACs over the northern polar ionosphere as a function of latitude and MLT. The simulation was performed without any dipole tilt and the evolution in the northern and southern polar ionosphere are therefore highly symmetric. Consequently, we will show in the following only the results of the northern polar ionosphere. Upward currents are color-coded blue while downward currents are red. The small insert in the top left of each diagram shows the direction of the IMF just outside the bow shock. The black and white lines are contours of the electric potential illustrating the pattern of ionospheric convection. When the IMF is strictly northward, we see the well-known four cell pattern with two so-called reversed convection cells at very high latitudes, creating sunward convection in the central polar region, and two viscous cells at somewhat lower latitudes. The two reversed cells are associated with the two elongated NBZ currents with clear maxima in the dayside, upward at the dawnside and downward at the duskside. Equatorward of the NBZ currents two region 1 type FAC regions are observed, downward at the dawnside and upward at the duskside.

[14] At the first three snapshots hardly any change is observed. Presumably this is at least partly due to the rather slow rotation of the IMF, but in addition reflects the delay between the arrival of the IMF change at the bow shock and the subsequent evolution of the FAC pattern. (We note that this means that if the results shown here are compared with the results of steady state simulations, one should not combine the results with the IMF insert in the same panel, but with the IMF insert two or three panels earlier). A time delay of 20–30 min between variations in the solar wind and the full development of the resulting currents in the high-latitude dayside ionosphere is also in good accordance with observations [*Friis-Christensen et al.*, 1985; *Clauer and Friis-Christensen*, 1988; *Ridley et al.*, 1998]. The first definite indication of a change in the FAC pattern due to the rotating IMF is observed at 0030:00 as a gradual increase of upward current in the central polar cap poleward of the original 2 NBZ currents. This is accompanied by a growth of the dawnside reversed convection cell at the expense of the duskside reversed

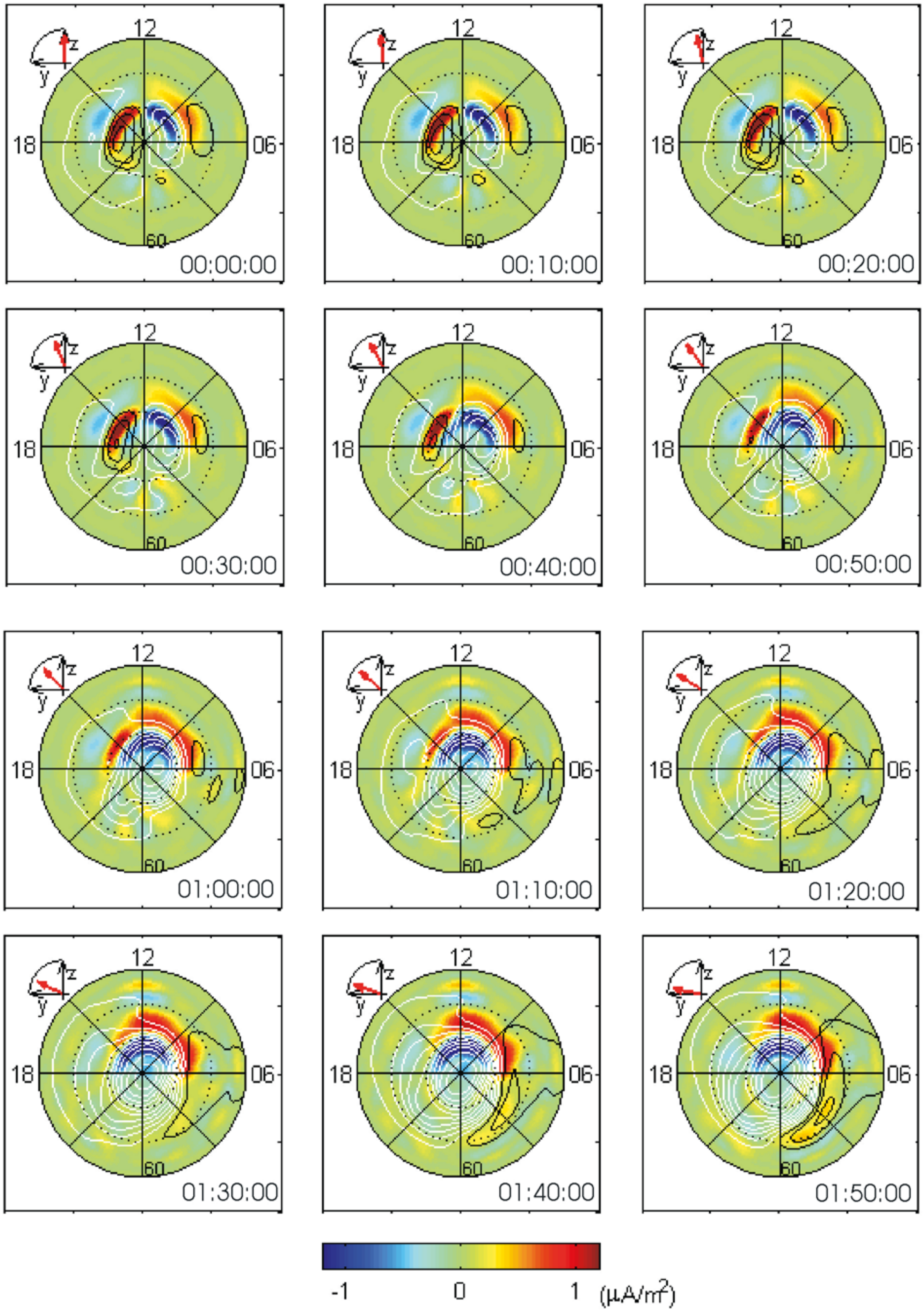
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Figure 2

cell, establishing a distorted and slightly skewed reversed two-cell pattern.

[15] As the IMF rotates further toward east, this process continues until, eventually, the reversed dusk cell disappears and only a single cell remains. At this time, around 0100:00, the size of IMF B_y and B_z are roughly equal. The former dawnside (blue) NBZ current now occupies the entire dayside polar region poleward of 80 degrees. The former duskside (red) NBZ current has significantly decreased or has rotated toward the dayside where it has coalesced with the dawnside region 1 current. This coalescence/disappearance starts with an intensification of the dawnside region 1 current in the noon region (around 0040:00–0050:00) and seems to be completed with the disappearance of the duskside reversed convection cell (around 0100:00). The growth of the dawnside NBZ current and the degeneration of the duskside NBZ and region 1 current for increasing B_y relative B_z is in close accordance with observations of FAC from the Magsat magnetic satellite data [*Iijima and Shibaji*, 1987].

[16] As the IMF rotates even further, past the point where $B_y = B_z$, a new convection cell starts to grow at the dawnside of the former dawnside reversed cell. Together these two cells now constitute a skewed, nonreversed, two-cell pattern. The new dawn cell is centered in the nightside region of the dawnside and its appearance is accompanied by a growth of the region 1 currents on the nightside, both on the dawnside and duskside. This final pattern is similar to what was simulated and analyzed previously by *Crooker et al.* [1998] and *Tanaka* [1999], using the constant IMF conditions $B_z = 0$ and $B_y > 0$ [*Crooker et al.*, 1998] and $B_y = B_z$ [*Tanaka*, 1999], respectively.

3.2. Magnetosphere: Reconnection Scenario

[17] There is no doubt that the ionospheric convection and FACs described above are caused by magnetic reconnection between the IMF and the Earth magnetic field at the simulated magnetopause. It is important therefore to understand the detailed geometry of the reconnection process: how it develops as the IMF rotates, and how it maps to the high-latitude ionosphere.

[18] We start by examining the development of the open/closed field line boundary in the ionosphere. Figure 3 shows polar diagrams of the northern hemisphere ionospheric electric potential, similar to the potentials shown in Figure 2 but now overlaid with a red region identifying the polar cap. The polar cap has been identified using a grid of field lines from the northern polar region, each of which was determined to be open or closed in the simulation box. In the beginning of the run, when the IMF is strictly northward, the magnetosphere is essentially closed, only very few and rather sporadic open field lines exist close to the pole on the dayside. This seems rather surprising, considering that the reversed convection pattern is generally believed to be caused by reconnection of the IMF with lobe field lines poleward of the cusp [*Reiff and Burch*, 1985]. Figure 4, showing a number of simulated field lines at time 0000:00, however, illustrates how this is possible. Because of the perfect north-south symmetry in the model, almost all reconnecting field lines will reconnect both in the northern and southern hemispheres, poleward of the northern cusp as well as poleward of the southern cusp. In the beginning of the simulation no other form of reconnection has occurred. Therefore the tail field lines are closed field lines and no open lobe field lines exist yet. Consequently, the result of the reconnection process is that closed tail field lines are converted to highly distorted closed dayside field lines while the magnetosphere remains closed. The subsequent evolution of these newly reconnected field lines is then causing the sunward convection in the central polar ionosphere. This reconnection scenario between the IMF and the closed tail field lines was suggested by *Cowley* [1983] and was further developed by *Crooker* [1992], as a way to resolve the theoretical objections raised against the concept of reversed convection on open lobe field lines [*Vasyliunas*, 1989; *Hill*, 1994]. It should be mentioned that the initial absence of a polar cap in the simulation is due to the fact that the simulation starts with a closed magnetosphere and strictly northward IMF. This is unlike the real magnetosphere where $B_z > 0$ is always preceded by $B_z < 0$. It is, however, interesting that the NBZ current system can develop in a completely closed magnetosphere.

[19] As the IMF rotates and the effect of this rotation starts to show up in the ionospheric convection and FACs, i.e., at 0030:00, this scenario changes, however. Now, a small but significant polar cap starts to grow on the dayside, being located highly asymmetrically on the dayside and on the dawnside with only a small extension into the dusk side. As the IMF rotates further, up to the point where IMF B_y and B_z are of roughly equal size (around 0100:00), the polar cap continues to grow both on the dayside and into the nightside. During this period, it remains highly asymmetric with respect to the noon-midnight meridian, being clearly displaced toward dawn. It also is clearly associated with the growing dawnside convection cell.

[20] This gradual and asymmetric opening of the magnetosphere as the IMF rotates can be understood in terms of changing reconnection geometry. When the IMF is strictly northward, the solar wind field lines can reconnect in both hemispheres. If the magnetosphere is to remain closed, the same, however, has to be true for the reconnecting Earth field lines. If the simulated magnetosphere starts out as a closed structure, the reconnecting Earth field lines will be closed tail field lines reaching the magnetopause poleward of the cusps. Both the northern and southern part of these tail field lines will be able to reconnect with the IMF. Only if all reconnecting solar wind field lines, as well as all reconnecting tail field lines reconnect in both hemispheres, will the magnetosphere remain essentially closed. This is illustrated in Figure 4 and also in Figure 5a, which is a cartoon of the reconnection geometry shown in Figure 4 but as seen from the Sun. If we now allow the IMF to rotate

Figure 2. Development of the simulated FAC pattern (color-coded) and electric potential (contour lines) in the northern polar region when the IMF (shown in the top left corner of each plot) rotates from northward to eastward. Upward FACs are blue, and downward FACs are red. White contour lines signify negative potential, and black contour lines signify positive potential. Contour line spacing is 10 kV. Read 00:00:00 as the time in hours:minutes:seconds.

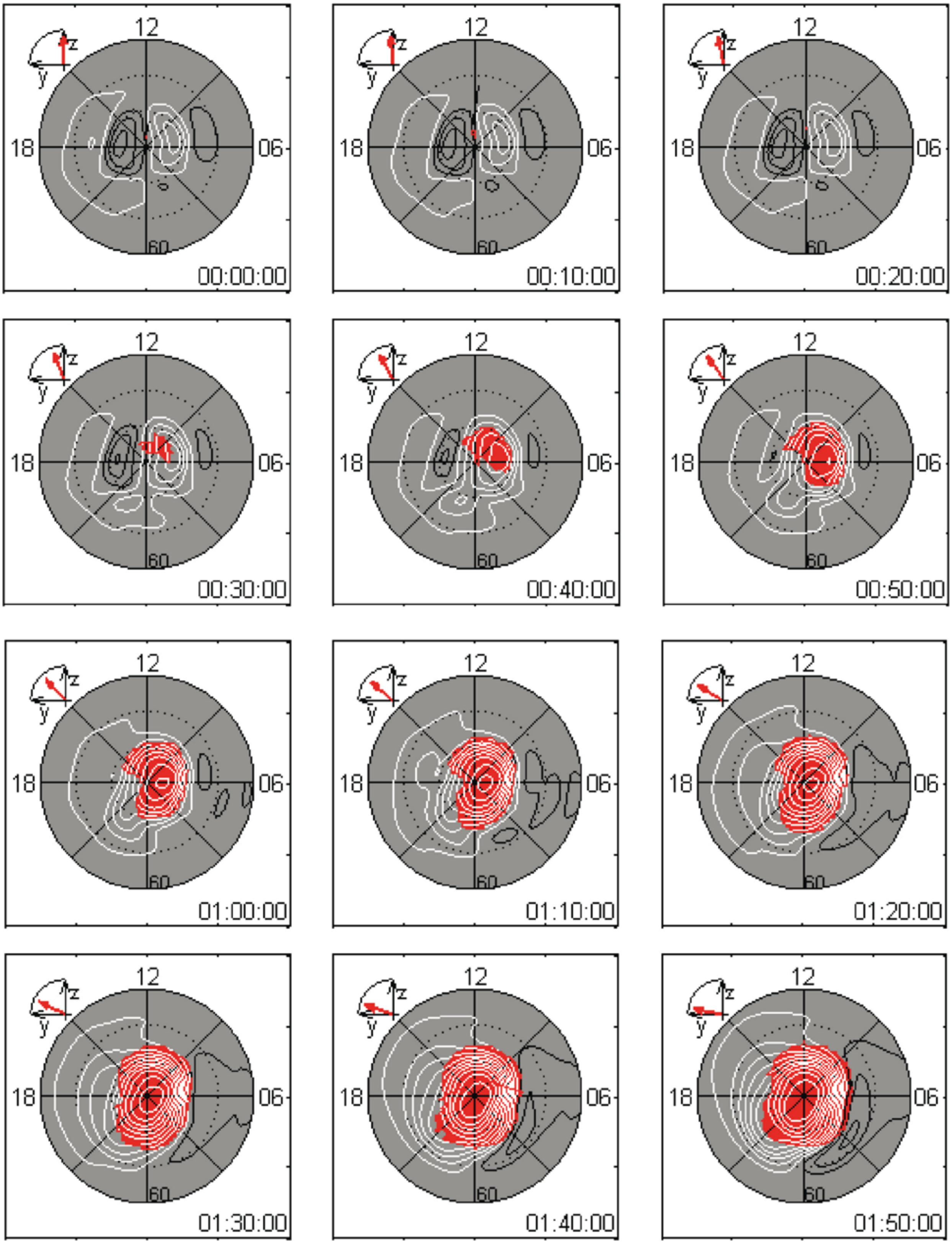

Figure 3. Plots illustrating how the polar cap slowly opens up when the IMF turns from northward to eastward. The red region is the polar cap. Superposed on this is shown contour lines of the electric potential, identical to that shown in Figure 2.

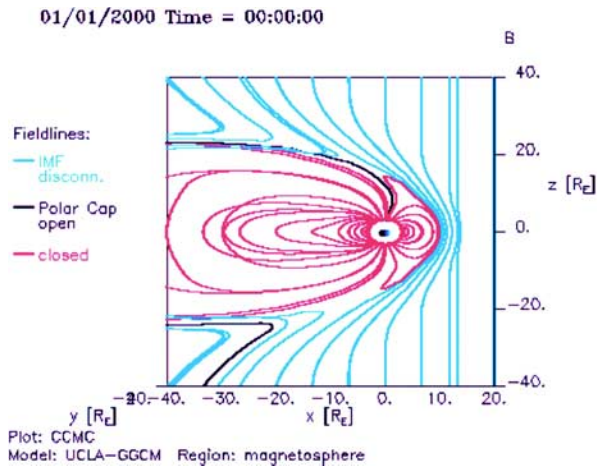

Figure 4. Simulated magnetic field lines for strictly northward IMF. The field lines reconnect in both "ends" (hemispheres).

slightly in the eastward direction, the reconnection region will move toward the duskside in the northern hemisphere and toward the dawnside in the southern hemisphere. In this case, the IMF will still be able to reconnect in both hemispheres creating highly distorted newly reconnected field lines, which now cross the noon meridian from northern dusk to southern dawn at the dayside. This is illustrated by the cartoon in Figure 5b. The resulting ionospheric convection still has a strong sunward component, but now also an eastward component. Concerning the effect on the field line topology, however, there is a very important difference between Figures 5a and 5b. While the solar wind field lines are still able to reconnect in both "ends" in Figure 5b, this, however, is no longer true for the Earth field lines. Because the reconnection regions are located asymmetrically in the northern and southern hemisphere, the closed field lines in the tail flanks will now only reconnect in one hemisphere. Thus the creation of a distorted dayside field line by reconnection in both hemispheres of a solar wind field line, in this case, has the additional result of creating two open field lines, one from each hemisphere. The introduction of an eastward (or westward) component in addition to the northward component of the IMF therefore invariably will result in a gradual opening of the magnetosphere. The open field lines created by this process will be located asymmetrically with respect to the noon-midnight meridian: in the northern hemisphere they will be found at the dawnside, and in the southern hemisphere at the duskside (for $B_y > 0$). This is exactly the asymmetry found in the simulation during the initial opening of the polar cap (0030:00–0100:00).

[21] Apart from preventing the closed Earth field lines from reconnecting in both ends the introduction of a nonzero IMF By has another effect that also acts to open up the magnetosphere, namely the effect of destroying the symmetry. In the case of strictly northward IMF, the reconnecting solar wind field lines encounter identical magnetic fields at both hemispheres. If the IMF also has an eastward component, this symmetry no longer exists. In this case, only the solar wind field lines passing through the line connecting the Earth and the Sun will encounter identical field geometries in both hemispheres. This means that the solar wind field lines will have a larger tendency to reconnect only in one hemisphere. If the reconnecting tail field lines are closed, each reconnected solar wind field line will then again result in two open field lines (Figure 5c). The asymmetry created by the slight rotation of the IMF therefore also works toward opening up the magnetosphere. The asymmetry increases when B_y increases relative to B_z and the tendency for the solar wind field lines to reconnect in only one hemisphere will therefore also increase.

[22] As described above, the introduction of a nonzero B_y component in addition to the positive B_z component of the

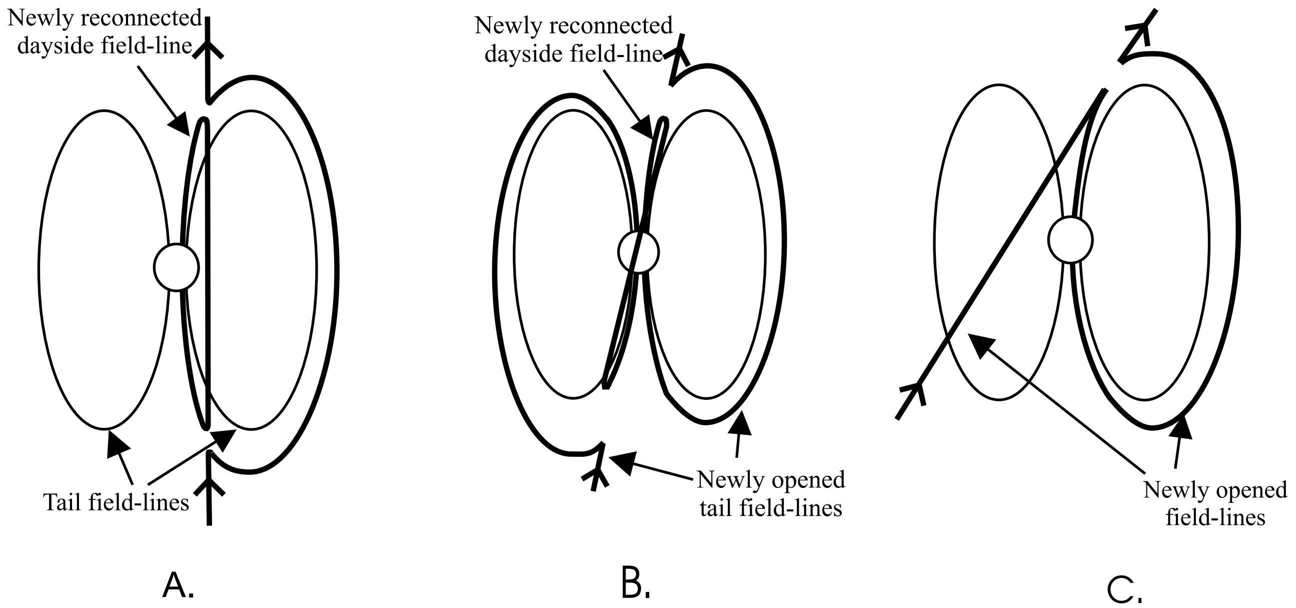

Figure 5. Cartoon of reconnection geometry as seen from the Sun. Note that the field lines drawn with a thin line are tail field lines just poleward of the cusp.

IMF therefore acts to open up the magnetosphere through two processes: an increasing tendency of the Earth field lines to reconnect only in one hemisphere and an increasing tendency of the solar wind field lines to reconnect only in one hemisphere. When a substantial amount of open polar cap field lines exist, we expect the solar wind field lines to start reconnecting on these open lobe field lines generating lobe cell convection. Such lobe cells have been found to exist in MHD simulations during steady state conditions [*Crooker*, 1988; *Raeder et al.*, 2000]. If, in this case, the solar wind field lines still reconnect in both ends, this process will now act to decrease the amount of open flux.

[23] In the simulation we can examine the field lines close to the open/closed field line boundary in more detail, looking for signatures of reconnection. Figure 6 shows the foot points of a grid of field lines entering the northern polar region at three selected times during the run. The light gray dots show the ionospheric foot points of open field lines and the black dots those of the closed field lines. The green rings indicate newly reconnected closed field lines, i.e., strongly kinked and skewed dayside field lines, which are rooted in the duskside in the northern hemisphere but in the dawnside in the southern hemisphere. These closed field lines cross the noon-meridian and therefore must be solar wind field lines having reconnected in both ends as illustrated at Figure 5b. Similar highly skewed dayside field lines were found by *Rastätter et al.* [2002] in a MHD simulation of a real $B_z > 0$ event, based on a different MHD code.

[24] With regard to the newly reconnected open field lines, they can be classified in two types according to the location of the reconnection region. Following the naming convention used by *Tanaka* [1999], field lines that have reconnected in the same hemisphere as they are rooted are called type 2 field lines and field lines having reconnected in the opposite hemisphere are called type 3 field lines (see Figures 5b and 5c). The red circles in Figure 6 mark field lines that show a signature of recent reconnection, i.e., sharp kinks, in the northern hemisphere (type 2), while the blue circles mark field lines that show signatures of recent reconnection in the southern hemisphere (type 3). An automatic algorithm was used to identify field lines with sharp directional changes (>90 deg), but in addition the marked field lines have been verified by visual inspection to clearly belong to one of the three types. Examples of each type of field lines are shown in Figure 7.

[25] All three plots in Figure 6 (left) display all three types of newly reconnected field lines. This shows that both reconnection scenarios illustrated in Figures 5b and 5c occur in the simulation whenever the IMF is tilted in the YZ plane.

[26] Observations of electron precipitation for IMF $B_z > 0$ suggest that the polar caps never close completely even after several days of profound magnetic quiet [*Meng*, 1981; *Makita and Meng*, 1984]. On the other hand observational evidence for occasional polar cap closure has also been presented [*Newell et al.*, 1997]. In this context the simulation results are important, because they designate a possible reason why the real magnetosphere rarely seems to close, namely the effect of IMF B_y. The reconnecting but closed magnetosphere, seen at the beginning of the simulation, is the result of a two hour run keeping the solar wind parameters fixed at the initial conditions, i.e., IMF strictly northward. In reality we do not expect the IMF B_y to stay identically zero for such prolonged time intervals. As described above, the course of the simulation clearly demonstrates that even a small tilt of the strictly northward IMF, either to the east or west will result in the development of an open polar cap.

[27] The dawn-dusk asymmetry of the location of the polar cap, seen in the simulation for $B_z > |B_y|$ is interesting because it is in accordance with observations of the auroral oval and particle precipitation. *Makita et al.* [1991] investigated auroral patterns and particle precipitation using DMSP F6 data and concluded that the open polar cap in the northern hemisphere was displaced toward dawn for $B_y > 0$ and toward dusk for $B_y < 0$. *Cumnock et al.* [1997, 2002] examined the development of theta aurora and its relationship to the IMF and found that the transpolar arc moved from dusk toward dawn when the IMF rotated from eastward through northward to westward. It is highly plausible that this could be associated with a closing polar cap on the dawnside simultaneously with the opening of a "new" polar cap in the duskside. The presently described reconnection scenario and modeling therefore seems promising in terms of explaining this type of theta aurora. Additional simulations beyond the scope of the present presentation, however, are needed to confirm this.

[28] Turning to the time development of the field line mapping and the reconnection geometry, the following can be observed. Figure 6 (top left) shows the occurrence of the three types of newly opened field lines at the time 0030:00, when we observe the initial opening of the magnetosphere. Only a small polar cap located mainly in the dawnside is observed at this time. The sharply kinked, recently reconnected open field lines, naturally, are observed close to the open/closed field line boundary but, interestingly, not only on the dayside but also at the nightside part of this boundary. The field lines having recently reconnected in the northern hemisphere (red) are located in the small part of the polar cap which extends into the dusk side. This is not surprising, since these field lines map close to the northern hemisphere reconnection region, which is displaced somewhat toward dusk due to the slight tilt of the solar wind field lines. The field lines having recently reconnected in the opposite southern hemisphere (blue) are located on the dawnside, but on the part of the polar cap boundary facing the nightside. This part of the open/closed field line boundary therefore must map to the dayside reconnection region in the southern hemisphere dawnside. The fact that the majority of the open field lines at this point are rooted in the dawnside ionosphere indicates that the majority of the open flux is created by reconnection in the opposite (southern) hemisphere. This points to the process illustrated in Figure 5b as the dominant reconnection process at this time of the run. The majority of the unmarked open field lines in Figure 5b can also be classified as type 3 but with a kink that is less sharp, which only means that these field lines reconnected less recently. The fact that most of the open-field lines are of type 3 indicates that at this time, most of the reconnecting solar wind field lines reconnect in both hemispheres (Figure 5b).

[29] Figure 6 (middle left) illustrates the situation a little later, at the time 0050:00. The polar cap has widened up, now extending considerably into the night side and also to

lower latitudes on the dayside. The large majority of the polar cap, however, is still located in the dawnside. The reconnection pattern also looks fairly similar. Both type 2 and type 3 field lines recently reconnected at the dayside magnetopause are still found near the open/closed field line boundary, with type 2 (red) at the dayside and duskside and type 3 (blue) at the nightside and dawnside.

[30] Figure 6 (bottom) illustrates the situation 50 min later (at 0140:00) when the IMF has rotated considerably and the new convection cell is beginning to form at the dawnside.

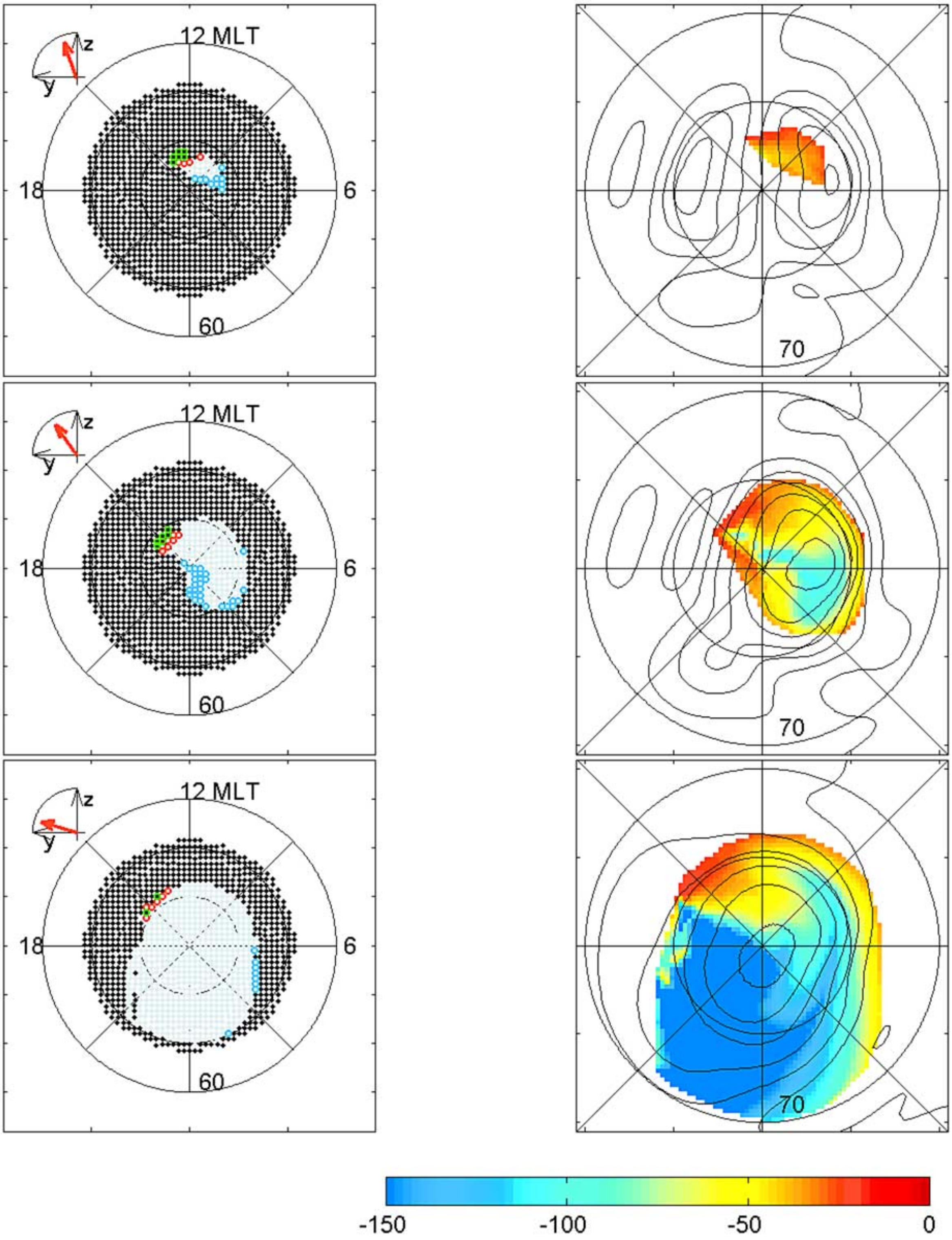

Figure 6

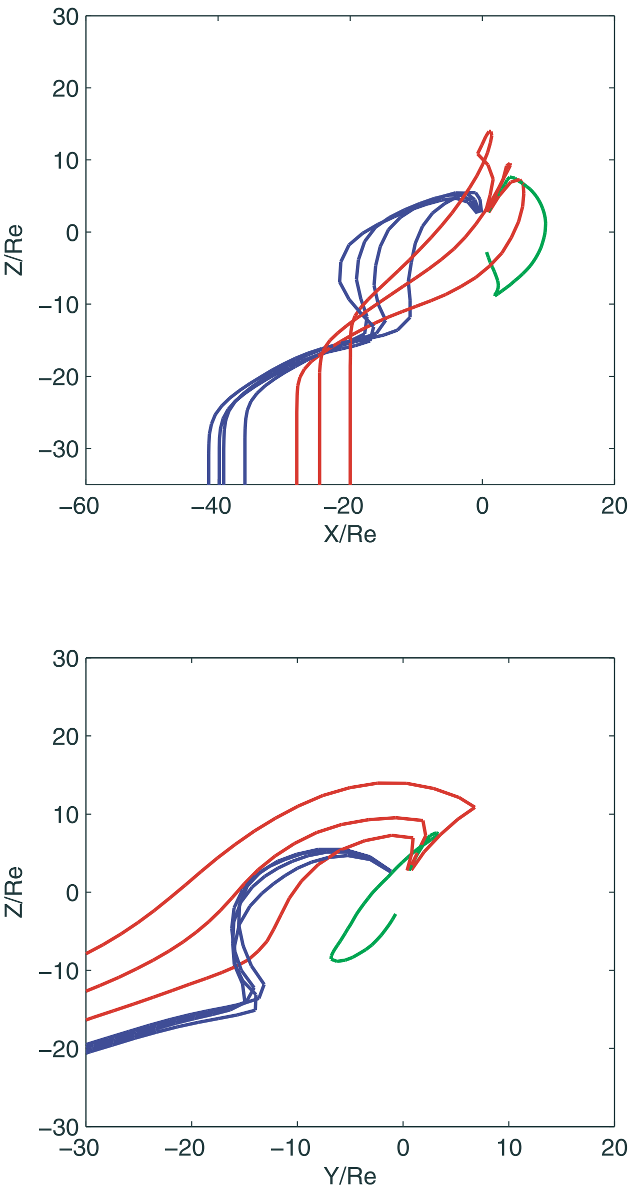

Figure 7. Examples of simulated newly reconnected field lines for which the ionospheric foot points are shown in Figure 6. Red field lines have reconnected in the same hemisphere as they are rooted, blue field lines have reconnected in the opposite hemisphere, and green field lines are double reconnected field lines. (top) View from the dawnside. (bottom) View from the Sun.

At this time the strong dawn-dusk asymmetry of the location of the polar cap has disappeared. All three types of newly reconnected field lines can still be found, but the number of newly reconnected closed dayside field lines has decreased. This indicates that the reconnection process illustrated in Figure 5c has now taken over as the dominant process. A number of the newly reconnected type 2 (red) field lines may also have been formed by reconnection between already open lobe field lines and the IMF. The existence of open field lines of type 3 (blue), however, shows that merging between the IMF and closed tail field lines still occurs at the dawnside flank of the magnetopause. These results are in accordance with the results of *Tanaka* [1999] using a steady state model run for IMF $B_y = B_z$.

[31] Figure 6 (right) illustrates the mapping of the field lines in a somewhat different way. For each open field line in the grid, we find the X coordinate of the point in the undisturbed solar wind, where this field line leaves the simulation box. This is illustrated in Figure 7 (top), as the points where the field lines hit the X axis. These X values are then used to color code the field lines foot points in the polar ionosphere. Assuming that reconnection takes place when the field line exit points are close to a certain X value, this X coordinate becomes, at least, an approximate measure of the time that has elapsed since the field line reconnected on the dayside.

[32] We see that at the initial opening of the magnetosphere, at time 0030:00 (Figure 6, top), all the open field lines connect to solar wind field lines with relatively small X values. This only means that they all reconnected relatively recently. At time 0050:00 (Figure 6, middle) the most recently reconnected field lines are found close to the open/closed field line boundary all the way around the polar cap. The field lines exiting the simulation box far downstream are located in the central polar cap, somewhat displaced toward the nightside. At time 0140:00, 50 min later (Figure 6, bottom), it is seen that field lines newly reconnected on the dayside are no longer formed on the part of the polar cap boundary facing the nightside. Open field lines near this boundary now leave the simulation box far down the tail. Interesting is also the “bifurcation” of the most recently reconnected (red/orange) region, which illustrates that the open field lines originate from two different reconnection regions, one in the northern and one in the southern hemisphere.

3.3. Field-Aligned Currents: Mapping Regions in the Magnetosphere

[33] The simulated evolution of the FAC in the polar ionosphere were described above. There is no doubt that the generation of these currents is related to the reconnection processes in the magnetosphere just described, and in this

Figure 6. Northern polar hemisphere at three instants during the run, from top to bottom: 0030:00, 0050:00, and 0140:00. (left) Grid of ionospheric foot points of magnetic field lines classified according to their magnetospheric characteristics. Black dots mark closed field lines, and gray dots mark open field lines. Colored circles mark field lines newly reconnected with the IMF, newly reconnected in the northern hemisphere magnetosphere (red), newly reconnected in the southern hemisphere (blue), and newly reconnected in both hemispheres (green), respectively. (right) Mapping to the polar ionosphere of the X coordinate at which the open field lines leave the simulation box. This is directly related to the time that has elapsed since dayside reconnection of a given field line. For the solar wind speed used here a distance of 100 R_e corresponds to 27 min.

section we focus our investigation on this relationship. Since the currents are field-aligned, at least in the inner magnetosphere, it makes good sense to follow the flux tubes that carry the FAC flowing between the ionosphere and the magnetosphere to determine which regions of the magnetosphere and which processes are responsible for the individual up and down going currents in the model. We will thus follow the magnetic field lines rooted in the individual FACs in the ionosphere out to the magnetosphere. The region in the magnetosphere spanned by the field lines rooted in an individual FAC will in the following be termed the magnetospheric ''mapping region'' of this FAC.

[34] Figure 8 shows a series of field lines originating in the ionosphere along the 11 MLT meridian at the three selected times of the model run described above. The 11 MLT meridian cuts through the upward (blue) NBZ current as well as through the downward (red) region 1 current observed to intensify close to noon when the IMF rotates. Figure 8 (top) show the FAC in the ionosphere together with the foot points of selected field lines along the 11 MLT meridian. Figure 8 (middle) the field lines are drawn as seen from the dawnside, and in Figure 8 (bottom) they are drawn as seen from the Sun. The field lines originating in the central parts of the upward NBZ current are blue, while the field lines originating in the central parts of the downward region 1 current are red. It is seen that the upward NBZ current maps magnetically to field lines draping over the mantle part of the magnetopause, while the downward region 1 current maps to a region close to the low-latitude part of the magnetopause. It is clear that the blue field lines are reconnected field lines, either closed, i.e., reconnected in both ends, or open. They are clearly not the most recently reconnected field lines but rather reconnected field lines which have been transported tailward by the solar wind and draped over the mantle. The shear or rotation in the magnetic field created in the poleward part of the cusp and the mantle part of the magnetopause by this process apparently is the source of the upward NBZ current. This is true both for the almost northward IMF case (0030:00) where this current forms on closed field lines, and for more rotated IMF (0050:00 and 0140:00) where it forms mainly on the open field lines. The dawnside region 1 current observed close to noon (at 0050:00 and 0140:00) seems to be the low-latitude counterpart of the same process. It forms as the result of the shear generated between the reconnected field lines and the low-latitude part of the cusp and magnetopause.

[35] The downward NBZ current on the duskside is formed in a process similar to the upward NBZ current. The field lines from this current also map to the mantle, where it is formed when reconnected field lines are convected tailward on the duskside. When the newly reconnected field lines are being transported tailward along the duskside flank rather than the dawnside, the magnetic shear will be in the opposite sense and hence also the current.

[36] In the case of strictly northward IMF the two NBZ currents are completely symmetrical, but when the IMF rotates toward east they develop quite differently. Figure 9 shows the field lines in the grid used in Figure 6 that are rooted in either of the two NBZ currents. When the IMF B_z is close to northward the upward NBZ current maps to the dawnside flank and mantle and the downward NBZ current maps to the duskside flank and mantle (Figure 9, left). When the IMF rotates toward east the mapping region of the upward NBZ current rotates or spreads northward toward the northern hemisphere mantle, while the mapping region of the downward NBZ current decreases somewhat in size at the nightside and rotates slightly toward the dayside (Figure 9, middle). When the IMF is close to eastward, the mapping region of the upward NBZ current has rotated further toward north while the downward NBZ current has completely disappeared (Figure 9, right). The FAC flowing into the ionosphere in the duskside at the position of the former downward NBZ current now clearly maps to the dawnside magnetosphere, and hence must be related to the solar wind flow around the dawnside of the magnetosphere and the associated draping of newly reconnected field lines. This current therefore can no longer be termed NBZ current, rather it is of the region 1 type, since it is created by the draping of newly reconnected field lines over the dayside, low-latitude part of the magnetosphere.

[37] Figure 10 shows the magnetospheric mapping region of the two dayside region 1 currents during the course of the simulation. When the IMF is close to northward both mapping regions are located at the low-latitude portion of the flanks close to the terminator (Figure 10, left). When the IMF rotates toward east the size of the duskside mapping region decreases while the dawnside mapping region increases both toward the dayside and nightside (Figure 10, middle). When the IMF is almost eastward the duskside upward region 1 current has almost disappeared, while the dawnside downward region 1 current now extends across noon into the duskside ionosphere, and its magnetospheric mapping region encompasses the entire dawnside low-latitude magnetopause.

[38] The mapping of the NBZ currents to the magnetosheath is in close accordance with observational evidence. Studies of DMSP F6 and F7 magnetic and particle precipitation data have associated the NBZ currents with the region of cooler, magnetosheath-like plasma [*Rich*, 1990; *Iijima*, 2000], and the FAC poleward of the ionospheric DPY current, which here has been identified as a magnified and rotated NBZ current, has been identified observationally with the plasma mantle region based on data from the DMSP and HILAT satellites [*Bythrow*, 1988]. In a recent study [*Korth et al.*, 2004] showed that high-latitude dayside aurora, occurring for northward IMF and $B_y > 0$, is colocated with the rotated upward NBZ current, and that their occurrence is ordered by the solar wind density in a way consistent with the interpretation that the magnetosheath plasma has ready access to the field lines carrying this current.

4. Summary

[39] The results of a global MHD simulation of solar wind-magnetosphere interaction, in which the IMF rotates slowly from northward to eastward, have been examined in detail. Main focus has been placed on the mapping between the high-latitude ionosphere and the magnetosphere, directly

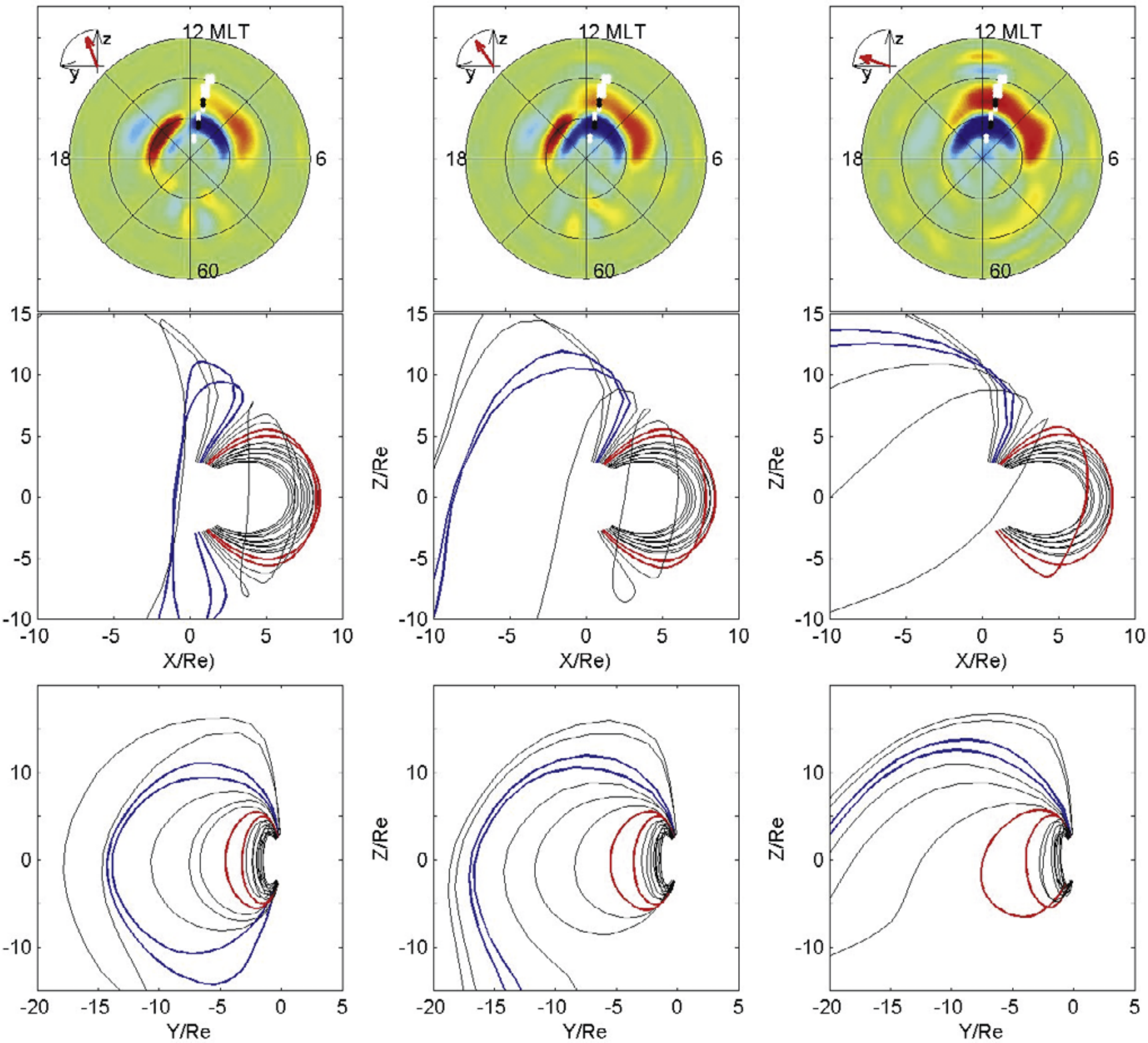

Figure 8. A series of field lines originating in the ionosphere along the 11 MLT meridian at the three specific times in the model run shown in Figure 6. (top) FAC in the ionosphere together with the foot points of a number of field lines along the 1100 MLT meridian (black and white dots). The foot points marked with a black dot in Figure 8 (top) correspond to the red and blue field lines in Figures 8 (middle) and 8 (bottom), while the foot points marked with a white dot in Figure 8 (top) correspond to the black field lines in Figures 8 (middle) and 8 (bottom). (middle) Field lines as seen from the dawnside and (bottom) the same field lines as seen from the Sun. The field lines originating in the central parts of the upward NBZ current are blue, while the field lines originating in the central parts of the downward region 1 current are red.

relating the changing ionospheric convection and field-aligned currents to the magnetospheric reconnection scenario and changing topology. It is found that the IMF B_y component plays a major role in the opening of the magnetosphere during northward IMF and in the geometry/location of the polar cap. The following conclusions have been drawn.

[40] 1. For strongly northward B_z, the magnetosphere remains mostly closed, even though reconnection on field lines poleward of the cusp is driving reversed convection as well as strong FAC in the dayside high-latitude ionosphere. In the simulation, this results from the phenomenon that most newly reconnected flux tubes reconnect also in the opposite hemisphere (creating closed field lines).

[41] 2. The presence of a B_y component in the IMF opens up the magnetosphere, even for strongly northward B_z. ''Double reconnecting'' solar wind flux tubes, however, also occur in the simulation in this case.

[42] 3. When reconnection occurs on closed tail field lines instead of open lobe field lines, the resulting opening

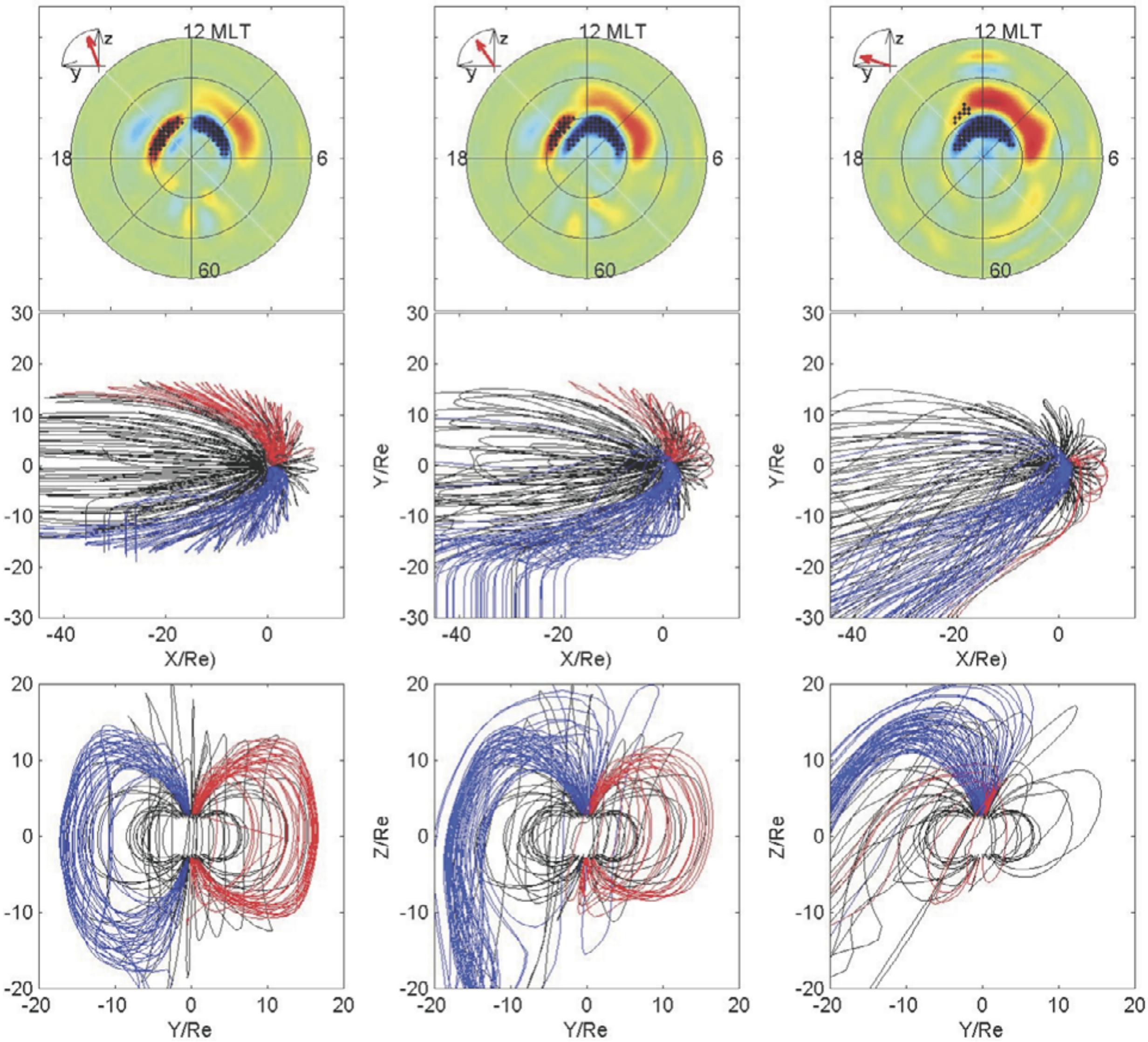

Figure 9. Field lines originating in the upward (blue) and downward (red) NBZ currrent in the northern polar ionosphere. The black field lines originate from a uniformly spaced grid over the polar ionosphere (see Figure 6) and illustrate the extent of the magnetosphere. The format is similar to Figure 8.

of the polar cap will occur asymmetrically with respect to the noon-midnight meridian. For positive B_y the polar cap will be displaced toward dawn and for negative B_y toward dusk. This is in accordance with observed patterns of aurora and particle precipitation for northward IMF.

[43] 4. As the IMF rotates from northward to more eastward in the simulation, one of the reversed convection cells (the dawnside cell in the northern hemisphere) keeps operating and grows stronger, while the other one decreases. In addition, as the magnetosphere opens (the lobe grows) a new cell grows up on the dawnside (in the northern hemisphere) of the former dawn cell, creating the usual (nonreversed) skewed two-cell convection pattern expected for B_y positive dominated conditions.

[44] 5. The field lines carrying both the very high latitude NBZ FAC and the lower latitude (region 1 type) FAC map out to cover major parts of the magnetopause. Newly reconnected field lines create shears in relation to existing magnetospheric field lines. The NBZ currents are created by the shear of the newly reconnected field lines against the lobe field as they are convected tailward by the solar wind. The region 1 type currents at lower latitudes are created by the shear of tailward convecting field lines against the dayside low-latitude closed field. The direction of the FAC (into or out of the ionosphere) is determined by the direction of the east-west directed convection (dawnward or duskward) of the field lines on the dayside.

[45] 6. Neither the NBZ FAC or the dayside region 1 currents can be said to exist exclusively on either closed or open field lines. Depending on the immediate time history of the magnetosphere both types of FAC can be generated on both open and closed field lines.

[46] 7. The results of the simulation partly confirms the model presented in the previous paper [*Vennerstrom et al.*, 2002] for the way the northward B_z FAC pattern changes

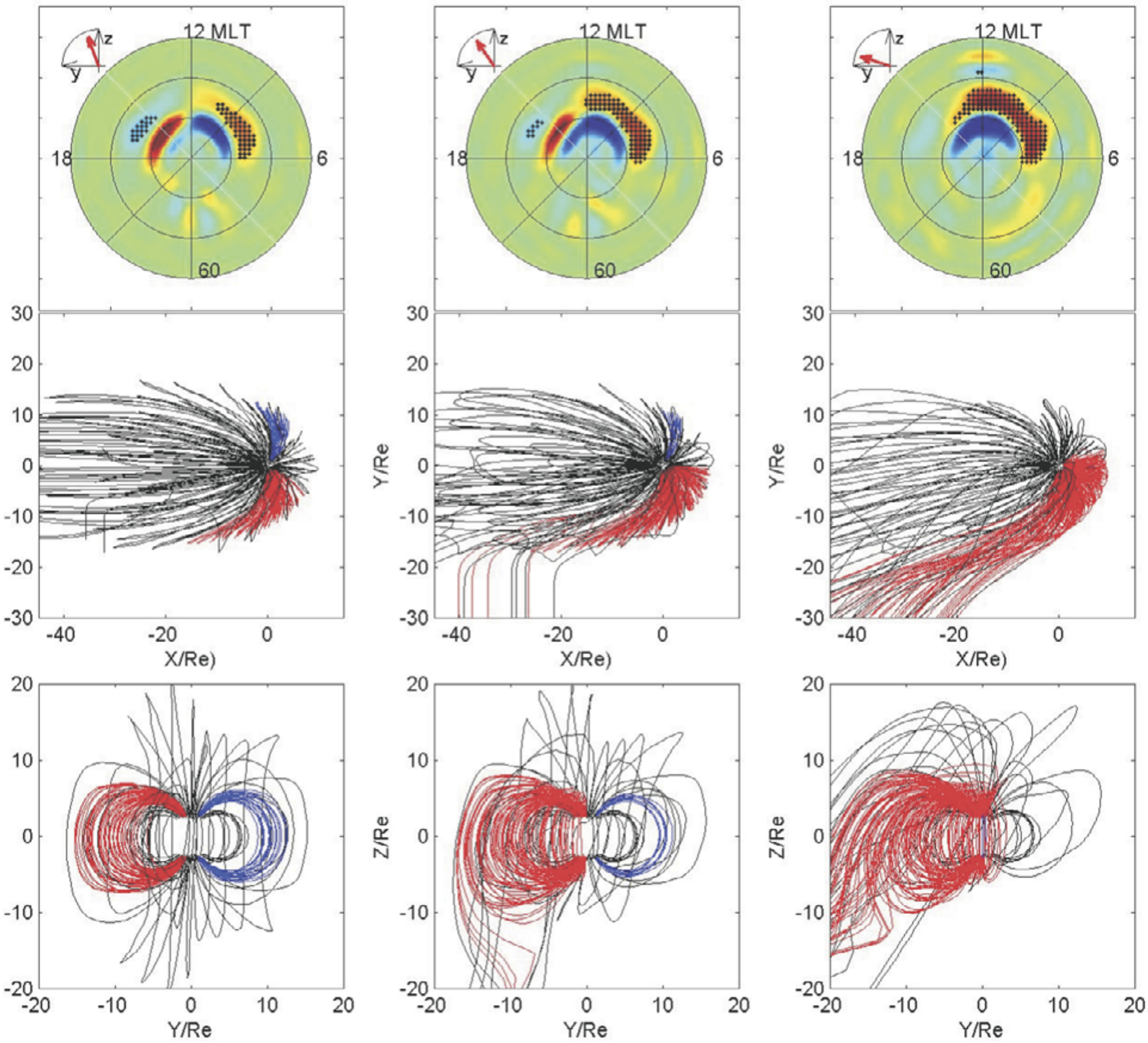

Figure 10. Field lines originating in the upward (blue) and downward (red) dayside region 1 current in the northern polar ionosphere. The black field lines originates from a uniformly spaced grid over the polar ionosphere (see Figure 6) and illustrate the extent of the magnetosphere. The format is similar to Figures 8 and 9.

as a function of B_y. However, the results also suggest modifications to our earlier interpretation. In the northern hemisphere, for positive B_y, the NBZ current located in the dawnside expands into the region poleward of the duskside NBZ current, which at the same time shrinks, starting from the nightside. In addition, the dawnside region 1 type current expands into the noon region.

[47] It is clear from this study that the effect of certain IMF conditions on the magnetosphere for northward IMF must depend significantly on its present state and history. A closer examination of this point is an interesting candidate for further study of solar wind-magnetosphere interaction during northward IMF. The present simulation was performed using a dipole tilt of zero. This implies strict symmetry between the northern and southern hemispheres which could be the reason for the prominent occurrence of "double" reconnecting flux tubes in the simulation. Examination of the effect of the dipole tilt is therefore an important second objective for further studies.

[48] **Acknowledgments.** The authors thank the Community Coordinated Modelling Centre (CCMC) and its staff for their swift operation and assistance, without which this study would not have been possible.

[49] Arthur Richmond thanks B. J. Anderson and Takesi Iijima for their assistance in evaluating this manuscript.

References

Burke, W. J., M. C. Kelley, R. C. Sagalyn, M. Smiddy, and S. T. Lai (1979), Polar cap electric field structures with a northward interplanetary magnetic field, *Geophys. Res. Lett.*, *6*, 21.

Bythrow, P. F. (1988), Birkeland current and charged particles in the high-latitude prenoon region: A new interpretation, *J. Geophys. Res.*, *93*, 9791.

Clauer, C. R., and E. Friis-Christensen (1988), High-latitude dayside electric field and currents during strong northward interplanetary magnetic field: Observations and model simulation, *J. Geophys. Res.*, *93*, 2749.

Cowley, S. W. H. (1983), Interpretation of observed relations between solar wind characteristics and effects at ionospheric altitudes, in *High Latitude Space Plasma Physics*, edited by B. Hultquist and T. Hagfors, p. 225, Springer, New York.

Crooker, N. U. (1988), Mapping the merging potential from the magnetopause to the ionosphere through the dayside cusp, *J. Geophys. Res.*, *93*, 7338.

Crooker, N. U. (1992), Reverse convection, *J. Geophys. Res.*, *97*, 19,363.

Crooker, N. U., J. G. Lyon, and J. A. Fedder (1998), MHD model merging with IMF B_y: Lobe cells, sunward polar cap convection, and overdraped lobes, *J. Geophys. Res.*, *103*, 9143.

Cumnock, J. A., J. R. Sharber, R. A. Heelis, M. R. Hairson, and J. D. Craven (1997), Evolution of global aurora during positive IMF B_z and varying IMF B_y conditions, *J. Geophys. Res.*, *102*, 17,489.

Cumnock, J. A., J. R. Sharber, R. A. Heelis, L. G. Blomberg, G. A. Germany, J. F. Spann, and W. R. Coley (2002), Interplanetary magnetic field control of theta aurora development, *J. Geophys. Res.*, *107*(A7), 1108, doi:10.1029/2001JA009126.

Friis-Christensen, E., Y. Kamide, A. D. Richmond, and S. Matsushita (1985), Interplanetary magnetic field control of high-latitude electric fields and currents determined from Greenland magnetometer data, *J. Geophys. Res.*, *90*, 1325.

Hill, T. W. (1994), Theoretical models of polar cap convection under the influence of a northward interplanetary magnetic field, *J. Atmos. Terr. Phys.*, *56*, 185.

Huang, C.-S., G. J. Sofko, A. V. Koustov, D. A. Andre, J. M. Ruohoniemi, R. A. Greenwald, and M. R. Hairston (2000), Evolution of ionospheric multicell convection during northward interplanetary magnetic field with $|B_z/B_y| > 1$, *J. Geophys. Res.*, *105*, 27,095.

Iijima, T. (2000), Field-aligned currents in goespace: Substance and significance, in *Magnetospheric Current Systems*, *Geophys. Monogr. Ser.*, vol. 118, edited by S. Ohtani et al., p. 107, AGU, Washington, D. C.

Iijima, T., and T. Shibaji (1987), Global characteristics of northward IMF associated (NBZ) field-aligned currents, *J. Geophys. Res.*, *92*, 2408.

Iijima, T., T. A. Potemra, L. J. Zanetti, and P. F. Bythrow (1984), Large-scale Birkeland currents in the dayside polar region during strongly northward IMF: A new Birkeland current system, *J. Geophys. Res.*, *89*, 7441.

Knight, S. (1972), Parallel electric fields, *Planet. Space Sci.*, *21*, 741.

Korth, H., B. Anderson, H. U. Frey, T. J. Immel, and S. B. Mende (2004), Conditions governing localized high-latitude dayside aurora, *Geophys. Res. Lett.*, *31*, L04806, doi:10.1029/2003GL018911.

Lyons, L. R. (1985), A simple model for polar cap convection patterns and generation of theta-auroras, *J. Geophys. Res.*, *90*, 1561.

Maezawa, K. (1976), Magnetic convection induced by the positive and negative *Z* components of the interplanetary magnetic field: Quantitative analysis using polar cap magnetic records, *J. Geophys. Res.*, *81*, 2289.

Makita, K., and C.-I. Meng (1984), Average electron precipitation patterns and visual aurora characteristics during geomagnetic quiescence, *J. Geophys. Res.*, 2861.

Makita, K., C.-I. Meng, and S.-I. Akasofu (1991), Transpolar auroras, thier particle precipitation and IMF B_y component, *J. Geophys. Res.*, *96*, 14,683.

Meng, C.-I. (1981), The auroral electron precipitation boundary during extremely quiet geomagnetic conditions, *J. Geophys. Res.*, *86*, 4607.

Moen, J., and A. Brekke (1993), The solar flux influence on quiet time conductances in the auroral ionosphere, *Geophys. Res. Lett.*, *20*, 971.

Newell, P. T., D. Xu, C.-I. Meng, and M. G. Kivelson (1997), Dynamical polar cap: A unifying approach, *J. Geophys. Res.*, *102*, 127.

Raeder, J. (1999), Modelling the magnetosphere for northward interplanetary magnetic fields: Effects of electrical resistivity, *J. Geophys. Res.*, *104*, 17,357.

Raeder, J. (2003), Global magnetohydrodynamics—A tutorial, in *Space Plasma Simulations*, *Lect. Notes Phys.*, vol. 615, edited by J. Buchner, C. T. Dunn, and M. Scholer, p. 212, Springer, New York.

Raeder, J., R. J. Walker, and M. Ashour-Abdalla (1995), The structure of the distant geomagnetic tail during long periods of northward IMF, *Geophys. Res. Lett.*, *22*, 349.

Raeder, J., J. Berchem, and M. Ashour-Abdalla (1998), The Geospace Environment Modeling Grand Challenge: Results from a Global Geospace Circulation Model, *J. Geophys. Res.*, *103*, 14,787.

Raeder, J., O. Vaisberg, V. Smirnov, and L. Avanov (2000), Reconnection driven lobe convection: Interball tail probe observations and global simulations, *J. Atmos. Sol. Terr. Phys.*, *62*, 833.

Raeder, J., et al. (2001), Global simulation of the Geospace Environment Modeling substorm challenge event, *J. Geophys. Res.*, *106*, 381.

Rastätter, L., M. Hesse, and M. Kuznetsova (2002), Magnetic field topology during July 14–16 2000 (Bastille Day) solar CME event, *Geophys. Res. Lett.*, *29*(15), 1747, doi:10.1029/2001GL014136.

Reiff, P. H., and J. L. Burch (1985), IMF B_y-dependent plasma flow and Birkeland currents in the dayside magnetosphere: 2. A global model for northward and southward IMF, *J. Geophys. Res.*, *90*, 1595.

Rich, F. J. (1990), Northward IMF patterns of high-latitude precipitation and field-aligned currents: The February 1986 storm, *J. Geophys. Res.*, *95*, 7803.

Ridley, A. J., G. Lu, C. R. Clauer, and V. O. Papitashvili (1998), 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.*, *103*, 4023.

Robinson, R., R. Vondrak, K. Miller, T. Dabbs, and D. Hardy (1987), On calculating ionospheric conductances from the flux and energy of precipitating electrons, *J. Geophys. Res.*, *92*, 2565.

Song, P., and C. T. Russell (1992), Model of the formation of the low-latitude boundary layer for strongly northward IMF, *J. Geophys. Res.*, *97*, 1411.

Tanaka, T. (1999), Configuration of the magnetosphere-ionosphere convection system under northward IMF conditions with nonzero IMF B_y, *J. Geophys. Res.*, *104*, 14,683.

Vasyliunas, V. M. (1989), Electrodynamics of the ionosphere/magnetosphere/solar wind system at high latitudes, in *Electromagnetic Coupling in the Polar Clefts and Caps*, edited by P. E. Sandholt and A. Egeland, p. 1, Springer, New York.

Vennerstrom, S., T. Moretto, N. Olsen, E. Friis-Christensen, A. M. Stampe, and J. F. Watermann (2002), Field-aligned currents in the dayside cusp and polar cap region during northward IMF, *J. Geophys. Res.*, *107*(A8), 1188, doi:10.1029/2001JA009162.

Wilhjelm, J., Friis-Christensen, and T. A. Potemra (1978), The relationship between ionospheric and field-aligned currents in the dayside cusp, *J. Geophys. Res.*, *83*, 5586.

T. Moretto and L. Rastätter, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.

J. Raeder, Institute for the Study of Earth, Oceans and Space, University of New Hampshire, Durham, NH 03824, USA.

S. Vennerstrom, Danish National Space Center, Juliane Maries Vej 30, Copenhagen, 2100 O, Denmark. (sv@spacecenter.dk)