Magnetohydrodynamic simulation of an equatorial dipolar paleomagnetosphere

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[1]   During polarity reversals of the Earth's internal geomagnetic field, the paleomagnetosphere must have undergone dramatic changes because the core field was essentially different from the present-day case, where the dipole moment is approximately aligned with the Earth's rotation axis (axial dipole) and perpendicular to the solar wind flow. According to one of the possible transition scenarios, the internal dipole moment, having much reduced in magnitude, could slowly turn around, staying close to the equatorial plane for a significant time. In this paper we present magnetohydrodynamic (MHD) simulations of a so-called equatorial dipolar paleomagnetosphere, where the internal dipole moment is perpendicular to the rotation axis, i.e., the dipole axis is in the equatorial plane. The magnitude of the dipole moment was chosen as small as one-tenth of the present value. With such a dipole field orientation, the dipole tilt in GSM coordinates changes, due to the Earth's rotation, between zero and 360 degrees in the course of the day, resulting in an extremely dynamic magnetosphere on the diurnal timescale. As a first approximation, we calculated steady-state solutions with different dipole tilts, or in other words with different angles between the dipole axis and the Sun-Earth line, to represent the paleomagnetosphere at different times of the day. We describe the regular diurnal variation of the geomagnetic field-line configuration and the topology of large-scale current systems, like the magnetopause currents and the tail current sheet. We investigate the so-called pole-on magnetosphere, where the dipole axis is aligned with the Sun-Earth line, in more details using different solar wind input parameters.   *INDEX TERMS:* 2740 Magnetospheric Physics: Magnetospheric configuration and dynamics; 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; 1535 Geomagnetism and Paleomagnetism: Reversals (process, timescale, magnetostratigraphy); 3210 Mathematical Geophysics: Modeling; *KEYWORDS:* paleomagnetosphere, MHD simulation, geomagnetic polarity reversal, equatorial dipole, pole-on magnetosphere, magnetospheric current system

1.   Introduction

[2]   Basically, the magnetosphere is formed through the interaction between the solar wind and the Earth's internal magnetic field. Consequently, to simulate paleomagnetospheres, we need information or at least some reasonable assumptions about the variability of solar wind parameters and the changes in the Earth's core field on geological timescales. Reversals of the geomagnetic field are well enough documented by paleomagnetic records, at least for the past 160 Myr. Although the most recent polarity transition, the Brunhes-Matuyama geomagnetic field reversal, occurred at about 780 ka [*Baksi et al.*, 1992], the mean geomagnetic reversal rate is about 4.5 per million years at present [*McFadden and Merrill*, 2000]. The reversal frequency is modulated on the long timescale of mantle convection, and there have been at least two long intervals with no reversals (Cretaceous normal and Permo-Carboniferous reversed polarity superchrons). The duration of a polarity transition lies between 1 and 8 thousand years, and the geomagnetic paleointensity may fall by as much as 1 order of magnitude during this time. Polarity reversals are generally preceded by several excursions of the virtual geomag-

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netic pole (VGP), when the VGP is located lower than 45 degrees geographic latitude. Unfortunately, the number and quality of paleomagnetic data are by far not enough to describe the transition paleomagnetic field uniquely in sufficient detail. For example, in order to calculate the first three terms (dipole, quadrupole, and octupole) in a spherical harmonic expansion, one would need at least 15 simultaneous paleomagnetic measurements uniformly distributed over the globe. The dating of paleomagnetic samples to a very high accuracy imposes another serious difficulty. Therefore the structure of the transition magnetic field is still controversial. Several transition scenarios can be conceived, none of which is excluded at the present state of our knowledge. (1) The dipole moment could decay to zero and quickly build up in the opposite direction, or (2) having much reduced in magnitude, the dipole moment could make excursions and finally turn around, or (3) the dipole moment could completely vanish and higher-order multipoles could dominate during the transition epoch. For recent reviews on geomagnetic polarity transitions see *Gubbins* [1994] and *Merrill and McFadden* [1999]. Numerical dynamo models have been quite successful to reproduce many observed features of the Earth's surface magnetic field, e.g., the westward drift, excursions of the VGP, and even polarity reversals [*Glatzmaier and Roberts*, 1995]. Although the parameter values are still orders of magnitude different from the physical ones, these dynamo models can help us to understand the structure and changes of the Earth's internal magnetic field during polarity transition epochs.

[3] So far, paleomagnetospheres have been modeled mainly theoretically, using scaling relations to determine different parameters of the paleomagnetosphere (e.g., distance to the solar wind stagnation point, tail radius, polar cap size, etc.) in the function of the dipole moment [*Siscoe and Chen*, 1975; *Siscoe*, 1979; *Saito et al.*, 1978; *Vogt and Glassmeier*, 2001]. We use three-dimensional numerical MHD simulations for the quantitative description of different kinds of paleomagnetospheres. Simulation results related to quadrupolar paleomagnetospheres are published in another paper by J. Vogt et al. (MHD simulations of quadrupolar paleomagnetospheres, submitted to *Journal of Geophysical Research*, 2004). Assuming the second transition scenario, the Earth must have had a dipole moment strongly tilted, sometimes even by 90 degrees, with respect to the Earth's rotation axis for considerable times during the excursions and reversals of the dipole moment. In this paper we discuss the simulation results of a so-called equatorial dipolar paleomagnetosphere, where the internal dipole moment is perpendicular to the rotation axis, i.e., the dipole axis is in the equatorial plane. The first, mainly qualitative description of such a paleomagnetosphere was given by *Saito et al.* [1978]. The magnetic field and current structures in an equatorial dipolar paleomagnetosphere show some common features with those expected in the magnetospheres of Neptune and Uranus [*Voigt et al.*, 1987; *Lepping*, 1994; *Voigt and Ness*, 1990], thus the conclusions of our paleomagnetospheric simulations could be utilized in the modeling of other planetary magnetospheres as well.

[4] The outline of the paper is the following. In section 2 we describe the input parameters of the actual numerical simulations. In section 3 we show and discuss the results
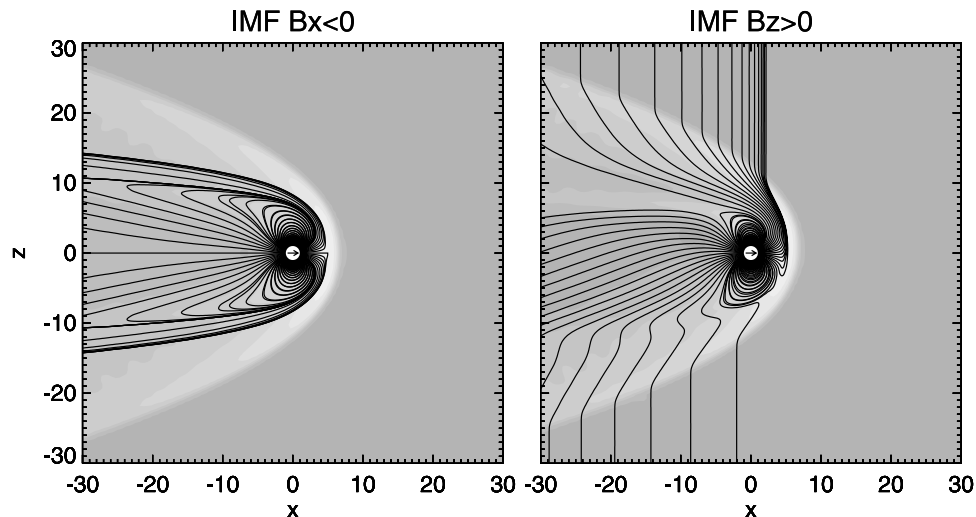
concerning the magnetic field configuration and the large-scale current systems in the simulated paleomagnetosphere. Finally, we summarize the main findings and present our conclusions in section 4.

2. Numerical Simulations

[5] Global magnetospheric MHD codes, including the University of Michigan BATS-R-US (Block Adaptive Tree Solar-wind Roe Upwind Scheme) MHD code [*Powell et al.*, 1999], are quite successful in modeling the near-Earth space environment. The most popular MHD codes have been compared against each other but, most importantly, reasonably well validated against a variety of in situ spacecraft and ground-based measurements [*Janhunen et al.*, 1995; *Lyon et al.*, 1998; *Fedder et al.*, 1998; *Raeder et al.*, 1998; *Winglee and Menietti*, 1998; *Gombosi et al.*, 1998; *Raeder et al.*, 2001; *Slinker et al.*, 2001; *White et al.*, 2001; *Siscoe et al.*, 2002; *Kabin et al.*, 2003; *Rae et al.*, 2004; *Ohtani and Raeder*, 2004; *Nakata et al.*, 2004].

[6] We adapted the BATS-R-US MHD code to simulate paleomagnetospheres with different kinds of internal magnetic fields. Since the magnetosphere is formed as a result of a coupled interaction among the solar wind, the Earth's internal magnetic field, and the conductive ionosphere, we need the following input parameters for the simulations of paleomagnetospheres: structure and strength of the internal magnetic field, solar wind parameters (plasma pressure, solar wind speed, interplanetary magnetic field (IMF)), inner (ionospheric) and outer boundary conditions. In this paper we simulate a dipolar paleomagnetosphere where the Earth's internal dipole moment is one-tenth of the present value and the Earth's dipole axis is perpendicular to the rotation axis (equatorial dipole). Since the dipole axis is in the equatorial plane, it rotates 360 degrees a day with respect to the z axis in GSM coordinates which is now located in the equatorial plane pointing from dawn to dusk. The Earth's rotation axis is now aligned with the y axis in GSM pointing to the southern geographic pole. Ideally, time-accurate MHD simulations are required to model the diurnal variation of such a paleomagnetosphere exactly. Principally, it is possible to run full-day time-accurate simulations with the BATS-R-US code, taking the Earth's daily rotation into account, but these simulations are very expensive regarding CPU time. As a first approximation, we ran steady-state simulations at different times of the day, i.e., with different rotation angles (or dipole tilt) between the dipole moment and the z axis in GSM, assuming that the magnetosphere changes slowly enough with the Earth's rotation to reach a state that is very close to the steady-state solution. This assumption is more or less valid most of the day except for those critical rotation angles where the magnetosphere suddenly opens up or closes down due to favorable or unfavorable relative IMF orientations. These parts of the simulations should be treated with caution.

[7] In the simulations the solar wind pressure and velocity were kept constant, assuming that the long-term averages of these solar wind parameters do not change too much in geological timescales. Note that the short-term variability of the solar wind speed can be as high as a factor of two in magnitude due to the alternation of slow and fast solar wind

Figure 1. Magnetic field configurations and pressure in a pole-on paleomagnetosphere with the interplanetary magnetic field (IMF) parallel (left) and perpendicular (right) to the solar wind flow direction. See color version of this figure at back of this issue.

streams. Varying the solar wind speed, however, would result in changes in the size of the magnetosphere in the first place, but the shape of the magnetosphere would remain basically the same. The size of the magnetosphere can be modeled also theoretically using scaling relations. Since we were focusing on the diurnal variation of the magnetic field configuration, we used a constant IMF orientation corresponding to the average Parker spiral in the away sector (where the magnetic field lines point away from the Sun). In case of the two pole-on configurations, where the dipole axis is aligned with the solar wind flow (dipole tilts of 90 and 270 degrees), we ran additional simulations with different IMF orientations, namely, zero IMF, IMF parallel, antiparallel, and perpendicular to the solar wind flow, in order to study the role of IMF orientation in the formation of open and closed magnetospheres.

[8] As inner boundary conditions, we used the simplest ionospheric boundary conditions that mimics the response of a highly conductive ionosphere and reproduces the equatorial convection patterns. The magnetosphere-iono-sphere coupling in paleomagnetospheres will be discussed more extensively in another paper.

[9] The simulations were run either on a Cray T3E computer or on a Linux cluster of PCs using 9600 blocks of $4 \times 4 \times 4$ cells in a simulation box of $32 \times 32 \times 32$ Earth radii. The smallest cell size, i.e., the highest resolution, was selected as 0.5 Earth radii.

3. Discussion

[10] In this paper we aim at studying the magnetic field configuration and the topology of large-scale current systems in an equatorial dipolar paleomagnetosphere. Since the dipole tilt changes 360 degrees in the course of the day due to the Earth's rotation, this paleomagnetosphere exhibits a dramatic diurnal variation. We focus on describing the dynamics of diurnal variations and discussing their possible consequences. As a case of unique geometry, we investigate the pole-on magnetosphere more thoroughly.

3.1. Pole-On Magnetosphere

[11] The so-called pole-on magnetosphere is a special case of the equatorial dipolar magnetosphere, where the dipole moment is either parallel or antiparallel to the solar wind flow direction, corresponding to 90-degree and 270-degree dipole tilt in the GSM coordinate system. During the daily rotation of the Earth, the equatorial dipole gets into pole-on position two times when one of the geomagnetic poles is directed toward the Sun. In the case of the Earth, this configuration cannot sustain for a long time because the Earth's rotation axis is quasi-perpendicular to the ecliptic plane. However, in case of other planets with a rotation axis quasi-parallel to their orbital plane (e.g., Uranus), magnetospheric configurations close to the pole-on geometry can be stable for a long time at some parts of their orbit.

[12] The magnetic field configuration in a pole-on pale-omagnetosphere is controlled, as in general, by the IMF orientation. Figure 1 shows simulation results of a pole-on paleomagnetosphere with sunward dipole moment when the IMF is parallel (left) and perpendicular (right) to the solar wind flow direction. Here we plotted magnetic field lines originating from the Earth's surface at every 5 degrees of geographic longitude in the equatorial plane (i.e., the x-z plane in GSM). A white circle represents the Earth, and a small arrow inside it shows the direction of the dipole moment. The two magnetic field configurations are essentially different. In the parallel IMF case there is no field line reconnection between the Earth's magnetic field lines and the IMF, and thus we have a completely closed magnetosphere. Note that this paleomagnetosphere is axially symmetric to the dipole axis. In the perpendicular IMF case, e.g., with IMF pointing from dawn to dusk (see right panel in Figure 1), the axial symmetry breaks down and the magnetosphere opens up as field line reconnection takes place in the dawn side of the dayside magnetopause. The open magnetic field lines are dragged by the solar wind into the tail where they reconnect again at the neutral point in the dusk side of the tail. The shape and position of the bow shock marked by the highest pressures (light colors) are
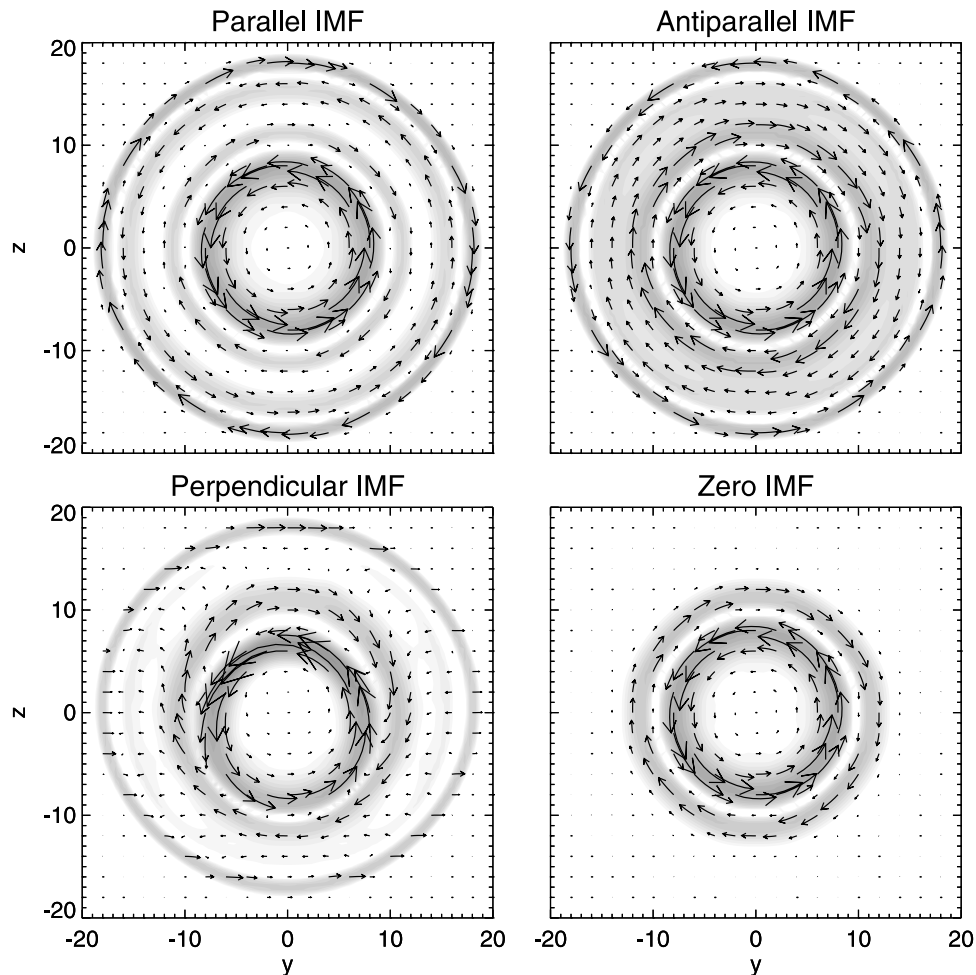
Figure 2. Current systems in the tail of a pole-on paleomagnetosphere with the IMF parallel, antiparallel, and perpendicular to the solar wind flow, and with zero IMF. See color version of this figure at back of this issue.

apparently not influenced by the change in the IMF direction.

[13] The topology of the current systems in the tail of a pole-on paleomagnetosphere is quite unique. In Figure 2 we plotted the currents flowing in a cross section of the tail at 10 Earth radii distance from the Earth in case of a pole-on magnetosphere with sunward dipole moment for different IMF conditions, namely IMF parallel, antiparallel, and perpendicular to the solar wind flow, and also for zero IMF. The current intensity is plotted on a color scale, dark colors representing stronger currents, while the arrows show the direction of the currents in the y-z plane. The length of each arrow is linearly proportional to the local current density. The neutral sheet is separated from the magneto-pause and forms a quasi-cylindrical or conical surface. In the parallel, antiparallel, and zero-IMF case, all currents flow circularly in the y-z plane because of the perfect axial symmetry. The direction of the neutral sheet currents (innermost current circle) is always opposite to the direction of the magnetopause currents or Chapman-Ferraro currents (second concentric current circle). In the parallel IMF case (upper left panel in Figure 2), an additional current ring is formed in the magnetosheath between the magnetopause and the bow shock (outermost current circle) due to the

curvature and gradient of the magnetic field in the axis-symmetric magnetosheath. The directions of the bow shock current and the magnetosheath current are also opposite. If we reverse the IMF direction from parallel to antiparallel (upper right panel in Figure 2), both the bow shock and magnetosheath currents reverse but the directions of the magnetopause and neutral sheet currents will remain unchanged. Conversely, if we reverse the polarity of the dipole from sunward to antisunward (not shown in this figure), the magnetopause and neutral sheet currents will reverse, while the bow shock and magnetosheath currents will keep on flowing in their original directions. If the IMF has a perpendicular component to the solar wind flow, e.g., pointing from dawn to dusk (lower left panel in Figure 2), the axial symmetry of the pole-on magnetosphere breaks down, the currents in the tail do not flow in circles any more, the magnetosheath ring current disappears, and the magneto-pause and neutral sheet currents have components out of the y-z plane, but the basic topology of the magnetospheric current system remains similar to the axis-symmetric cases. The currents on the cylindrical neutral sheet flow in elliptical streamlines, and current densities are higher on the duskside. Without interplanetary magnetic field (lower right panel in Figure 2), the currents in the bow shock and magnetosheath

disappear, but the magnetopause and neutral sheet currents show the same topology and flow in the same directions as in case of parallel or antiparallel IMF. The only notable difference is in the intensity of the magnetopause currents. With parallel IMF the magnetopause currents are weaker, whereas with antiparallel IMF they are stronger than the magnetopause currents with zero IMF, which results from the additional current contribution from the magnetosheath. The radius of the tail magnetopause does not change significantly (though it is slightly larger with zero IMF than with nonzero IMF) because the magnetic pressure in the magnetosheath plays a minor role in the pressure balance at the tail magnetopause.

3.2. Diurnal Variation in the Magnetic Field Configuration

[14] The above-discussed pole-on positions of the equatorial dipole, corresponding to dipole tilts of 90 and 270 degrees in GSM, are not stable configurations in the case of the Earth, as the Earth's rotation axis is quasi-perpendicular to the solar wind flow and therefore the dipole tilt changes from zero to 360 degrees in the course of the day, with a constant angular velocity of 15 degrees per hour. In this section we are going to describe the diurnal variation of the magnetic field configuration in the equatorial dipolar paleomagnetosphere assuming a constant IMF direction corresponding to the Parker spiral in the away sector, which is one of the two most probable IMF directions in the solar wind. We ran a series of steady-state MHD simulations varying the dipole tilt, or equivalently the Earth's rotation angle, in 10-degree steps, i.e., every 40 min in UT. The steady-state solutions differing very much from the neighboring ones should be treated with caution, as the time interval between two simulations may not be enough to reach the steady state. These intervals can be modeled more exactly with time-accurate simulations.

[15] In Figure 3, snapshots of the diurnal variation of the magnetic field configuration in the equatorial plane are presented every 2 hours of the day, i.e., in 30-degree steps of the dipole tilt. A small arrow in white circle (the latter representing the Earth) indicates the orientation of the dipole moment and hence the direction of field lines connected to the Earth. The total plasma pressure is plotted in the background on a logarithmic color scale, where light colors correspond to high pressures. High plasma pressure is characteristic for the magnetosheath and also for the tail plasma sheet, but the highest pressures mark the parabolic curve of the bow shock. We start the description of the magnetic field configuration from the pole-on position with 90-degree dipole tilt, where the dipole moment points toward the Sun (first panel in the second row in Figure 3). At this time of the day, the magnetosphere is open, field line reconnection takes place at the nose of the magnetopause, and the reconnection point is located very close to the noon-midnight meridian in the dawnward side of the dayside cusp. The open magnetic field lines are convected by the solar wind downstream into the tail, where they reconnect again at the neutral point in the duskward half of the tail. Two hours later (second panel in the second row in Figure 3) after the dipole moment has turned 30 degrees with the Earth, the reconnection point has moved a little bit dusk-ward on the dayside magnetopause and at the same time it

has shifted to a somewhat lower geomagnetic latitude. In the course of time, or equivalently with increasing dipole tilt, the reconnection point moves more and more duskward on the dayside magnetopause and at the same time it shifts to lower and lower geomagnetic latitudes. On the other hand, the neutral point in the tail gradually moves dawnward until it reaches the noon-midnight meridian at a dipole tilt of 180 degrees (first panel in the third row in Figure 3). At this point the dipole moment points toward dusk and it is perpendicular to the solar wind flow. (Topologically, this magnetic field configuration corresponds to the magnetic field configuration of the present-day magnetosphere for an IMF with comparable southward and antisunward components.) With further increasing dipole tilt, the dayside reconnection point continues to move duskward and to shift to lower geomagnetic latitudes, whereas the neutral point, now located in the dawnward half of the tail, continues to move dawnward. When the dipole moment becomes parallel to the Parker spiral (third panel in the third row in Figure 3), the reconnection takes place close to the geomagnetic equator on the duskside of the dayside magnetopause. After this point, while the dayside reconnection point moves further toward dusk, it begins to shift to higher geomagnetic latitudes toward the opposite geomagnetic pole. Finally, the reconnection point gets very close to dusk on the dayside magnetopause and its geomagnetic latitude approaches the northern geomagnetic pole (third panel in the fourth row in Figure 3). Then the dipole moment becomes perpendicular to the solar wind flow (first panel in the first row in Figure 3). The magnetosphere is still open, as field line reconnection still takes place very close to dusk in the dayside magnetosphere at the poleward cusp boundary. (Topologically, this magnetic field configuration corresponds to the magnetic field configuration of the present-day magnetosphere for an IMF with comparable northward and antisunward components.) Rotating further, the dipole moment is getting antiparallel with the Parker spiral, there is no reconnection at the dayside magnetopause any more, and the magnetosphere becomes closed (see the second and third panels in the first row in Figure 3). Having been closed for a while, the magnetosphere suddenly opens up again, as field line reconnection starts again at the dawnward boundary of the dayside cusp. With this we arrived at our starting point, i.e., the pole-on configuration with sunward dipole moment (first panel in the second row in Figure 3). We can conclude that the reconnection point in the equatorial plane moves on the dayside magnetopause from the vicinity of the noon-midnight meridian close to dusk in the course of the day. The magnetosphere is open most of the time except for a short interval when the dipole moment is antiparallel to the IMF.

[16] Reversing the IMF direction, i.e., using a Parker spiral in the toward sector, we obtain a diurnal variation in the magnetic field configuration topologically similar to that described above but shifted by 180 degrees in dipole tilt or 12 hours in time.

3.3. Diurnal Variation in the Large-Scale Current Systems

[17] In Figures 4 and 5 we plotted the large-scale currents for the same series of steady-state MHD simulations discussed in the previous section. Figure 4 shows currents
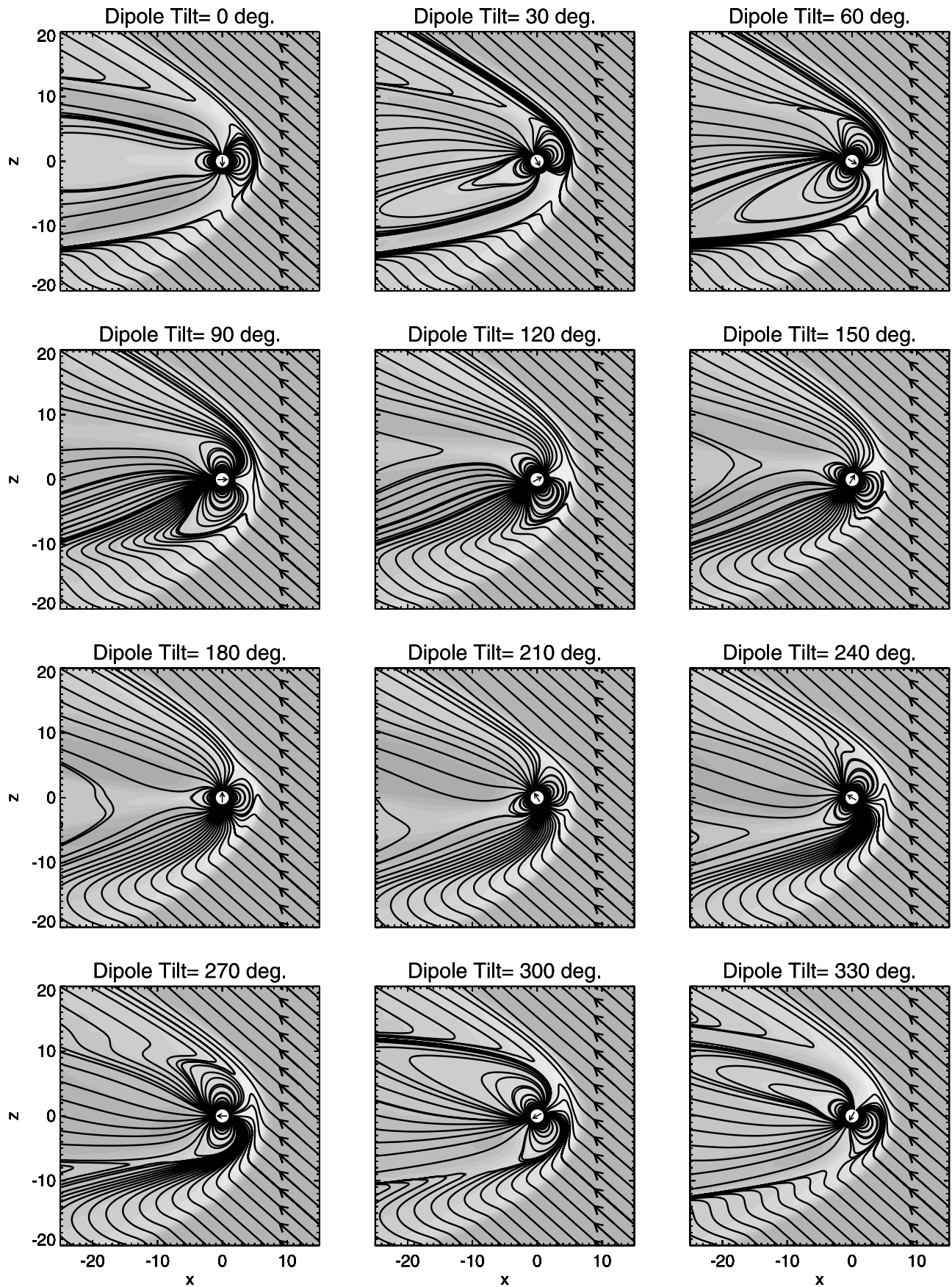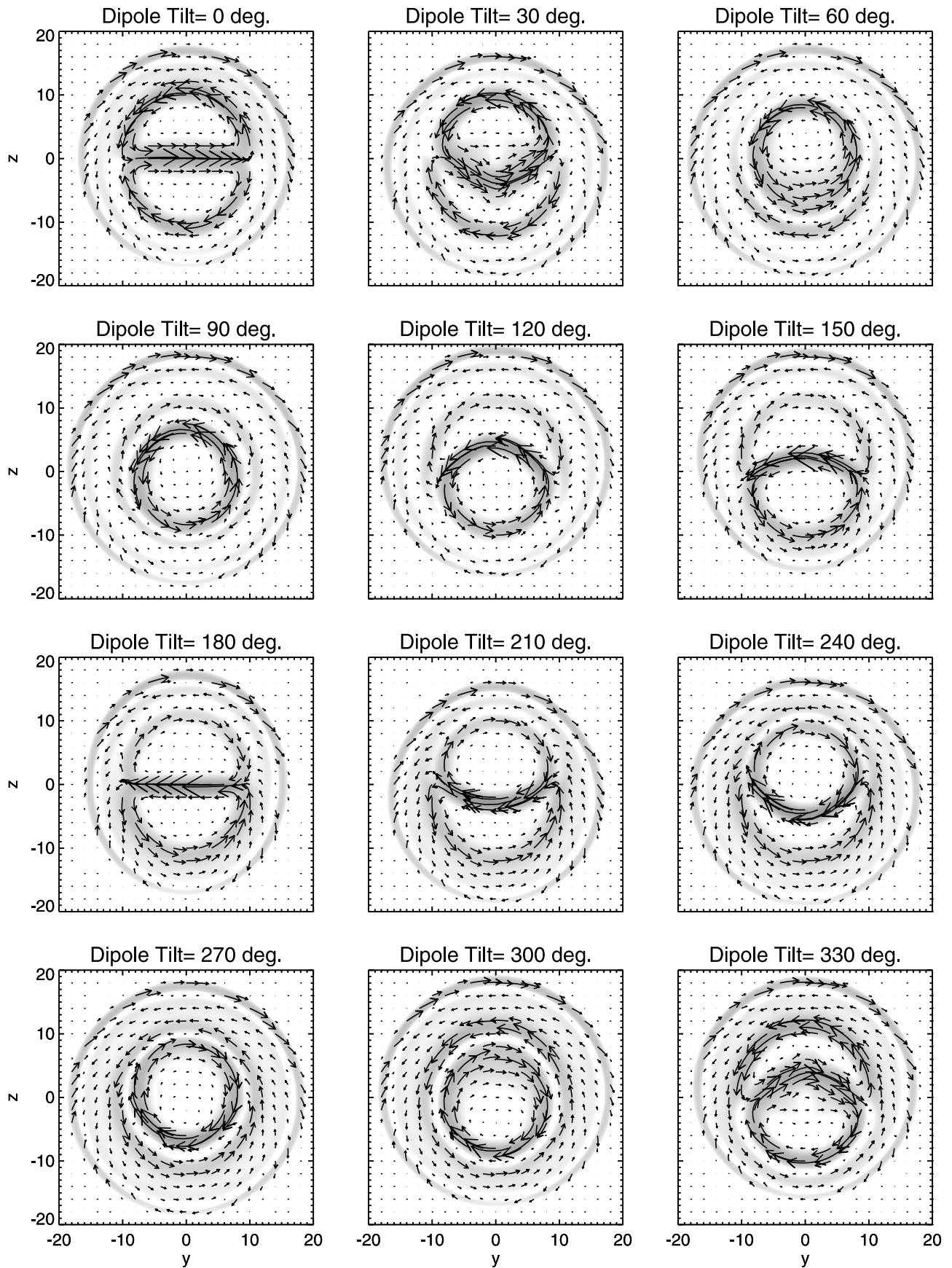
Figure 3. Diurnal variation of the magnetic field configuration and pressure in an equatorial dipolar paleomagnetosphere. See color version of this figure at back of this issue.
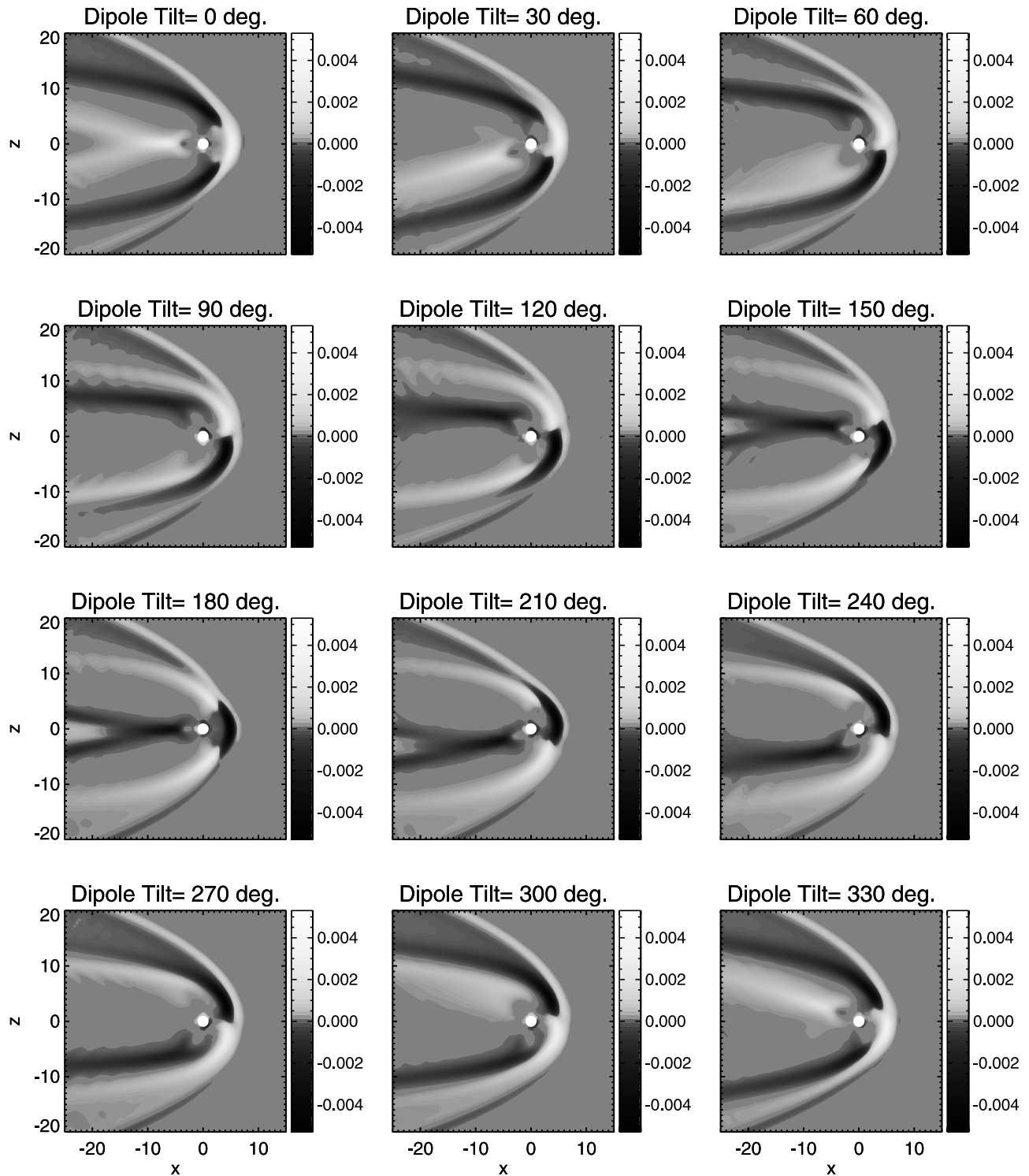
Figure 4. Diurnal variation of the currents flowing across the equatorial plane in an equatorial dipolar paleomagnetosphere. Blue and red colors indicate northward and southward flow direction, respectively. See color version of this figure at back of this issue.

crossing the equatorial plane in northward (blue colors) and southward (red colors) directions, whereas Figure 5 depicts currents flowing in the y-z plane in a cross section of the tail at 10 Earth radii distance from the Earth. Here the current intensity is plotted on a color scale, dark colors representing stronger currents, while the arrows show the direction of the

currents in the y-z plane. We remind the reader that in case of an equatorial dipolar paleomagnetosphere, the z(GSM) axis points from dawn to dusk and the y(GSM) axis points toward the geographical South Pole. First, we would like to point out that the directions of the bow shock and magneto-sheath currents do not change during the day with the

Figure 5. Diurnal variation of the current system in the tail of an equatorial dipolar paleomagneto-sphere. See color version of this figure at back of this issue.

changing dipole tilt. It is not at all surprising, as it was shown in section 3.1, that these currents are controlled by the orientation of the IMF. In general, the topology of the magnetopause and tail current sheet (neutral sheet) shows a 12-hour cycle due to the diurnal change in the dipole tilt, but the direction of currents are opposite in magnetospheric current systems separated by 180 degrees in dipole tilt or 12 hours in time, which results in a 24-hour cycle. At zero dipole tilt the neutral sheet is flat and the cross-tail currents flow from north to south and close on the magnetopause (first panel in the first row in Figure 5). Then the neutral sheet begins to bend more and more toward dawn, forming an arcade, while its connections with the magnetopause move toward dusk (second panel in the first row in Figure 5). Finally, the duskward edges of the neutral sheet meet each other, forming a quasi-cylindrical surface, and the neutral sheet currents close in a circle (third panel in the first row in Figure 5). The quasi-cylindrical neutral sheet then detaches from the magnetopause and moves dawnward (first panel in the second row in Figure 5) until it connects again to the magnetopause with its dawnward part (second panel in the second row in Figure 5). The neutral sheet currents begin to close again on the magnetopause and the connection points start to move toward dusk (third panel in the second row in Figure 5). The neutral sheet becomes less and less curved until it is flat again after 12 hours at 180 degrees dipole tilt (first panel in the third row in Figure 5). Now the cross-tail currents flow in the opposite direction, i.e., from south to north. The topology of the tail current sheet changes similarly in the second half of the day but now the direction of the currents is reversed.

4. Conclusions

[18] We presented the MHD simulations of an equatorial dipolar paleomagnetosphere where the magnitude of the dipole moment was one-tenth of the present value. This type of paleomagnetosphere represents a possible magnetospheric configuration during polarity transitions. As the dipole axis is perpendicular to the Earth's rotation axis, the dipole tilt in GSM coordinates changes between zero and 360 degrees in the course of the day, resulting in a regular diurnal variation in the magnetic field configuration and the large-scale magnetospheric current systems. We found that the equatorial dipolar paleomagnetosphere is open most of the day, and it becomes closed only for a short interval, when the dipole moment is more or less antiparallel to the IMF. Dayside field-line reconnection in the equatorial plane takes place along the duskward half of the magnetopause, regularly moving from the noon-midnight meridian toward dusk in the course of the day. Simultaneously, the geomagnetic latitude of the reconnection point changes roughly from 90 through 90 degrees. Depending on the relative orientation of the dipole moment and the IMF, the openness of the magnetosphere varies regularly in the course of the day. This implies a regular diurnal variation in a number of magnetospheric phenomena like particle precipitation, auroral occurrence, substorms, geomagnetic activity, etc. The energetic particle fluxes in the upper atmosphere are also expected to show a diurnal modulation especially at lower energies. In case of the pole-

on geometries, solar wind plasma can directly penetrate into the magnetosphere through the dayside cusp, and simultaneously, inner magnetospheric plasma can freely escape from the center of the tail.

[19] The topology of the magnetospheric current systems, like the shape of the tail current sheet, is controlled by the dipole tilt, whereas the bow shock and magnetosheath currents are controlled by the IMF orientation. It is the relative orientation of the IMF with respect to the dipole moment that determines whether the magnetosphere is open or closed. The basic topology of the tail current sheet exhibits a 12-hour cycle, transforming from a flat current sheet connected to the magnetopause into a quasi-cylindrical surface separated from the magnetopause. The directions of the currents in the magnetopause and the neutral sheet reverses every 12-hours, thus producing a 24-hour cycle in the properties of large-scale magnetospheric currents.

[20] This project is part of a multi-institutional modeling effort coordinated within the DFG Priority Program Geomagnetic Variations. MHD simulations help to identify paleomagnetospheric configurations which are expected to yield significant particle fluxes into the polar regions. A particle tracing scheme developed at the Technische Universität Braunschweig (A. Stadelmann et al., A magnetic field model for cosmic ray flux in paleomagnetospheres, submitted to *Annales Geophysicae*, 2004) is utilized to calculate these fluxes, then ionization profiles in the upper and middle atmosphere are computed at the University Osnabrück [*Quack et al.*, 2001]. These profiles are important input variables for an atmospheric chemistry model implemented at the University Bremen [*Sinnhuber et al.*, 2003], which computes the resulting ozone concentrations in the middle atmosphere.

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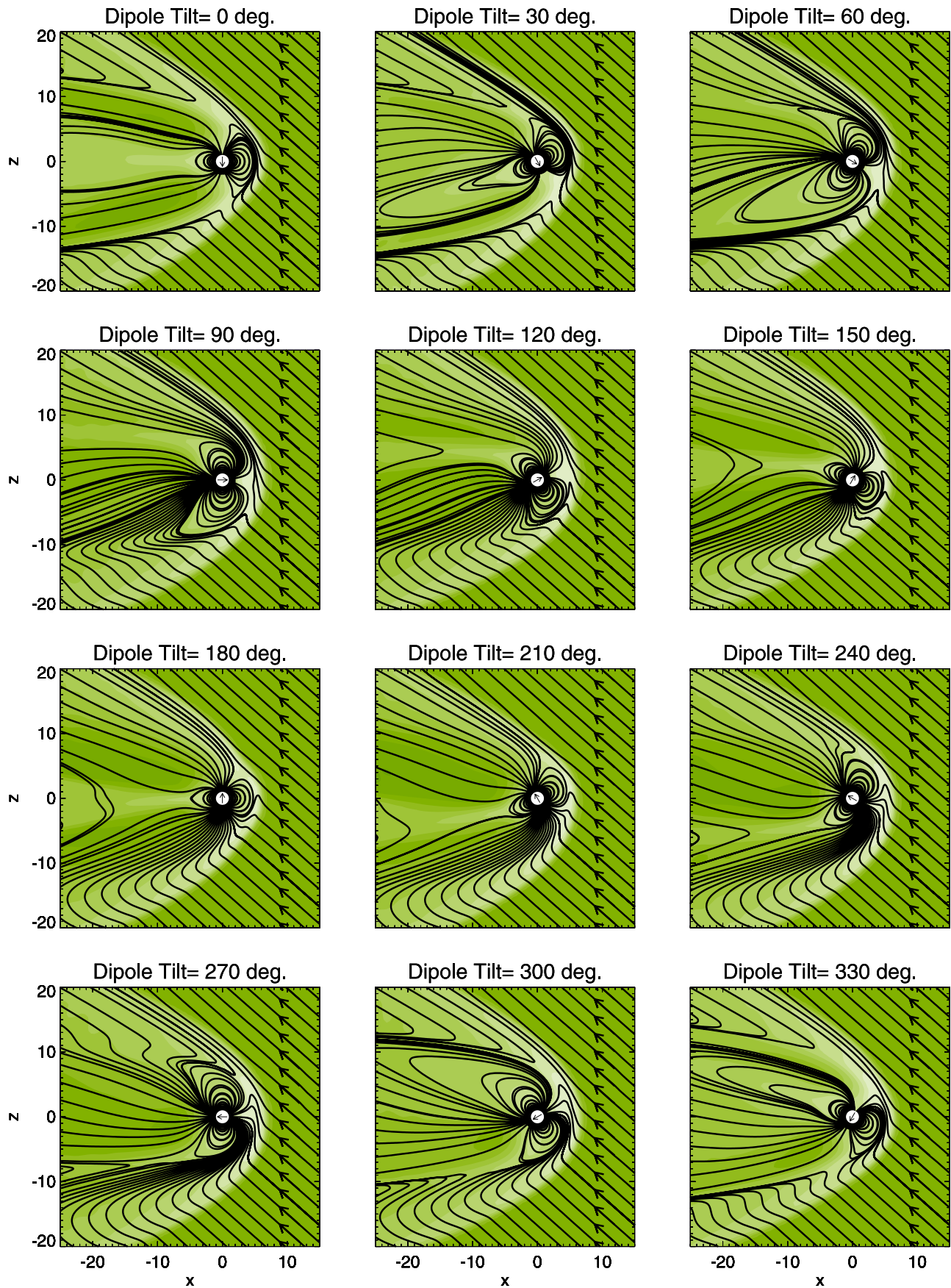
J. Vogt and B. Zieger, School of Engineering and Science, International University Bremen, P.O. Box 750561, D-28725 Bremen, Germany. (j.vogt@iu-bremen.de; b.zieger@iu-bremen.de)
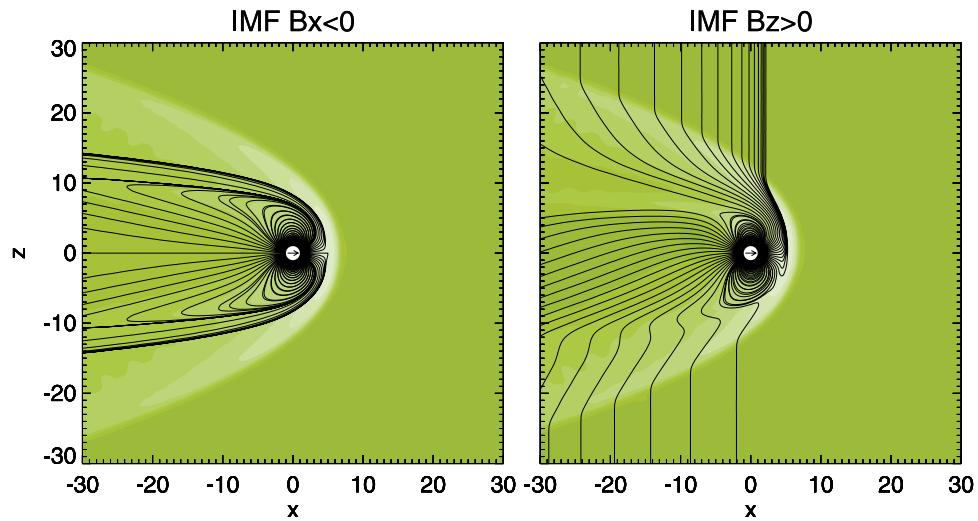
IMF Bx<0

IMF Bz>0

Figure 1. Magnetic field configurations and pressure in a pole-on paleomagnetosphere with the interplanetary magnetic field (IMF) parallel (left) and perpendicular (right) to the solar wind flow direction.

Parallel IMF

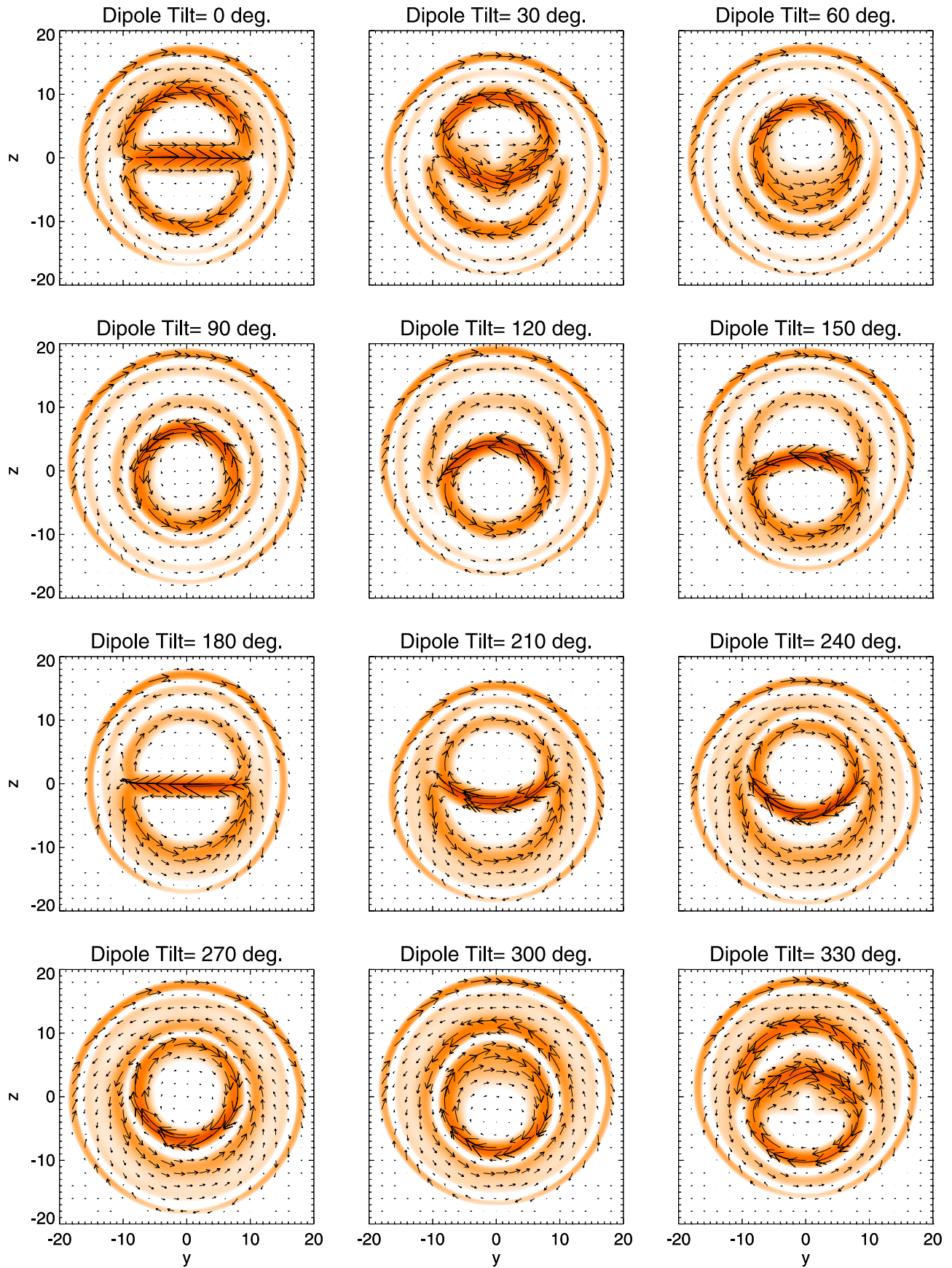**Antiparallel IMF**

Perpendicular IMF
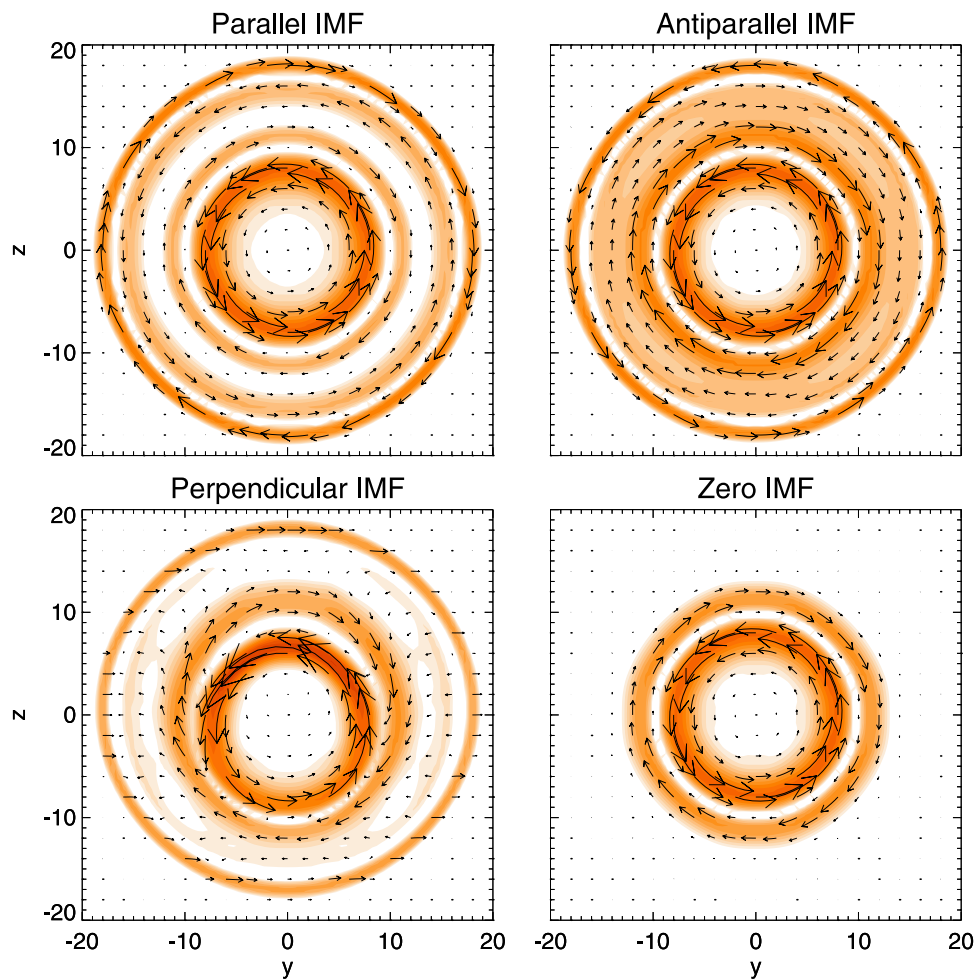
Zero IMF

Figure 2. Current systems in the tail of a pole-on paleomagnetosphere with the IMF parallel, antiparallel, and perpendicular to the solar wind flow, and with zero IMF.

Figure 3. Diurnal variation of the magnetic field configuration and pressure in an equatorial dipolar paleomagnetosphere.
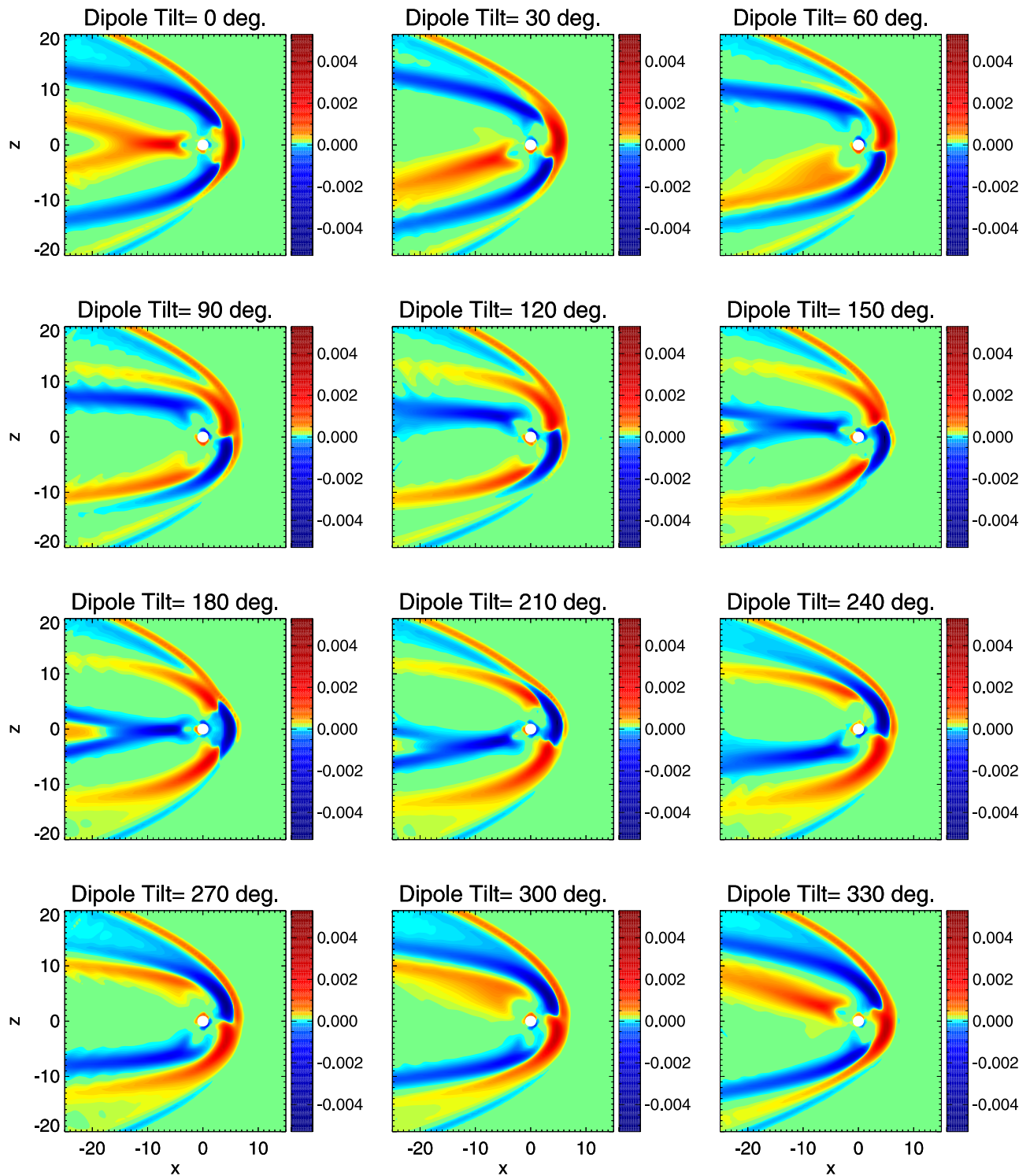
Figure 4. Diurnal variation of the currents flowing across the equatorial plane in an equatorial dipolar paleomagnetosphere. Blue and red colors indicate northward and southward flow direction, respectively.

Figure 5. Diurnal variation of the current system in the tail of an equatorial dipolar paleomagneto-sphere.