The Geospace Environment Modeling Grand Challenge: Results from a Global Geospace Circulation Model

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Abstract. We have used our Global Geospace Circulation Model (GGCM) to simulate two time intervals that were proposed as the Geospace Environment Modeling (GEM) Grand Challenge for modelers to investigate to what extent and accuracy models can predict the ionosphere’s response to the solar wind and interplanetary magnetic field. In this paper we present comparisons of our GGCM with the comprehensive experimental study by Lyons [this issue] (which provided synoptic maps of the polar cap electrodynamics and particle precipitation) for the two time intervals, January 27, 1992, 1325-1715 UT and 1730-1930 UT. We find a very good agreement between the potential patterns predicted by our model and those obtained by the assimilative mapping of ionospheric electrodynamics (AMIE) procedure. We also find that the separatrix and cusp locations predicted by our model generally compare well with those obtained from particle precipitation data. The soft electron zone of ionospheric precipitation, as defined by Lyons, lies almost entirely in the region for which our model predicts open field lines. However, the model predicts cross polar cap potential drops that are roughly a factor of 2 larger than those predicted by AMIE.

1. Introduction

Global simulations of Earth’s magnetosphere were first developed some 20 years ago [Leboeuf et al., 1978] in order to study the interaction of the solar wind with the magnetosphere. The early two- and three-dimensional simulations [Brecht et al., 1981; Lyon et al., 1981; Ogino, 1986; Walker et al., 1993], although continuously being improved, employed very simple boundary conditions for the earthward side and were essentially unable to account for the ionospheric response to magnetospheric convection. The first step toward the implementation of a realistic ionospheric boundary condition was reported by Fedder and Lyon [1987]. The link between the magnetosphere and the ionosphere was established by mapping field-aligned currents (FACs) from the magnetosphere into the ionosphere. A two-dimensional potential equation for the ionospheric convection pattern was then solved, assuming constant ionospheric conductance. The ionospheric potential was mapped back to the magnetospheric boundary and used as a boundary condition for the magnetospheric flow and field. In this manner, the ionosphere is transformed from its passive role in the solar wind-magnetosphere interaction, and becomes a controlling factor of magnetospheric convection.

It became later apparent that assuming constant conductance may be too crude an approximation. More recent models have therefore used refined models of the ionospheric response that involve calculating the ionospheric Hall and Pedersen conductances self-consistently [Fedder et al., 1995; Raeder, 1995; Raeder et al., 1995]. However, it is difficult to assess how good these models are because the ionospheric conductance cannot be measured directly, and observation-based models provide only statistical averages [Spiro et al., 1982; Hardy et al., 1987]. Likewise, measurements of the ionospheric electric field and the FACs are also limited in their temporal and spatial extent, which makes it difficult to compare them with a global model.

The Geospace Environment Modeling (GEM) Grand Challenge now presents a novel and unique opportunity to test the accuracy and physical realism of our model, because it provides us with a comprehensive set of ionospheric potential
maps and ancillary data [Lyons, this issue]. In this paper we focus on the events on January 27, 1992, that are centered around 1520 and 1830 UT. We choose these two events primarily because they are characterized by fairly stable IMF conditions. In the remainder of the paper we first give a brief introduction of our model and then compare the model results with the findings of Lyons et al. [1996]. In the last section we discuss our results and address the differences between observations and the predictions of the simulation model.

2. The Model

For this study we use a global MHD code which includes an ionospheric model for the closure of field-aligned currents. In order to accommodate the large simulation volume with a long tail and long simulation times the simulation code was parallelized for running on Multiple Instruction-Multiple Data (MIMD) machines by using a domain decomposition technique [Fox et al., 1988]. The model solves the ideal MHD equations (modified as described below) for the magnetosphere and a potential equation for the ionosphere. Numerical effects, such as diffusion, viscosity, and resistivity, are necessarily introduced by the numerical methods. These permit viscous interactions and to a limited extent magnetic field reconnection. The only explicit diffusive term is the anomalous resistivity that is included in Ohm’s law. The effects of numerical diffusion and the anomalous resistivity term are discussed by Raeder et al. [1996].

2.1. Outer Magnetosphere

The magnetospheric (MHD) part of the model is solved using a finite difference method which is conservative for the gasdynamic part of the normalized MHD equations:

\[
\frac{\partial \rho}{\partial t} = - \nabla \cdot (\rho \mathbf{v})
\]

\[
\frac{\partial \rho \mathbf{v}}{\partial t} = - \nabla \cdot (\rho \mathbf{v} \mathbf{v} + p \mathbf{I}) + \mathbf{j} \times \mathbf{B}
\]

\[
\frac{\partial e}{\partial t} = - \nabla \cdot \{ (\epsilon + p) \mathbf{v} \} + \mathbf{j} \cdot \mathbf{E}
\]

\[
\frac{\partial \mathbf{B}}{\partial t} = - \nabla \times \mathbf{E}
\]

\[
\mathbf{v} \cdot \mathbf{B} = 0
\]

\[
\mathbf{E} = - \mathbf{v} \times \mathbf{B} + \eta \mathbf{j}
\]

\[
\mathbf{j} = \nabla \times \mathbf{B}
\]

\[
e = \frac{1}{2} \rho v^2 + \frac{p}{\gamma - 1}
\]

where the symbols have their usual meanings. The \( \mathbf{j} \times \mathbf{B} \) and \( \mathbf{E} \cdot \mathbf{j} \) terms are treated as source terms because the very low plasma \( \beta \) and the large magnetic field gradients near the Earth do not allow the use of the full conservative form of the MHD equations. The model of the anomalous resistivity is given by

\[
\eta = \alpha j'^2 \quad \text{if} \quad j' \geq \delta, \quad 0 \quad \text{otherwise}
\]

\[
j' = \frac{|j| \Delta}{|B| + \epsilon}
\]

where \( j \) is the local current density, \( B \) the local magnetic field, \( \Delta \) is the grid spacing, and \( \epsilon \) is a very small number introduced to avoid dividing by zero. The normalized current density \( j' (0 \leq j' \leq 1) \) is used as a switch for the resistivity. In places where the resistivity is switched on it becomes proportional to the square of the local current density. Similar resistivity models have been used in the past to model the kinetic effects that lead to anomalous resistivity [Sato and Hayashi, 1979; Hoshino, 1991]. The parameters \( \alpha \) and \( \delta \) determine the value of the resistivity and the current density threshold that must be reached for the resistivity to be switched on. These parameters are chosen such that the resistivity \( \eta \) is nonzero only at a very few gridpoints in strong current sheets.

The numerical grid is rectangular and nonuniform with the highest spatial resolution (about 0.5 \( R_E \)) near Earth. It extends 20 \( R_E \) in the sunward direction, 400 \( R_E \) in the tailward direction and \( \pm 40 \ R_E \) in the Y and Z directions. The gasdynamic part of the equations is spatially by using a technique in which fourth order fluxes are hybridized with first order (Rusanov) fluxes [Harten and Zwas, 1972; Hirsch, 1990]. The magnetic induction equation is treated somewhat differently [Evans and Hawley, 1988] in order to conserve \( \nabla \cdot \mathbf{B} = 0 \) exactly. The time stepping scheme for all variables consists of a low order predictor with a time centered corrector, which is accurate to the second order in time. The outer boundary conditions are fixed at the given solar wind values on the upstream side. At the other boundaries we apply open, i.e., zero normal derivative, boundary conditions.

2.2. Ionosphere

The inner boundary, where the MHD quantities are connected to the ionosphere, is taken to be a shell of radius 3.7 \( R_E \) centered at Earth. The choice of this radius is a compromise necessitated by numerical considerations, such as exotenuously high Alfvén speeds and very large magnetic field gradients closer to the Earth. However, this choice allows for the proper mapping of all relevant field-aligned current (FAC) systems down to about 59º magnetic latitude. The placement of the inner boundary also inhibits the formation of a ring current. Inside this shell we do not solve the MHD
equations, but assume a static dipole field. The important physical processes earthward of that shell are the flow of FACs and the closure of these currents in the ionosphere. Every few time steps (corresponding to a time interval of less than 5 s in real time) we use the static dipole field to map the magnetospheric FACs from the 3.7 $R_E$ shell onto the polar cap. We then use the FACs as input for the ionospheric potential equation:

$$\nabla \cdot \Sigma \cdot \nabla \Phi = -j \parallel \sin I$$  \hspace{1cm} (11)

which is solved on the surface of a sphere with a radius of 1 $R_E$. Here $\Phi$ denotes the ionospheric potential as a function of magnetic latitude and local time, $\Sigma$ is the tensor of the ionospheric conductance, $j \parallel$ is the mapped FAC with the downward current considered positive and corrected for flux tube convergence, and $I$ is the inclination of the dipole field at the ionosphere. The boundary condition $\Phi = 0$ is applied at the equator. For the ionospheric Hall and Pedersen conductances, $\Sigma_H$ and $\Sigma_P$, which enter the conductance tensor $\Sigma$ [Kamide and Matsushita, 1979], three ionization sources are taken into account. First, for the solar EUV ionization we use an empirical model [Moen and Brekke, 1993] that depends only on the solar 10.7 cm flux ($F_{10.7}$) and the solar zenith angle ($\chi$):

$$\Sigma_H = (F_{10.7})^{0.63}(0.81k + 0.54k^{1/2})$$  \hspace{1cm} (12)

$$\Sigma_P = (F_{10.7})^{0.49}(0.34k + 0.93k^{1/2})$$  \hspace{1cm} (13)

$$k = \cos \chi$$  \hspace{1cm} (14)

Second, we compute the mean energy $E_0$ and energy flux $F_E$ of precipitating electrons that are accelerated by a parallel potential drop $\Delta \Phi \parallel$ in regions of upward field-aligned currents [Knight, 1972; Lyons et al., 1979]:

$$F_E = \Delta \Phi \parallel |j \parallel|$$  \hspace{1cm} (15)

$$E_0 = e\Delta \Phi \parallel$$  \hspace{1cm} (16)

$$\Delta \Phi \parallel = \frac{e^2 n_e}{\sqrt{2\pi m_e k T_e}} \max(0, -j \parallel)$$  \hspace{1cm} (17)

Third, diffuse electron precipitation is modeled by assuming complete pitch angle scattering of electrons at 3.7 $R_E$ [Kennel and Petschek, 1966]:

$$F_E = n_e (k T_e / 2 \pi m_e)^{3/2}$$  \hspace{1cm} (18)

$$E_0 = k T_e$$  \hspace{1cm} (19)

in which $n_e$, $T_e$, and $m_e$ are the electron density, temperature, and mass, respectively, taken at the 3.7 $R_E$ shell. The conductances are then computed from the electron precipitation parameters using the empirical relation [Robinson et al., 1987]:

$$\Sigma_P = \frac{40E_0/(16 + E_0^2)F_E^{1/2}}{\Gamma}$$  \hspace{1cm} (20)

$$\Sigma_H = 0.45E_0^{6/8}\Sigma_P$$  \hspace{1cm} (21)

Using the mapped FACs and ionospheric conductances, the potential equation is solved using a pseudospectral Galerkin method [Canuto et al., 1987], and the ionospheric potential is mapped to the 3.7 $R_E$ shell where it is used as a boundary condition for the magnetospheric flow by taking $v = (-\nabla \Phi) \times B / B^2$.

2.3. Initial Conditions

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. This procedure ensures a divergence-free transition from the constant solar wind field to the magnetospheric field. The dipole orientation in the simulation corresponds to the Earth’s dipole orientation at 1520 UT on January 27, 1992 (about 8.53° away from the Sun in the northern hemisphere and 15.6° toward dawn), and is held constant during the entire run. The simulation box is initially filled with tenuous (0.1 cm$^{-3}$) and cold (5000 K) plasma of zero velocity. The simulation run is started with a southward IMF and average solar wind parameters in order to let the unphysical initial conditions evolve into a magnetospheric configuration. After one hour, we start to rotate the IMF vector toward its orientation at the beginning of the interval of interest (see Plate 1), which is approximately 2 hours and 20 min after the beginning of the simulation.

3. Solar Wind Observations

On January 27, 1992, the IMP 8 spacecraft was near (36.2,−20) $R_E$ in geocentric solar ecliptic (GSE) coordinates, i.e., upstream of the bow shock and in the dawn sector. Plate 1 shows the IMP 8 measurements (black dots) and the data stream that was used to drive the MHD model (red lines) in GSE coordinates. The two intervals that we address in this paper, 1325-1715 UT and 1730-1930 UT, are marked by gray shading. The IMF, plasma density, and plasma $v_x$ velocity data are fairly complete for these time intervals; however, only a few data points are available for the plasma temperature and the transverse flow components. For the simulation, we set the plasma temperature to a constant
Plate 1. Solar wind observations on March 29, 1993. Dots show the IMP 8 measurements, the red lines show the processed data that were used as model input. The panels show, from top to bottom, in GSE coordinates: \( B_x \), \( B_y \), \( B_z \), \( v_x \), \( v_y \), \( v_z \), the temperature, and the number density.

value \((7 \times 10^4 \text{ K})\) that is most consistent with the available data. The \( v_y \) and \( v_z \) components of the solar wind flow are simply set to zero. Neither of these parameters is expected to affect the results significantly. We also set the IMF \( B_z \) component to zero, because a nonzero and time varying \( B_z \) is difficult to use as input to an MHD model and because in this case the IMF \( B_z \) was the minor IMF component compared to the \( B_y \) and \( B_z \) values.

Plate 1 also shows that no data were available prior to 1325 UT, the beginning of the first time interval. For the time leading to the first interval, we use first about one hour of due southward IMF, followed by a smooth transition into the first observed values, which lasts for about 80 min. The initial southward IMF is the most efficient way to generate the initial magnetospheric configuration [Raeder et al., 1996], while the following transition is just an ad hoc assumption for the lack of better data. Ideally, we would like to use about 3 hours of IMF and solar wind plasma observations prior to an event to rule out any effects of the solar wind and IMF history. However, in this study we are address the ionospheric potential patterns, which develop in response to the IMF on a time scale of about 15 min. Thus, because we later compare the average over 4 hours with the averaged observations, we consider the present, although incomplete, IMF and plasma data to be sufficient for this study.

During the first interval, 1325-1715 UT, the IMF was on average northward directed, with a large negative (–20 nT) \( B_y \) component. The solar wind speed was average, about 350 km s\(^{-1}\), while the solar wind density was well above average, between 10 and 20 cm\(^{-3}\). Thus the solar wind dynamic pressure was about 2 to 3 times larger than normal.

During the second time interval, from 1730 to 1930 UT, the conditions were similar, except that the IMF \( B_z \) component was smaller and at times negative (in the GSE system). In geocentric solar magnetospheric (GSM) coordinates, which are more relevant to the day side reconnection geometry, the IMF \( B_z \) component was negative almost throughout the entire interval due to the downward dipole tilt and the large negative \( B_y \) (see Figure 1 of Lyons et al. [1996], which shows the field values in the GSM system). Also, the solar wind density fluctuated less than in the first interval and stayed around 12 cm\(^{-3}\) during this period.

4. Comparison With the Model

In Plates 2, 3, and 4 we compare the model and the analysis by Lyons et al. [1996]. The Plates are identical to Figures 6, 7, and 5, respectively, in the Lyons et al. [1996] paper, except that we superimposed the results from our model. There are some data in these Plates that we do not discuss in this paper; the complete discussion of the experimental findings
can be found in the work of Lyons et al. [1996]. Additional information about the AMIE procedure and detailed information about the data that were used to obtain the potential patterns can be found in the work of Lu et al. [1994, 1995].

4.1. The 1325-1715 UT Period

Plate 2 shows the results of the comparison for the 1520 UT ± 115 min time period. During this period, the IMF was on average northward, with a very large $B_p$ component of about −20 nT. The black contour lines are the potential lines estimated by Lyons et al. [1996] using the AMIE procedure [Richmond, 1992; Lu et al., 1994, 1995], and the red contours are the potential contours from our model. The model potential contours were produced by averaging the 4-min resolution potentials over the entire 4-hour time period in order to make the model results more comparable with the AMIE results. However, the instantaneous potential patterns do not look significantly different from the averages shown here.

There is in general a good correspondence between the observational and the model potential patterns. In particular, the ionospheric flow is characterized by a dominant, near circular, lobe cell centered at high magnetic latitudes, and a smaller, crescent shaped cell at lower magnetic latitudes. Both of the northern hemisphere model cells have 2 extrema (150 kV at 0800 MLT, 87° MLAT, 139 kV at 1200 MLT, 83° MLAT, and −31 kV at 1830 MLT, 71° MLAT, −33 kV at 2300 MLT, 73° MLAT; MLT and MLAT are magnetic local time and magnetic latitude, respectively). However, these extrema barely constitute separate cells, but are a small deviation from the large scale convection pattern. The smaller, crescent shaped cell is located on the duskside in the northern hemisphere and on the dawnside in the southern hemisphere, consistent with the sign of the IMF $B_p$ [Heeiles, 1984; Heppner and Maynard, 1987]. The modeled lobe cells are somewhat larger than the lobe cells obtained by AMIE. The lobe cells are also centered at somewhat higher latitudes than the lobe cells obtained by AMIE, which are located near 1000 MLT, 85° MLAT, and 1430 MLT, 85°, respectively. As a result, the dayside convection throat moves to lower magnetic latitudes and closer to noon in the model. There are also two small convection cells in the AMIE patterns for the northern hemisphere located around 0300 MLT, 67° and 83°, respectively. These cells are not reproduced by the model; however, they are of minor size and do not significantly change the flow patterns.

While the modeled potential patterns agree well with the AMIE derived patterns, the model predicts a significantly larger magnitude. In the northern hemisphere, AMIE estimates a potential drop of 40 - 60 kV (AMIE potential contours are at 10 kV intervals. The smallest (largest) contour are −30 (10) kV. Thus the potential minimum could be just a bit larger than −40 kV, and the maximum just smaller than 20 kV, without requiring the drawing of a new contour) Our model predicts a potential drop of 183 kV, with a minimum of −33 kV and a maximum of 150 kV. In the southern hemisphere, AMIE estimates 70 - 90 kV, while our model predicts 143 kV with a minimum of −121 kV and a maximum of 22 kV, located at 1800 MLT, −87° MLAT, and at 0530 MLT, −72° MLAT, respectively. Possible causes of this discrepancy will be discussed in the next section.

The green contour in Plate 2 is the 800 pPa (picopascal) contour of the magnetospheric pressure, mapped from the inner boundary of the MHD model at 3.7 $R_E$ into the ionosphere. We have found that the pressure contours are a good indicator of the position of the cusp. Comparison with the observed cusp locations, marked by the letter C in the Plate 2 (near 1140 MLT, 75° MLAT in the northern hemisphere, and near 1500 MLT, −78° MLAT in the southern hemisphere), shows that the model predicts the cusp local time well. However, it predicts its magnetic latitude to be about 2° - 3° more equatorward than the observed cusp locations. One should note, however, that the cusp footprint is of finite extent and that there are no satellite tracks going through the predicted cusp location. Thus the predicted cusp location is essentially consistent with the observations.

The black dots mark the observed plasma sheet-polar rain boundary, which more or less coincides with the magnetic separatrix. The blue line in Plate 2 denotes the separatrix (open-closed boundary) in a magnetospheric pressure contour at 1500 UT, and the yellow line denotes the MHD separatrix at 1600 UT. The model separatrix very closely follows the observed plasma sheet-polar rain boundary in the northern dusk and the southern dawn hemisphere. In the northern dawn and southern dusk hemisphere the model predicts the separatrix to be equatorward of the observed plasma sheet-polar rain boundary, but poleward of the inner edge of the soft electron zone (i.e., the “SEZ” as defined in the Lyons et al. [1996] paper).

Lyons et al. [1996] also considered the possibility that the separatrix coincides with the inner edge of the SEZ. This scenario is shown in Plate 3, which shows their ionospheric synoptic map for the 1520 UT interval (Figure 7 of Lyons et al. [1996]). In this Plate, we have also overlaid the separatrix obtained from the MHD model, using the same color coding as in Plate 2. From Plates 2 and 3 it is evident that the model separatrix either coincides very well with the plasma sheet-polar rain boundary or lies more equatorward than does the observed plasma sheet-polar rain boundary. When the latter is the case, the SEZ is also present, and the model separatrix lies close to the equatorward boundary of the SEZ. Thus, our model indicates that the SEZ lies on open field lines at all times.
Plate 2. Comparison between the observed ionospheric parameters and results from the model for the 1325 to 1715 UT time period. The underlying figure is reproduced from the Lyons et al. [1996] paper (Figure 6). The black lines are the potential contours obtained by AMIE. The red contours are isopotentials from the model, the green contour is the 800 pPa (picopascal) contour of the MHD pressure, indicating the cusp location, the blue contour is the open-closed boundary at 1500 UT, and the yellow contour is the open-closed boundary at 1600 UT.
Plate 3. Comparison between the separatrix location inferred by Lyons et al. [1996] (heavy solid and dashed lines, Figure 7 of that paper) and from our model for the 1325-1715 UT time period. The blue contour is the open-closed boundary from the model at 1500 UT, and the yellow contour is the open-closed boundary from the model at 1600 UT.
**Plate 4.** Comparison between the observed ionospheric parameters and results from the model for the 1730-1930 UT time period. The underlying figure is reproduced from the Lyons et al. [1996] paper (Figure 5). The black lines are the potential contours obtained by AMIE. The red contours are isopotentials from the model, the green contour is the 800 pPa (picopascal) contour of the MHD pressure, indicating the cusp location, the blue contour is the open-closed boundary at 1700 UT, and the yellow contour is the open-closed boundary at 1800 UT.
4.2. The 1730-1930 UT Period

The main difference between the 1325-1715 UT and the 1730-1930 UT period is the sign of the IMF $B_z$. In GSM coordinates, $B_z$ is predominantly negative from 1730 to 1930 UT, with an average value of $-5.7$ nT. Plate 4 shows the comparison between the observed potentials and separatrices, and the model results. This interval is similar to the previous case, in that the potential patterns are dominated by large lobe cells that are centered close to the magnetic pole, with smaller, crescent shaped cells in the northern dusk and southern dawn hemispheres. The modeled and observed potential patterns compare very well, except for minor differences.

In the northern hemisphere, AMIE obtains a lobe cell of 20-30 kV at 0630 MLT, 84° MLAT, while the model predicts two potential extrema of 138 kV at 0730 MLT, 85° MLAT, and 140 kV at 1100 MLT, 82° MLAT, respectively. However, the flow patterns are nearly the same because these two small cells cause only a minor flow deviation. For the crescent-shaped dusk cell in the northern hemisphere we find that the modeled cell lies at roughly the same latitude, but more sunward than the AMIE cell ($-43$ kV at 1800 MLT, 71° MLAT, versus $-50$ to $-60$ kV at 1945 MLAT, 70° MLAT). Thus the modeled and AMIE cells are about equal in location and shape but are significantly different in their strength.

In the southern hemisphere we find a similar correspondence. AMIE shows a lobe cell that is very similar in shape and location compared with the modeled cell ($-70$ to $-60$ kV at 1430 MLT, $-83°$ MLAT for AMIE, versus $-131$ kV at 1700 MLT, $-85°$ MLAT for the model). Like in the northern hemisphere, the crescent cell of the model (31 kV at 0630 MLT, $-71°$ MLAT) lies somewhat sunward, but roughly at the same latitude as the crescent cell of the AMIE model (20-30 kV at 0430 MLT, $-70°$ MLAT). Each of the models produces one more small cell in the nightside, AMIE around 2230 MLT, $-75°$ MLAT, and the model at 0200 MLT, $-66°$ MLAT. However, because of the southward IMF orientation one would expect the nightside regions to be much less stationary than during the previous northward IMF interval. These features may therefore be time dependent and not captured very well by either the AMIE analysis (which assumes the ionosphere to be stationary) or the averaged patterns of the MHD model.

Despite the rather good match of the potential patterns, there are significant differences in the strength of the potential flow. AMIE predicts a potential drop of 70 - 90 kV for the northern and 80 - 100 kV for the southern hemisphere. The model predicts, respectively, 183 kV in the northern and 132 kV in the southern hemisphere. These discrepancies are similar to those that we found in the previous case and will be discussed in the next section.

The open-closed boundary compares reasonably well with the separatrix obtained from the data in the northern hemisphere (the blue and yellow lines versus the heavy black line in Plate 4). On the dayside and on the flanks, the open field line region of the model appears to be slightly larger than the open field line region found from the particle data. However, the model also shows a slight expansion of the polar cap, with the separatrix moving equatorward in the northern dusk and southern dawn and in the southern dusk hemisphere. In the southern hemisphere, the separatrix locations match well in the dawn sector. In the dusk sector, the model predicts the separatrix about 6° equatorward from where the precipitation data indicate its location.

5. Summary and Discussion

We have used our Global Geospace Circulation Model (GGCM) to simulate two time intervals, January 27, 1992, 1325-1715 UT and 1730-1930 UT, that were proposed as the GEM Grand Challenge. Comparison of the simulation results with the results of the Lyons et al. [1996] study shows that the potential patterns are very similar. Our comparison of the separatrix locations predicted by AMIE with those by our model also found in general good agreement. Further, our model results indicate that the region of soft electron precipitation (SEZ) lies on open field lines at all times. This is consistent with the suggestion by Lyons et al. [1996] that the SEZ is mostly located on open field lines, though neither the observations nor this model provides definitive proof.

The most significant difference between the AMIE analysis and our model is the magnitude of the cross polar cap potential. Our model predicts values that are roughly twice as large as those obtained by AMIE. This discrepancy is difficult to explain, but a number of factors may play a role:

1. The reconnection rate in our model may be too large, or the size of the reconnection region may be too large. Although the occurrence of magnetic reconnection at the magnetopause between the magnetospheric field and the IMF is a well-established fact, little is known about the controlling factors, in particular about the kinetic effects that enable or inhibit magnetic reconnection. Because our model solves the MHD equations numerically, reconnection due to numerical effects is unavoidable. We also include a anomalous resistivity term that we have found to be necessary to produce realistic tail dynamics during substorms [Raeder et al., 1996]. We do not know, however, how the combined action of numerical resistivity, anomalous resistivity, and finite grid resolution affects reconnection rates at the magnetopause or the extent of the reconnection region, i.e., the length of the X
line. If reconnection at the magnetopause is primarily controlled by local conditions, it is quite possible that the magnetosphere is too open and that too large a fraction of the solar wind electric field maps into the ionosphere. However, if reconnection is primarily controlled by external factors, like the Alfvén speed in the inflow region, the reconnection rates of the model are likely to be correct.

2. The ionospheric conductances, in particular the Pedersen conductance may be too low in our model. If one views the reconnection process at the magnetopause as a current generator, then the ionospheric Pedersen conductance determines the magnitude of the potential in a linear way. In reality, however, the magnetosphere is most likely both a current and a voltage source for the ionosphere, and thus the current-voltage relationship is nonlinear [Lysak, 1985]. Because our model for the ionospheric conductance is empirical (see equations (12) - (21)), we may be underestimating the Pedersen conductance, particularly in the nightside where the conductance is dominated by precipitation. We have compared the conductance distribution in our model with that from empirical models [Robinson et al., 1987; Spiro et al., 1982] and found no differences that would be significant enough to explain the differences in the potential drops.

3. Our model does not adequately account for region 2 (R2) currents. R2 currents originate from the inner magnetosphere, where MHD is not a good description of the dominating plasma processes. As a consequence, the R2 currents in the model, although present, may be too weak. Because the R2 currents enter the ionosphere close to the R1 currents with the opposite sign, they provide an effective partial short circuit for the R1 currents and thus would tend to diminish the Pedersen current that closes across the polar cap. However, in the cases presented here, the strongest field-aligned currents with an R1 sense enter the ionosphere on the dayside at high magnetic latitudes and drive the lobe cells. In this situation one would not expect significant R2 currents to be close by, because the R2 currents enter the ionosphere at much lower magnetic latitudes [Ijima and Potemra, 1976]. This makes it difficult to explain the large potential drops as an R2 current effect.

4. There may be significant conductivity in the nightside F region that is not accounted for in the model. It was suggest by R. A. Greenwald (private communication, 1997) that the nightside ionospheric F region may contribute significantly to the Pedersen conductance. Usually the highest conductivities are found in the E region, where both the electron density and the electron-neutral collision frequencies are high. However, the electron density of the F region is much higher than that of the E region, so that in regions where the E region conductivity becomes very low, the F region may contribute significantly to the overall conductance, despite the low collision frequencies. Furthermore, the recombination rate of F region electrons is low. Therefore enhanced conductivity regions could drift far from their source regions. Enhanced F region conductance would imply that some of the FACs close above the E region, thereby reducing the electric field there. Neither the AMIE model nor our GGCM takes explicit account of F region conductivity. However, some F region conductance may be implicitly included in the height-integrated conductivity used by AMIE. We are not aware of any quantitative model of this phenomenon, but it offers a possible explanation for the high cross polar cap potentials.

5. The AMIE potentials may be too low. AMIE relies not only on data but to a large extent also on other parameters that are not measured directly but instead are obtained from empirical models or by educated guesses. In particular, the ionospheric conductances are input parameters that may significantly affect the resulting cross polar cap potentials. Recent AMIE studies with varying conductance distributions, like those obtained from Polar images [Lammerzahl et al., 1997; Germany et al., 1997] have shown larger potential drops [Emery et al., 1996; Richmond et al., 1997]. The AMIE patterns of the events considered here were obtained using a very large database (67 magnetometers, 4 radars, 4 DMSP satellites, and 1 NOAA satellite) [Lu et al., 1994, 1995]. That makes it very unlikely that the AMIE results have errors as large as a factor of two. However, even with such a large database, the long time averaging and the unequal spatial and temporal data coverage of the data that were used may still account for a fraction of the potential differences.

We acknowledge that none of these explanations for the significant differences between the AMIE cross polar cap potentials and those from our model is satisfactory. However, the good agreement between the observed and the modeled potential patterns and separatrices shows that the field topology of the model is basically correct. In order to investigate the source of the high cross polar cap potentials, more event studies are required and more detailed comparisons between AMIE and GGCMs must be undertaken.

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