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Coupling of Two Computational Models of the Earth's Magnetosphere

by

Michikazu Hojo

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE

Master of Science

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ABSTRACT

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The first major step has been completed in a long range project to merge the Fedder-Lyon Global 3D magnetohydrodynamic code and the Rice Convection Model (RCM) of the Earth's magnetosphere. Using MHD results as initial and boundary conditions, RCM runs were carried out for three different values of the energy invariant $\lambda$ of the plasma-sheet ions: $\lambda = $ negligibly small as in ideal MHD, $\lambda$ estimated from global MHD results, and $\lambda$ estimated from observations. In the first two runs, the RCM produced thin, well-defined patterns of region-2 magnetic-field-aligned currents shielding the inner magnetosphere from the convection electric field. These results differed substantially from the MHD result, indicating inaccuracy in the MHD code's numerical method when applied to the inner magnetosphere. The third run produced weak shielding and non-classic current patterns, which provide insight into the effect of plasma-sheet temperature on shielding.
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I. INTRODUCTION

Over the past 20 years, many computational models with different approximations and formalisms have been developed in the effort to produce a global model which can predict the behavior of the Earth's magnetosphere and its coupling to the ionosphere. Yet, none of the computational models developed so far have been successful at producing all of the global scale magnetospheric processes with reasonable accuracy. One of the crucial difficulties is that no single formulation is sufficient to treat the entire magnetosphere, since different basic approximations and formulations are required in different regions of the magnetosphere. For example, one-fluid magnetohydrodynamics, which has enjoyed considerable success in treatment of solar-wind/magnetosphere interactions [e.g., Fedder and Lyon, 1987], is clearly inadequate for the inner magnetosphere. The main motivation of this research is to treat two different regions of the magnetosphere by merging two models which have different theoretical bases.

This thesis describes the first phase of work to merge two existing large-scale models of the magnetosphere: the Fedder-Lyon Global 3D magnetohydrodynamic magnetospheric-simulation code that was originally produced at the Naval Research Lab and the Rice Convection Model (RCM) of the inner magnetosphere that was developed at Rice University. The Fedder-Lyon code uses the MHD formalism to treat the middle and outer magnetosphere while the RCM uses the adiabatic-drift formalism to treat the inner and middle magnetosphere appropriately. This thesis presents the results of the first phase of this long-range project, in which RCM simulations are performed by using the MHD result to provide RCM initial and boundary condition. In this chapter, the essential ideas and theoretical formalisms of magnetospheric physics are outlined. Chapter II gives an overview of the two computational models to be merged. The third chapter describes how the MHD results were processed to serve as input for the RCM. The fourth chapter
displays and discusses the RCM run results. The final chapter summarizes this first phase of this long range project, and the second and third phase are briefly described.

A. Overview and Terminology

The magnetosphere is the region of space where the Earth's magnetic field dominates the physics of various large-scale phenomena. The standard coordinate system for magnetospheric work is Geocentric Solar Magnetospheric (GSM) coordinates. The origin of these coordinates is located at the center of the Earth. For the case where the Earth's dipole is perpendicular to the Earth-Sun line, $x_{\text{GSM}}$ is sunward, $y_{\text{GSM}}$ is duskward, and $z_{\text{GSM}}$ is northward. We assume that the solar wind flows in the $-x_{\text{GSM}}$ direction. The unit of length in this coordinate system is 'Earth Radii' ($R_{E}$).

Figure 1 shows a schematic view of the Earth's magnetosphere system in the plane containing the Sun and the rotational axes of the Earth ($x_{\text{GSM}}-z_{\text{GSM}}$ plane). The 'Interplanetary Magnetic Field' (IMF) is the field associated with 'Solar Wind', a magnetized plasma which flows approximately radially outward from the Sun. The 'Bow Shock' is the shock wave formed by the encounter of the supersonic plasma flow from the Sun with the Earth's magnetic field. It deflects this supersonic flow around the Earth's magnetosphere. Inside the bow shock is the 'Magnetosheath', where turbulent subsonic plasma is hotter and denser than it was in the undisturbed solar wind. Magnetosheath plasma flows along field lines through the 'Polar Cusp' all the way into the ionosphere. The Earthward boundary of the magnetosheath is the 'Magnetopause', the outermost boundary of the magnetosphere.

On the night side of the magnetosphere, geomagnetic field lines are stretched in the antisunward direction by the solar wind, forming a long 'Magnetotail'. The northernmost and southernmost layers of the magnetotail constitute the 'Plasma Mantle', where low-
energy ions flow antisunward. The 'Tail Lobes' lie just inside the plasma mantle and are almost devoid of plasma. The central region of the magnetotail which contains hot charged particles is called the 'Plasma Sheet'. The 'Neutral Sheet' is a thin region inside the plasma sheet, where magnetic field is small. It separates the northern part of the tail (where $B$ is mainly sunward) from the southern part (where $B$ is mainly tailward).

![Diagram of the Earth's magnetosphere](image)

**Figure 1** A schematic view of the Earth's magnetosphere system in the plane containing the rotational axis of the Earth and the Sun ($x_{GSM}$-$z_{GSM}$ plane).

Figure 2 shows the innermost part of the magnetosphere. The 'Plasmasphere' is the region near the Earth where the magnetic field is close to dipolar. It contains relatively dense and cold plasma that is mostly of ionospheric origin. Much less dense but very energetic plasma particles can be found in the 'Van Allen Belts' or 'Trapped-Radiation Belts'. These particles are trapped in the magnetic field, and they bounce rapidly back and
forth between northern and southern hemispheres along field lines. They also drift slowly east or west, depending on the sign of their charge, and go round and round the Earth.

![Diagram of the magnetosphere](image)

Figure 2 Plasma regions viewed in the magnetospheric equatorial plane. Arrows indicate flow velocities.

There are three main classes of magnetic field lines. Magnetic field lines which connect to the solar wind but do not enter the Earth are called 'Interplanetary Field Lines'. Field lines that connect the Earth and the interplanetary medium are 'Open Field Lines'. Most field lines in the magnetosphere are 'Closed Field Lines', which come from and return to the Earth. The modeling region of the Rice Convection Model is the inner and middle magnetosphere, where all field lines are closed.
B. Magnetospheric Convection and Current System

The most basic dynamic process in the Earth's magnetosphere is magnetospheric convection. Figure 3 shows the average observed pattern of flow in the upper ionosphere. The plasma flows antisunward over the polar caps and sunward along the auroral zone. Many years ago, two types of physical processes were proposed that might drive this systematic circulation of plasma through the magnetosphere: the 'Reconnection Process' suggested by Dungey [1961], and 'Viscous Interaction' suggested by Axford and Hines [1961].

![Figure 3](image)

Figure 3  Average observed pattern of convection flow in the Earth's ionosphere, in a reference frame that rotates with the Earth. The flow lines are equipotentials.

In Dungey's open model of the magnetosphere, interplanetary field lines are carried towards the day side magnetopause. As shown in Figure 4, these field lines connect with closed field lines that come from just inside the dayside magnetopause and change their topology to form open field lines above the Earth's northern and southern polar caps. These open field lines are carried antisunward through the thin outer layer of the magnetosphere, and they can be brought together in the distant tail and reconnected to form closed field lines and interplanetary field lines. While interplanetary field lines more
downstream to rejoin the solar wind, reconnected field lines now flow sunward through the plasma sheet and return to the day side magnetosphere to complete the convection.

![Diagram](image)

Figure 4  An interplanetary field line connects with a closed field line and changes its topology to form an open field line, as described in the open model of the magnetosphere.

In the closed model suggested by Axford and Hines, the antisunward flow in the outer region of the magnetosphere is caused by the antisunward flow in the magnetosheath which exerts viscous force on closed field lines just inside the magnetopause, dragging them antisunward. Eventually they return to the dayside magnetosphere through the plasma sheet. In either process, there is an overall antisunward flow in the outer layer and sunward flow in the interior of the magnetosphere, which explains the plasma flow pattern seen on the ionosphere.

The sunward flow in the interior of the magnetosphere corresponds to an electric field that roughly points from dawn to dusk near the equatorial plane of the magnetosphere (the plane containing the Earth's equator). In the outer magnetosphere, the plasma particle motion is dominated by \( \mathbf{E} \times \mathbf{B} \) drift. Plasma sheet particles also gradient and curvature drift, contributing to this westward-flowing 'Tail Currents' (Figure 5). As convecting plasma flows into the inner/middle magnetosphere, the gradient/curvature drift begins to dominate over \( \mathbf{E} \times \mathbf{B} \) drift. In the inner magnetosphere, positively charged particles gradient/curvature drift westward and negatively charged particles drift in the opposite direction, producing 'Ring Current'. In the ionosphere, two types of current flow across
field lines. 'Pedersen currents' flow along the component of $\mathbf{E}$ that is perpendicular to $\mathbf{B}$, and 'Hall currents' flow in the direction of $-\mathbf{E} \times \mathbf{B}$.

Figure 5  
Major types of current in the Earth's magnetosphere. The view is from slightly above the magnetic equatorial plane.

Ionospheric and magnetospheric currents are connected by 'Field Aligned Currents' or 'Birkeland Currents'. There are two major ring structures of Birkeland currents, as shown in Figure 6. 'Region-1 Currents' constitute the more poleward set. They are directed down into the ionosphere on the dawn side, up out of the ionosphere on the dusk side. The field lines that carry the region-1 currents are connected to the outer magnetosphere and the magnetospheric boundary layers. The 'Partial Ring Currents' flowing westward through the inner plasma sheet are connected to the ionosphere by 'Region-2 Currents', which flow down into the ionosphere on the dusk side, up out of the ionosphere on the dawn side.
Figure 6  Typical patterns of Birkeland current in the Earth’s ionosphere. Adapted from Iijima and Potemra [1978].

C. MHD and Adiabatic-Drift Formalisms

The Fedder-Lyon global MHD code solves the ideal magnetohydrodynamic (MHD) equations, which consist of Maxwell’s equations and three fluid equations to conserve mass, momentum, and energy. These are

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0
\]  (1)

\[
\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla p + \mathbf{J} \times \mathbf{B}
\]  (2)

\[
\frac{\partial \mathbf{B}}{\partial t} + \nabla \times \mathbf{E} = 0
\]  (3)

\[
\mu_0 \mathbf{J} = \nabla \times \mathbf{B}
\]  (4)

\[
\mathbf{E} + \mathbf{v} \times \mathbf{B} = 0
\]  (5)

\[
\frac{\partial E_p}{\partial t} + \nabla \cdot [(E_p + p) \mathbf{v}] = \mathbf{J} \cdot \mathbf{E}
\]  (6)

where the fluid energy density is defined as

\[
E_p = \frac{1}{2} \rho \mathbf{v}^2 + \rho u
\]  (7)
and \( \mathbf{E} \) and \( \mathbf{B} \) are the electric and magnetic fields, \( \rho \) is the mass density, \( \mu_0 \) is magnetic permittivity of free space, and \( \mathbf{J} \) is the current density, \( \mathbf{v} \) is the fluid velocity, \( \rho \) is the fluid pressure, and \( u = \rho / (\gamma - 1) \) is the fluid internal energy density, where \( \gamma = 5/3 \) for an ideal gas.

Although the MHD formalism is a good approximation for a large region of magnetosphere, results from the global MHD codes show clear problems in the inner magnetosphere. For instance, the region-2 current system produced in MHD simulations is weak and patchy. Since real plasma particles gradient/curvature drift in addition to the \( \mathbf{E} \times \mathbf{B} \) drift in the inner magnetosphere, they do not satisfy equation (5). It is clear that the lack of gradient/curvature drift in MHD formalism limits the accuracy in MHD results when applied to the inner magnetosphere.

The theoretical basis of the RCM is the adiabatic drift formalism, which can be applied to various regions of the inner and middle magnetosphere. The formula for drift velocity of a nonrelativistic particle of charge \( q \) is

\[
\mathbf{v}_D = \frac{\mathbf{E} \times \mathbf{B}}{B^2} + \frac{W_\perp \mathbf{B} \times \nabla B}{q B^3} + \frac{2W_\parallel \mathbf{B} \times \kappa}{q B^2} \tag{8}
\]

The three terms on the right represent \( \mathbf{E} \times \mathbf{B} \), gradient, and curvature drift. Specifically, \( \kappa = (\mathbf{b} \cdot \nabla) \mathbf{b} \) is the curvature vector, and

\[
W \equiv W_\perp + W_\parallel \equiv \frac{m}{2} \left( v_\perp^2 + v_\parallel^2 \right) \tag{9}
\]

where \( v_\perp \) is the velocity of the particle's cyclotron motion which is perpendicular to \( \mathbf{B} \) and \( v_\parallel \) is the velocity parallel to \( \mathbf{B} \). Since these drift velocities vary with position along the particle's bounce path, use of (8) to track a particle requires careful integration of the cross-field drift of the particle at different positions along the field line. Fortunately, the gradient/curvature drift terms in the above equation can be written in a bounce-averaged form [Wolf, 1983]
where $W_K$ is the kinetic energy of the particle. If the pitch angle distribution is assumed isotropic, then the average drift velocity is given by (10), with

$$W_K = \lambda V^{-2/3}$$

where $\lambda$ is the energy invariant, and

$$V = \int_{s_0}^{s_1} \frac{ds}{B}$$

is the flux-tube volume (the volume of a tube of unit magnetic flux), the magnetic field line segments integrated from the southern ionosphere to the northern ionosphere along a field line. Thus, the more commonly used expression for gradient/curvature drift of a single particle is now reduced to an expression for the average drift of all particles of a given chemical species and given energy on the field line.

The RCM's counterpart to the continuity equation in MHD is the particle-conservation equation, which is written as

$$\frac{\partial N}{\partial t} + \nabla \cdot (N v_D) = 0$$

where $N$ is the number of mapped particles per unit area in the equatorial plane and $v_D$ is the bounce-averaged drift velocity of such particles in that plane. Using Faraday's law and flux-tube content (the number of particles per unit magnetic flux)

$$\eta = \frac{N}{B}$$

the particle-conservation equation (13) can be rewritten as

$$\left( \frac{\partial}{\partial t} + v_D \cdot \nabla \right) \eta = 0$$

Also, the particle pressure in a monatomic gas is equal to two thirds of the energy density;

$$p = \frac{2}{3} \sum_s n_s W_k s = \frac{2}{3} V^{-5/3} \sum_s n_s \lambda_s$$
where $s$ is the particle species. Note that, if $n_s$ and $\lambda_s$ are constant, equation (16) states that the thermodynamic parameter $pV^{5/3}$ is constant under adiabatic compression or expansion, as would be expected for an ideal gas with $\gamma = 5/3$.

Finally, the equation that couples the inner/middle magnetosphere and ionosphere is the Vasyliunas equation [Vasyliunas, 1970], which can be derived from either MHD or the adiabatic drift formalism. The momentum equation of ideal MHD (without the inertial term) is

$$\nabla p = \mathbf{J} \times \mathbf{B}$$

(17)

Crossing with $\mathbf{B}$ and solving for the current density perpendicular to the field line yields

$$J_\perp = \frac{\mathbf{B} \times \nabla p}{B^2}$$

(18)

With $B/B^2 = (\nabla V)_\parallel$ where $V = \int_a^b ds / B$, equation (18) can be rewritten as

$$\mathbf{J} = \nabla V \times \nabla p + f \mathbf{B}$$

(19)

where $f$ is constant along a field line. The term $f \mathbf{B}$ can be interpreted as a current flowing along field lines without diverging, connecting the northern and southern ionosphere. Dotting equation (19) with a unit vector in the direction of $\mathbf{B}$, applying (19) to the northern- and southern-ionosphere ends of the same field line, and subtracting, obtain the Vasyliunas equation

$$\frac{J_{\text{lin}}}{B_{\text{in}}} - \frac{J_{\text{lis}}}{B_{\text{is}}} = \frac{\mathbf{B}}{B} \cdot \nabla V \times \nabla p$$

(20)

where $J_{\text{lin}}$ is the density of Birkeland current flowing along field lines into the northern ionosphere, $B_{\text{in}}$ is the magnetic field strength there, $J_{\text{lis}}$ and $B_{\text{is}}$ are the corresponding quantities in the southern ionosphere [Heinemann and Pontius, 1990].

In the adiabatic drift formalism, the same equation is derived as follows. The current density due to gradient/curvature drifting mapped particles is
\[ j_{GC} = \sum_s N_s q_s v_{GC} \]  

(21)

where \( N_s \) is the number of mapped particles of species \( s \) per unit area in the equatorial plane, \( q_s \) is the charge for species \( s \), and \( v_{GC} \) is the bounce-averaged gradient/curvature drift velocity on the equatorial plane. Setting the total current flowing out of the flux tube to zero and replacing \( N_s \) with \( \eta_s B \) and \( v_{GC} \) with \( B \times \nabla W_K / q B \) \( B^2 \) gives

\[
\frac{J_{lin}}{B_{in}} - \frac{J_{lis}}{B_{is}} = -\frac{1}{B} \left[ \nabla \cdot \left( \sum_s \eta_s \lambda_s \hat{b} \times \nabla \left( V^{-2/3} \right) \right) \right]
\]

\[
= -\frac{1}{B} \nabla \left( \sum_s \eta_s \lambda_s \right) \cdot \hat{b} \times \nabla V^{-2/3}
\]

(22)

Since \( p = \frac{2}{3} V^{-5/3} \sum_s \eta_s \lambda_s \), equation (22) is equivalent to (20), the same expression derived in MHD. Note that since \( \lambda \) and \( \eta \) in the Vasyliunas equation are constant along the drift path of plasma particles, (22) implies that Birkeland currents flow only in regions of the magnetosphere where the flux tubes do not have equivalent plasma distributions.
II. COMPUTATIONAL MODELS

A. Fedder-Lyon Global MHD Code

The Fedder-Lyon Global MHD Code has been developed over fifteen years [Brecht et al., 1982], and it is a self-consistent, time-dependent, three-dimensional global magnetohydrodynamic simulation model of the Earth's magnetosphere. It derives the electric and magnetic fields of the outer magnetosphere and the solar wind by solving the MHD equations (1) - (7) numerically. There are two distinct parts in this model: a model that simulates solar wind and magnetosphere region, and a model that simulates a conducting ionosphere. A major problem in the model, which simulates the magnetosphere and solar wind region, is that the Hall term, \( (m / \rho e) (J \times B) \) is neglected in the generalized Ohm's law equation (5) [Siscoe, 1983], where \( m \) is the ion mass, \( \rho \) is the mass density, and \( e \) is the ion charge. Also, its single-fluid representation cannot represent the inner-magnetospheric situation, where gradient/curvature drifts transport electrons and ions in different direction.

The MHD code's modeling region of the solar wind region and magnetosphere is the interior of cylinder with its axis along the Earth-Sun line, and it extends from \( x_{\text{GSM}} = 20 \ R_E \) to \( x_{\text{GSM}} = -300 \ R_E \). The three-dimensional non-orthogonal simulation mesh includes the Earth's magnetosphere and a portion of the solar wind region. The inner boundary is a geocentric sphere of radius 3.5 \( R_E \), and the radius of the cylinder is 120 \( R_E \).

In order to obtain the boundary conditions on the inner boundary of the cylindrical modeling region, a two-dimensional ionosphere simulation on a portion of a geocentric spherical shell at \( -1 \ R_E \) is carried out in parallel. The net Birkeland current \( J_\parallel \) for the ionosphere is determined by applying equation (4) at 3.5 \( R_E \) to find \( J_\parallel \) there, then mapped to the ionosphere assuming a dipole field and \( J_\parallel / B = \text{constant} \). For the case of a uniform ionospheric Pedersen conductance \( \Sigma \), the equation
\[ \nabla^2 \Phi_E = \frac{J_B}{\Sigma} \]  

is solved for the electric potential \( \Phi_E \) in the ionosphere. This electric potential is then mapped outward to 3.5 \( R_E \) to define the electric field there. Therefore, the mapped potential represents the average of \( E \times B \) convective flow. It is important to mention that the three-dimensional simulation mesh at the inner boundary is much coarser than the RCM grid in the same region, because the global MHD model must cover a much larger region of magnetosphere than the RCM does (Figure 7). Therefore, any sheet current that is smaller than the mesh size is not resolved. Also, note that the time delay of information exchanged between the ionosphere and inner boundary of the magnetosphere due to the distance (1 to 3.5 \( R_E \)) is neglected.

The MHD simulation result that was used as the RCM input is an approximately steady magnetospheric state for southward IMF [Mobarry et al., 1996]. The southward IMF was chosen because its field direction favors reconnection at the dayside magnetosphere and convective flows. The MHD result shows a region-1 current system with reasonable total currents; however, the region-2 current system is almost always weak and patchy regardless of the direction of the interplanetary magnetic field. Some inaccuracy of the MHD code in the inner magnetosphere results from relatively coarse simulation mesh. Also, the Birkeland current is calculated from equation (4) in the MHD code; however, \( |V \times B| \) is generally small compared to \( |B| \) divided by the scale length, since the magnetic field is dominated by the dipole field in the inner magnetosphere. Therefore, \( V \times B \) must be calculated very carefully if Birkeland currents are to be computed from equation (4). On the other hand, the MHD model can supply sufficiently accurate pressure and flux tube volume for the Rice Convection Model, which uses Vasyliunas' equation (20) to compute Birkeland currents. Also, the RCM has a much finer grid since it is designed to simulate the inner magnetosphere. Thus, major deficiencies in the global MHD
Figure 7  A comparison of the areas covered in the magnetosphere by the global MHD code and the RCM. The upper panel shows the MHD grid in the noon-midnight meridian. The lower panel shows a typical RCM modeling region, with the magnetic field lines drawn roughly corresponding to the RCM's grid spacing.
model can be addressed by the RCM.

B. Rice Convection Model

Most deficiencies that the global MHD code exhibits in the inner magnetosphere can be overcome by the Rice Convection Model (RCM), which is designed to simulate the inner and middle magnetosphere. The first version of this self-consistent model appeared in 1973 [Jaggi and Wolf, 1973]. Since then it has been applied extensively to study the large scale motions of plasmas in the magnetosphere-ionosphere system.

The RCM calculates the magnetospheric electric field and plasma distribution self-consistently with the ionospheric electric field and current distribution. The basic logical loop of this self-consistent scheme was first suggested by Vasyliunas [1970], and the modified form that is currently used is shown in Figure 8. The five main sections of the calculation are shown in the square boxes. The starting point is the top box where the initial magnetospheric particle distribution is assumed to be known at time \( t \). In this work, the initial magnetospheric particle distribution is calculated from the pressure distribution in the MHD run result. The RCM usually runs with approximately 30 different particles (species), with each of them having a charge \( q \), an energy invariant \( \lambda \), and flux tube content \( \eta \) (number of particles per unit magnetic flux); however, the RCM runs presented in this thesis were carried out in a single-species mode to simplify the first step of the merging of two computational models. Also, it is difficult to set up runs that have arbitrary spatial dependence in the boundary condition of \( \eta \) for each species of plasma particles.

In the next step (moving counterclockwise from the top), the plasma distribution and the magnetic field model can be used to compute the divergence of the density of gradient/curvature drift current using equation (21). Moving to the left bottom box, the
distribution of field aligned current is obtained by using the Vasyliunas Equation. With the field aligned current from the magnetosphere and appropriate boundary conditions at the high- and low-latitude boundaries of the calculation, the RCM computes the ionospheric potential distribution in the right bottom box. In the next box, this potential distribution is mapped along field lines out into the magnetosphere to determine the magnetospheric electric field. Finally, the magnetospheric particle distribution is adjusted by moving the particles by a distance $v \Delta t$ where $v$ is the $E \times B$ and gradient/curvature drift velocity given in equation (11), and $\Delta t$ is the time step of simulation. Once the new magnetospheric
particle distribution is determined for time $t + \Delta t$, the computational cycle starts over from the top box.

As described in the previous chapter, the RCM solves a set of equations similar to the MHD equations. However, there are three crucial differences between the RCM and MHD. First, equation (17) lacks the inertial term in the momentum equation (2) compared to the pressure gradient and $\mathbf{J} \times \mathbf{B}$ terms. Neglect of this term means that the RCM cannot be applied to the regions of the magnetosphere and plasma sheet where flow velocities are fast and time scales are shorter than or comparable to the MHD-wave travel times. Next, equation (4) is not solved self-consistently. In the past RCM runs, the inputted magnetic fields have been semi-empirical models. Although these models vary with time to represent magnetospheric conditions that vary with time, they are not forced to be consistent with the currents calculated in the RCM. Finally, MHD uses a single fluid approximation, but the transport and energy equations in the RCM include multiple fluids (~30 species) to allow the plasma-sheet particles to gradient/curvature drift differently according to their charges and energies.

The use of the Vasyliunas equation (20) and an inputted magnetic field model allow the RCM's main computation to consist of two two-dimensional calculations carried out in parallel instead of full three-dimensional calculations. Two dimensional calculations are carried out on a time-independent ionospheric grid which is set before each run. The results of the two dimensional calculations are displayed on an equatorial grid, which is mapped along field lines from the fixed ionospheric grid. When a time dependent magnetic field is provided, the equatorial grid becomes time dependent. For the runs presented in this thesis, the magnetic field model provided from the MHD result remains constant during the runs, so that the equatorial grid is also fixed as well.
Since the RCM treats an entire closed field line as a unit by assuming the particle population along the field line to be uniform, a three dimensional particle population can be represented in terms of a series of contour lines. By using this method, sharp gradients of particle populations can be represented by a series of contour lines, and Birkeland currents along the field lines can be calculated precisely, without the numerical diffusion or overshoot phenomena that usually accompany very sharp gradients when they are represented by densities at grid points. While the particles which represent a series of 'edges' were free to move inside the modeling region, these 'edges' were 'pinned' on the high-$L$ boundary in order to keep the pressure consistent with MHD at the boundary. Also, the MHD electrostatic potential was used and held constant on the high-$L$ boundary.

Two main deficiencies of the RCM are its restriction to subsonic-flow regions, and the pressure-balance inconsistency [e.g., Erickson and Wolf, 1980; Kivelson and Spence, 1988]. It has been shown that the observation-based models that provide realistic magnetic field are inconsistent with the thermodynamic relation $p V^{5/3} = \text{constant}$ in the plasma sheet, where $V = \text{flux tube volume}$. Since the RCM is based on the adiabatic drift formalism, its results correspond approximately to this thermodynamic relation; therefore, there is often a considerable inconsistency between $\mu_0^{-1} \nabla \times B$ in the magnetic field model and the currents implied by the RCM. A friction code was recently used successfully to calculate $B$ from RCM-computed particle distributions [Toffoletto et al., 1996]. However, once the global MHD code and the RCM are fully merged, the MHD code can provide its self-consistent magnetic field to the RCM, and it can be adjusted to the pressure distribution computed in the RCM. Also, the MHD code is not limited to subsonic flow, so that merger with a global MHD code can remove both of these main deficiencies of the RCM.
III. RCM RUN DATA SETUPS

A. Data-Interface Routines from the MHD Code to the RCM

The result of a typical MHD run that had come to an approximate steady state in southward IMF was fed into the Rice Convection Model via data-interface routines. Such routines were necessary since the RCM uses quite different computational methods to treat the inner magnetosphere. These routines involve coordinate transformations of data, calculations of flux tube volume and flux tube content, etc. Three essential quantities were passed from the global MHD results to the RCM: the 3D magnetic field $B$, pressure distribution $P$, and electrostatic potential $\Phi_E$. The MHD magnetic field was used to map the RCM ionospheric grid onto the equatorial plane and to compute flux tube volume $V$. With the flux tube volume and the MHD pressure distribution, flux tube content $\eta$ was calculated. The MHD electrostatic potential was taken as the high-$L$ boundary condition for the RCM. Figure 9 is the flow chart showing an overview of this interface.

First, the 3D MHD results, which were originally expressed on the MHD code's non-orthogonal grid were interpolated to each point on a half-$R_E$-spaced rectilinear grid which extends from $10$ to $-30\ R_E$ in $x_{GSM}$ and $15$ to $-15\ R_E$ in both $y_{GSM}$ and $z_{GSM}$. An ionospheric RCM grid was separately generated, with $31$ unevenly spaced points in latitude and $96$ evenly spaced points in local time coordinate. This grid is always spherical polar on the ionosphere, but the center can be shifted toward the night side to cover more tailward region in the equatorial plane. In the runs presented in the next chapter, the grid was not shifted. A field line tracer used this grid as a starting point, and while it was tracing the field line, it also computed the flux tube volume. When the tracer reached the equatorial plane, the equatorial mapping point was determined. At this point of the coupling project, the magnetic field was not adjusted to the changes in the inner-magnetospheric pressures and field aligned currents calculated in the RCM at each time step, so that it remained
constant throughout the runs. Correspondingly the mapped equatorial grid points did not change in time, and the simulations were therefore not fully self-consistent.

![Diagram showing the flow of data from MHD to RCM](image)

Figure 9: The flow chart of the data-interface routines from the MHD code to the RCM.

The flux tube contents $\eta$ can be now calculated at each grid point inside the RCM modeling region by using the computed flux tube volume, the pressure from the global MHD result, and the energy invariant $\lambda$, which was initially set to an assigned value. Then contours of constant flux tube content were calculated. Specifically, the plasma sheet was assumed to have ions with a single energy invariant. Although the RCM is normally run with both ions and electrons having $\sim 15$ different energy levels, it is difficult to set up runs that have arbitrary spatial dependence in the boundary condition of $\eta$ for each species of plasma particles.

Once the contours of constant particle population density were completed, the high-$L$ boundary was placed along a contour of constant $\eta$ which has maximum electrostatic
potential at the dawn side and minimum electrostatic potential at the dusk side. This electrostatic potential configuration produces the dawn to dusk electric field that causes the plasma particles to flow sunward as in the magnetospheric convection. The reason for placing the boundary along a contour of constant $\eta$ was to avoid the 'Interchange Instability', which is a general property of plasmas in the magnetosphere.

![Diagram of electrostatic potential configuration](image)

**Figure 10** The conditions for interchange instability in the magnetosphere. The view is of the equatorial plane. The shaded region has higher $\eta$ than the unshaded region.

Figure 10 illustrates the conditions for interchange instability. As the gradient/curvature drift currents flow westward along contours of constant $V$, positive charges start to build up on the west side of the bulge, negative charges on the east side.

To prevent these charges building up excessively, Birkeland and ionospheric Pedersen currents flow. While the Birkeland currents flow along field lines, Pedersen currents tend to flow eastward across the bulge, producing an eastward electric field in the bulge. The result is the bulge particles flowing away from the Earth due to $\mathbf{E} \times \mathbf{B}$ drift, and the system is stable if the particle population $\eta$ decreases earthward, unstable if $\eta$ increases earthward.
In case of the plasma particle distribution from the MHD result, the interchange instability is rather subtle, and the system becomes unstable as time proceeds. The plasma configuration is such that there is a high-\( \eta \) region in the central part of the magnetosphere on the night side (Figure 11). As the magnetospheric convection proceeds, this high-\( \eta \) region starts to develop 'finger-like' structures on the dawn and dusk sides. The region earthward of this structure is stable; however, the outer part of the high-\( \eta \) region is unstable. Placing the boundary along a contour of constant \( \eta \) prevents including such a structure inside the modeling region, so that interchange instability can be avoided in the simulation. (For these initial runs, we wanted to avoid interchange instability, because it is difficult to treat with high numerical accuracy.)

![Diagram](image)

Figure 11: Illustration showing the possibility of interchange instability produced by a maximum in \( pV^{5/3} \) in the interior of the plasma sheet.

In addition to these data setups and new representation of the particle population, several simplifications where made in the setup of the RCM run. First, the electrons were assumed to be cold, and since cold electrons do not gradient/curvature drift, they were neglected in the simulation. Next, the Earth was assumed not to rotate, and its magnetic
pole was assumed to be perpendicular to the solar-wind velocity. Further, the ionospheric conductance was assumed to be specially uniform in both hemispheres. All of these assumptions were made in the RCM to make it maximally consistent with the MHD simulation run. Also, in order to be consistent with the MHD model's inner boundary condition, the low-$L$ boundary was placed at $L = 3.0$, and the electrostatic potential at this boundary was set to zero, essentially making the ionosphere a perfect conductor on the equatorward boundary of ionosphere simulation.

B. Consistency Tests for the RCM Inputs

Since the computational method in the Rice Convection Model is quite different from that in the global MHD code, the data transferred from the MHD code to the RCM were represented slightly differently after the transfer process. For instance, the RCM grid is quite a different grid from the MHD grid, and the region-2 Birkeland currents are calculated along the edges (contours of constant $\eta$), so that these currents appear only along the edges. Therefore, it was necessary to compare the MHD result and the RCM input to check for consistency.

In the data-interface routines, the 3D magnetic field $\mathbf{B}$ and the pressure distribution $P$ were taken from the MHD results, and the electrostatic potential $\Phi_E$ was taken along the RCM's high-$L$ boundary. Also, pressure along MHD field lines is assumed to be constant in the RCM. It is important to mention that 'the RCM input' in the above paragraph is actually the RCM output after the input data was fed in and one cycle of the RCM's logical loop ("magnetospheric particle distribution" - "gradient/curvature drift currents" - "field-aligned currents" - "ionospheric electric field" - "magnetospheric electric field") was completed. In other words, the MHD results and the RCM 'zero-time' results were
compared for the pressure, the field aligned current density, and the electrostatic potential distributions.

The magnetic field transfer involves transforming from the MHD code's non-orthogonal grid to the RCM grid. In the RCM, pressure is assumed to be a constant along a field line, and the pressure distribution from the MHD result on the equatorial plane was used to calculate the flux-tube content $\eta$. Figure 12 shows field lines and the pressure contours in the noon-midnight meridian plane ($x_{\text{GSM}}-z_{\text{GSM}}$ plane). Specifically, the top plot shows MHD magnetic field lines traced from the RCM grid in the northern ionosphere to the southern ionosphere. The bottom plot shows contours of constant pressure in the MHD solution. The geocentric circle of radius $3.5 \, R_E$ shows the MHD model's earthward boundary, and no data is available in the region earthward of it. The MHD pressure contours roughly follow the magnetic field lines, indicating that pressure is approximately constant along those lines.

Note that the RCM forces the pressures to be constant along the magnetic field lines, while the MHD code applies the momentum equation (2) at each grid cell along the field line. There is numerical error each time the MHD code does that, because the grid cells are not very small. Therefore, as the calculation takes place from one grid cell to another along the field line, a pressure difference gradually builds up along the line. Thus, the pressure tends to diffuse numerically across field lines.

Although the electrostatic potential along the high-$L$ boundary was taken from the MHD result and was held constant, the electrostatic potential inside the RCM modeling region was calculated from the Birkeland currents (field-aligned currents). Figure 13 compares the density of Birkeland currents into northern and southern ionosphere, which were counted together and mapped onto the equatorial plane. As mentioned earlier, since the RCM calculates these currents along the edges, the current distribution patterns were
Figure 12  Magnetic field lines and the pressure contours from the MHD results, displayed in the noon-midnight meridian plane. Pressure is in eV/cm$^3$ (natural log scale).
Figure 13

Comparison of the density of Birkeland currents, in μA/m², into northern and southern ionosphere counted together. Top panel shows the result from RCM, and the bottom shows MHD result.
affected by the shapes and locations of these edges. However, both results share similar
large-scale features in the distribution patterns. Furthermore, when all positive densities
and all negative densities are summed separately, the calculated total positive and negative
current densities from the MHD result and the RCM 'zero-time' result were equivalent.
Also, it is important to note that the region-2 Birkeland currents are visible but weak and
patchy.

Those currents are generated by divergence of gradient/curvature current, which
occurs mostly near the equatorial plane. However, the MHD code computes the Birkeland
current at $3.5 \, R_E$. The information about the Birkeland current gets from the equatorial
plane to $3.5 \, R_E$ by repeated application of the condition given by equation (4), which
implies that the divergence of $\mathbf{J}$ equals to zero. Also, there is again some error in
computing Birkeland current at the cells along the field line, due to finite cell size, and it
builds up. Thus, most of the discrepancy between MHD and RCM Birkeland currents is
probably numerical error in the MHD code.

Figure 14 shows the electrostatic potential distribution on the equatorial plane. The
strong resemblance in these distribution patterns indicates that the slight reconfiguration of
the current distribution did not affect the electrostatic potential substantially. This is
probably because the Birkeland currents are weak and unimportant inside the RCM
modeling region.
Figure 14  Comparison of the electrostatic potential distribution in volts. Top panel shows the result from RCM, and the bottom shows the MHD result.
IV. RUN RESULTS AND DISCUSSION

Three RCM runs were carried out with three different values of the ion energy invariant $\lambda$. In the first run, the energy invariant $\lambda$ was set to a negligibly small value so that the ions were transported by $\mathbf{E} \times \mathbf{B}$ drift only, as in ideal MHD. In the second run, $\lambda$ was set to the value estimated from the global MHD run in order to maximize consistency. In the third run, $\lambda$ was set to a higher value, corresponding to an ion temperature that is closer to typical observed values. The output from these runs are all displayed in the same format. Each pair of color-plotted output shows four parameters from the RCM runs at a magnetosphere time $t$. The first parameter is the electrostatic potential $\Phi$ in volts. The second parameter is the density of the Birkeland currents, in $\mu A/m^2$, into the northern and southern ionosphere counted together. A positive sign indicates currents down into the ionosphere, and negative indicates currents up from the ionosphere. These parameters are displayed on top and bottom of the following odd numbered figures. The third parameter is the effective potential ($\Phi + \lambda V^{-2/3}/q$) in volts, where contours of constant effective potential are instantaneous ion flow lines. Equation (10) implies that ion flow velocities are parallel to those lines, given the unchanging magnetic field. If the potential were constant in time, the contours would be ion drift paths. The fourth parameter is the edges, the contours of constant flux-tube content $\eta$, in Wb$^{-1}$. These parameters are displayed on top and bottom of the following even numbered figures. The thick light-green curve in the diagrams shows the high-$L$ boundary of the calculation, and the dotted geocentric circle of radius 3.0 $R_E$ shows the low-$L$ boundary of the calculation.

A. $\lambda = \text{Negligible}$

Figures 15 to 20 show results from the first run, where the energy invariant $\lambda$ was set to a negligibly small value, making the RCM run with ideal MHD condition
\((E + v \times B = 0)\). Figure 15 and 16 show the initial configuration ('zero-time' result). The region-2 currents are visible but weak and patchy, and positive currents (going into the ionosphere) and negative currents (leaving out from the ionosphere) are somewhat mixed on the night side. The contours of constant flux-tube content are spread over the outer part of the modeling region. The penetration of equipotential contours inside the innermost edge shows the electrostatic potential ranging roughly from \(10^4\) on the dawn to \(-10^4\) on the dusk side across the region, indicating no sign of shielding of the inner magnetosphere from the convection electric field. Note, however, that the penetration of the equipotential contours is limited by the perfectly-conducting boundary condition at \(L = 3.0\). The effective potential appears identical to the electrostatic potential, since \(\lambda\) was set to a negligibly small value, so that the expression for the effective potential is approximately equal to the electrostatic potential.

After one hour of simulation time (Figures 17 and 18), the edges have nearly aligned to the equipotential contours. Also, they spread less widely and the ions on the night side have come closer to the Earth due to the convective motion of the plasma. The pattern of the region-2 current going into the ionosphere on the dusk side and out from the ionosphere on the dawn side have become clearer, and the current itself has become stronger and better defined. The electric field inside the innermost edge has become weaker due to the shielding effect. The configuration reaches an approximately steady state after the RCM has run for a total of eight hours simulation time (Figures 19 and 20). The edges of the plasma-sheet ions are very close to each other and align well with contours, and they have moved even closer to the Earth on the night side. The region-2 currents have become very clear and strong. The electrostatic potential is nearly zero in the region earthward of the innermost edge, indicating that the inner magnetosphere is strongly shielded from the convection electric field.
Figure 15
Initial RCM configuration. Top panel displays the electrostatic potential $\Phi$ in volts. The bottom displays the density of the Birkeland currents, in $\mu$A/m$^2$, into the northern and southern ionosphere counted together.
Figure 16

Initial RCM configuration. Top panel displays the effective potential \((\Phi + \lambda V^{-2/3}/q)\) in volts. The bottom displays the contours of constant flux-tube content \(\eta\) in Wb\(^{-1}\).
Figure 17 RCM result with energy invariant $\lambda = 1$, after one simulation hour. Top panel displays the electrostatic potential $\Phi$ in volts. The bottom displays the density of the Birkeland currents, in $\mu$A/m$^2$, into the northern and southern ionosphere counted together.
Figure 18  RCM result with energy invariant $\lambda = 1$, after one simulation hour. Top panel displays the effective potential ($\Phi + \lambda V^{-2/3}/q$) in volts. The bottom displays the contours of constant flux-tube content $\eta$, in Wb$^{-1}$. 
Figure 19  RCM result with energy invariant $\lambda = 1$, after eight simulation hours. Top panel displays the electrostatic potential $\Phi$ in volts. The bottom displays the density of the Birkeland currents, in $\mu$A/m$^2$, into the northern and southern ionosphere counted together.
Figure 20  RCM result with energy invariant $\lambda = 1$, after eight simulation hours. Top panel displays the effective potential ($\Phi+\lambda V^{-2/3}/Q$) in volts. The bottom displays the contours of constant flux-tube content $\eta$, in Wb$^{-1}$. 
B. $\lambda = 600$

Figures 21 and 22 show the final results of the RCM run in which $\lambda$ was set to 600 eV($R_E$/nT)$^{-2/3}$. With this value of $\lambda$, the RCM run is roughly consistent with the MHD temperature of about 2.3 keV at the high-$L$ boundary on the night side. The electrostatic potential and region-2 Birkeland currents are very similar to the previous run result in the ideal MHD limit, except that the plasma-sheet ions have moved slightly to the west by gradient/curvature drift. The effective potential, however, is different from the previous case. In the ideal MHD limit, gradient/curvature drift was neglected, and the plasma-sheet ions simply drifted from the magnetotail to the day side magnetopause by magnetospheric convection at $v_D = E \times B / B^2$. In this run, the plasma sheet ions gradient/curvature drift westward in addition to convective motion, and these drift motions dominate in the region near the Earth. Therefore, there are two distinct types of plasma particle trajectories, open and closed trajectories. Open trajectories lead from the magnetotail to the day side magnetopause, and closed trajectories that circle round and round the Earth. The separatrix between these is called the 'Alfvén layer', the approximate location of which can be seen in the Figure 22. The separatrix lies between the open contour lines with $\Phi_{\text{eff}} = 1.12 \times 10^4$ volts and the closed contour lines with $\Phi_{\text{eff}} = 1.12 \times 10^4$ volts. For a positively charged ions, superposition of the westward motion due to gradient/curvature drift and the sunward (eastward) $E \times B$ drift motion causes a 'Stagnation Point' on the dawn side. The region earthward of the Alfvén layer is shielded, and the plasma particles in this region are trapped and circle the Earth.
Figure 21  RCM result with energy invariant $\lambda = 600$, after eight simulation hours. Top panel displays the electrostatic potential $\Phi$ in volts. The bottom displays the density of the Birkeland currents, in $\mu A/m^2$, into the northern and southern ionosphere counted together.
Figure 22

RCM result with energy invariant $\lambda = 600$, after eight simulation hours. Top panel displays the effective potential ($\Phi + \lambda V^{-2/3}q$) in volts. The bottom displays the contours of constant flux-tube content $\eta$, in Wb$^{-1}$. 
C. $\lambda = 4000$

The above two results show the classic RCM behavior, in which clear and strong region-2 currents are visible and the inner magnetosphere is strongly shielded. However, the results of the RCM run with $\lambda = 4000$ show non-classic RCM behavior (Figure 23 and 24). This simulation run was intended to represent an average ion energy close to typical observations. Since a higher value of energy invariant was chosen, the plasma-sheet ions have moved much more to west by gradient/curvature drift, as they should have. On the other hand, the region-2 currents are poorly defined and weak. Also, the region earthward of the inner most edge is not as strongly shielded, and the plasma-sheet ions have not come as close to the Earth compared to the previous cases. One of the reasons for this non-classic RCM behavior is that the modeling region was not large enough to include the Alfvén layer for these ions, as it can be seen in the top plot of Figure 24. Since the location of the stagnation point moves out as the particle energy increases [Wolf, 1995], the modeling region that was large enough for the previous cases became too small. Consequently, the particles were not allowed to shield effectively. Another reason is that all ions were assigned to the same value of $\lambda$. Normally, the RCM is run with $\sim 15$ different values of energy invariant for both ions and electrons. In such cases, the plasma-sheet particles with lower energy invariant could participate in shielding as they did in the previous cases, even if the particles with higher energy invariant could not. The second suggestion for the non-classic behavior cannot be tested until the newer version of the RCM which can solve the difficulty in setting up runs with arbitrary spatial dependence in the boundary condition of $\eta$ is developed. However, the first suggestion was tested by setting the boundary further from the Earth to include the Alfvén layer. The result showed that the inner magnetosphere was semi-shielded from the convection electric field. More detailed investigation of the cause of weak shielding will be carried out in the future.
Figure 23  RCM result with energy invariant $\lambda = 4000$, after two simulation hours. Top panel displays the electrostatic potential $\Phi$ in volts. The bottom displays the density of the Birkeland currents, in $\mu$A/m$^2$, into the northern and southern ionosphere counted together.
Figure 24 RCM result with energy invariant $\lambda = 4000$, after two simulation hours. Top panel displays the effective potential $(\Phi + \lambda V^{-2/3}q)$ in volts. The bottom displays the contours of constant flux-tube content $\eta$, in Wb$^{-1}$. 
V. CONCLUDING COMMENTS

The first phase of the long range project of merging the Rice Convection Model into the Fedder-Lyon 3D global MHD code was successful. Several RCM runs were performed with MHD results as input. When the RCM was set to run in either the ideal MHD limit where the transport by gradient/curvature drift was neglected, or with the ion temperature from the global MHD code to maximize consistency, classic RCM results were obtained. These results showed large changes in the magnetospheric configuration from the initial configuration provided by the global MHD simulation in approximately steady state. Major changes in the configuration includes the inner edge of the plasma sheet moving closer to the Earth on the night side, the region-2 Birkeland current system showing a much clearer pattern and becoming sharper and defined, and the inner magnetosphere being strongly shielded from the convection electric field.

As mentioned in the introduction, there are three main phases in this long range project of merging two magnetospheric simulation models. The next phase involves revision of the MHD code so that it advances the MHD variables on two different grids, the original cylindrical grid and a second grid system that is aligned with the magnetic field and thus evolves in time. That will automatically keep track of the mapping between the magnetosphere and the ionosphere, time-step by time-step. By doing so, the feeding back of the RCM result to the global MHD code becomes efficient, and the RCM result can be used as the initial condition and boundary condition at the low-$L$ boundary of the MHD code. In the mean time, a new version of the RCM is being developed to run with multiple energy invariant for plasma-sheet ions and electrons, and the physics of the interchange instability is also being studied in more detail by using the current version of the RCM with an empirical B-field model. For the RCM runs discussed in this thesis, the simulation model was not fully self-consistent since the magnetic field had never been adjusted to the
pressure distribution calculated in the RCM at each time-step. However, by the end of this second phase, the data transfer between two simulation models would be done time-step by time-step, so that the merged simulation model will be fully self-consistent, and the electrodynamics would be coupled in the two codes. In the final phase, these codes will be fully coupled and be tested against selected data sets.
REFERENCES


