Rice Convection Model simulation of the substorm-associated injection of an observed plasma bubble into the inner magnetosphere:

2. Simulation results

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Received 4 February 2009; revised 13 June 2009; accepted 25 June 2009; published XX Month 2009.

We present results from a Rice Convection Model simulation of the early expansion phase of a substorm that occurred 22 July 1998. The theoretical basis of the simulation is the idea that the plasma injected into the inner magnetosphere during a substorm primarily consists of a low-content plasma bubble, which is made up of flux tubes with lower values of the entropy parameter \( P^{5/3} \) than their neighbors. As discussed in an accompanying paper, to simulate this event, we carefully tailor model inputs to fit Geotail observations of the bubble at \( X_{GSM} \approx -9 R_E \). We find that both potential and induction electric fields play important roles in transporting and energizing the particles during the event. The potential electric field associated with Birkeland currents that flow along the east and west sides of the bubble (i.e., the substorm current wedge) is characterized by a localized strengthening of the westward auroral ionospheric electric field within the bubble, as well as the production of a region of enhanced westward flow just Equatorward of the diffuse electron aurora. The inner edge of the modeled plasma sheet assumes a dented-in form that is similar in shape to the injection boundary proposed many years ago on observational grounds. Flux tubes that are pushed earthward ahead of the bubble at onset form a sharp pressure peak near local midnight and geosynchronous orbit, and the particles on those tubes contribute significantly to the injection of particles into the inner magnetosphere.


1. Introduction

[2] A well-established feature of substorms is the rapid earthward transport of particles from the plasma sheet to the inner magnetosphere [Moore et al., 1981; Reeves et al., 1996; Sergeev et al., 1998]. Evidence is mounting that plasma bubbles (flux tubes with lower entropy than their neighbors) play a central role in the process of particle injection [Lyons et al., 2003; Apatenkov et al., 2007]. Here the entropy is characterized by the parameter \( PV^{5/3} \), where \( P \) is pressure and \( V = \int ds/B \) is the volume of a tube of unit magnetic flux.) earthward bursty bulk flows have also been associated with bubbles [Sergeev et al., 1996; Kauristie et al., 2000; Nakamura et al., 2005], mostly somewhat further out in the plasma sheet.

[3] Presumably, the bubble is created as the result of an inner or middle plasma sheet event that strongly violates entropy conservation. Candidate mechanisms include reconnection at an X line in the middle plasma sheet [Birn et al., 2006], or perhaps tail current disruption [Lui, 1994; Wolf et al., 2009] or some other inner plasma sheet event. Our goal in this paper is not to argue about what specific mechanism causes the sudden violation of entropy conservation but rather to calculate its effect on the inner magnetosphere and the corresponding ionospheric region.

[4] This paper reports our effort to represent and understand the physics of bubble injection using the Rice Convection Model (RCM). We present results of the simulation of a substorm that occurred 22 July 1998, during which Geotail at \( X_{GSM} \approx -9 R_E \) observed a clear and unambiguous earthward-moving plasma bubble. Our objective is to understand how the bubble evolves as it moves toward the inner magnetosphere and how it affects magnetospheric and ionospheric electric fields and other parameters. An accompanying paper [Zhang et al., 2008] (hereafter referred to as...
Paper 1), describes details of how Geotail data were used to set boundary conditions and specify the input magnetic field. This paper concentrates on run results and their interpretation.

[5] In some ways, the present two papers represent a long-delayed sequel to a series of papers that described earlier RCM simulations of an observed substorm [Harel et al., 1981a, 1981b; Spiro et al., 1981]. In the old simulations, the substorm was represented in the model mainly as a burst of enhanced convection. In those simulations, a time-dependent substorm current wedge was included, much as in the present case, but there, the effect of the current wedge was only modest. Although many improvements have been made in the code in the intervening years, the main physical difference in the two simulations lies in the fact that we now recognize that the plasma transported earthward in a substorm is a plasma bubble of decreased entropy, and we carefully set the tailward boundary condition of the model for consistency with the bubblelike plasma observed by Geotail. In contrast with the earlier RCM runs, the present simulations emphasize the unloading aspect of the substorm, an aspect not considered in treating the substorm as a directly driven process of enhanced convection. In our present view, the essence of substorm injection consists of the unloading of plasma sheet flux tubes through reduction of their entropies, in violation of the adiabatic $P\rho^{5/3}$ is almost equal to the constant condition. These unloaded flux tubes then form a bubble that makes its way earthward and strongly affects the inner magnetosphere. Along with the earthward-moving bubble, a plasmoid is formed (or, in 3-D, possibly a set of closed high-entropy flux tubes) which moves rapidly down tail and has little effect on the inner magnetosphere. The present paper focuses on the effects of the plasma bubble on the inner magnetosphere.

[6] We first present a brief overview of the general results of the simulation, followed by more detailed discussions of the following six specific physical issues associated with the simulation:

[7] 1. Induction and potential electric fields are investigated in the equatorial plane near substorm onset. Our simulations indicate that equatorial electric fields during substorm expansion phase represent a complex combination of convection, induction, and corotation. We examine the different components in some detail and come to tentative conclusions.

[8] 2. The validity of the RCM’s equations is examined for conditions of fast flow. RCM simulation of a substorm expansion requires application of the model in circumstances outside its nominal range of validity. Using results from full MHD thin filament calculations [Chen and Wolf, 1999], we estimate the errors associated with using the model in this way, paying particular attention to which features of the RCM simulation results should be believed and which should not.

[9] 3. Electric field changes are studied in the nightside auroral zone and midlatitude trough, associated with the early expansion phase of the substorm. Our simulation results suggest that the injection of a bubble into the inner magnetosphere naturally gives rise to increased westward electric field (equatorward motion) in the ionospheric footprint of the bubble and poleward electric field (westward motion) west of the bubble. In the final phase of the bubble motion, the westward motion is concentrated in the trough region and resembles a polarization jet or subauroral ion drift (SAID) event [Galperin et al., 1973; Spiro et al., 1974, 1979]. SAID and SAPS (subauroral polarization stream) events [Foster and Yo, 2002] have long been a feature of RCM simulations of periods of strong convection [e.g., Harel et al., 1981b; Garner et al., 2004], but this simulation shows one occurring briefly in a time of weak polar cap potential, driven by the injection of the substorm-associated bubble.

[10] 4. Effects of substorm expansion on prompt penetration electric fields at low- and midlatitudes are evaluated. Our simulations predict the existence of a characteristic pattern of prompt penetration electric field at low- and midlatitudes associated with substorm expansion. During bubble injection the electric field across the nightside low- and midlatitude ionosphere is eastward, a pattern usually associated with overshielding following an abrupt decrease in convection strength. Observational evidence on this subject, while meager, suggests that this might be a real physical signature of bubble injection.

[11] 5. Particle injection is examined. The major characteristics of geosynchronous particles in substorm expansion phases were established many years ago [Mcllwain, 1974; Mauk and Meng, 1983]. Observationally, the substorm event of 22 July 1998 exhibited no obvious signature in particles at geosynchronous orbit, probably because the event occurred in a period of northward or weakly southward IMF and correspondingly weak convection. This interpretation is supported by our simulations which predicted the particle injection to be largely limited to the region outside geosynchronous orbit. Of interest, however, is that the simulated plasma sheet inner edge has a characteristic shape resembling the structure suggested by early injection boundary measurements.

[12] The primary goal of this paper is to identify physical effects of injection of a bubble into the inner magnetosphere. Because we are driving the model just from solar wind data and observations of single spacecraft in the inner plasma sheet, there is no chance that we will obtain an accurate, detailed representation of all aspects of the substorm within the modeling region. We will attempt to place the features of the simulation in context with published observations. We will not emphasize detailed comparisons with observations made during the simulated event, though we will describe those comparisons briefly.

2. Overview of Simulation Results: Entropy, Birkeland Current, and Electric Potential Distributions

[13] In our simulation of the 22 July 1998 substorm event we set the expansion phase onset to be at 0655 UT. The RCM was initialized by running the model with steady inputs for four hours prior to that, in order to bring the code to approximate equilibrium. The input magnetic field became more dipolar over a 5-min interval starting at 0655 UT. Following dipolarization, the code was run for another half hour with nearly constant inputs, and no further depolarization, to determine how inner magnetospheric conditions evolve.

[14] Figure 1 provides an overview of the simulation results. Figures 1a–1f show the simulated ion entropy function and contours of average proton (H$^+$) effective
potential for six times in the event. Black contours show the average H\textsuperscript{+} effective potential, given by

\[ \Phi_{\text{eff}} = \Phi_{\text{ion}} + \Phi_{\text{cor}} + \left\langle \lambda \right\rangle V^{-2/3}, \]

where \( \Phi_{\text{ion}} \) is the potential in the rest frame of the ionosphere, which rotates with the Earth; \( \Phi_{\text{cor}} \) converts to a frame that does not rotate with the Earth; \( \left\langle \lambda \right\rangle \) is the ion temperature, which is specified on the tailward boundary but varies in space and time within the modeling region. The contours of constant \( \Phi_{\text{eff}} \) represent the drift path of a particle that is gradient/curvature drifting and also \( \mathbf{E} \times \mathbf{B} \) drifting in the potential electric field. \( \Phi_{\text{cor}} \) cannot be displayed in terms of equipotentials but will be discussed in section 3.1.) Figures 1g–1l show Birkeland currents and electrostatic potential distributions in the rest frame of the ionosphere. Figures 1a and 1g show the results at the end of the growth phase, and Figures 1b–1f and 1h–1l show results at different times in the expansion phase.

[15] As depicted Figures 1a–1f, the front of the low-\( PV^{5/3} \) bubble region, imposed as a boundary condition beginning at 0655 UT at \( X = -20 \) and centered at midnight, propagates earthward almost along the midnight meridian. Over the next several minutes it evolves into an entropy-depleted channel, extending from the tailward boundary through the inner plasma sheet, and terminating near geosynchronous orbit. As time passes, the shape of the depleted channel is more and more strongly affected by energy-dependent gradient/curvature drift. Closer to the Earth, the depleted channel turns to the west and eventually spreads out in local time, as different energy particles in the depleted channel gradient/curvature drift at different velocities. Birkeland currents, which form the classic substorm current wedge, flow down into the ionosphere on the east side of the wedge, up from the ionosphere on the west side. The strong westward potential electric field in the channel drives ionospheric current westward across the channel. These general features were discussed in the paper on our earlier RCM simulation of an idealized substorm [Zhang et al., 2008]. In section 3 we present a more detailed discussion of several significant physical features that appeared in our simulation of the 22 July 1998 substorm event.

3. Detailed Discussion of Simulation Results

3.1. Equatorial \( \mathbf{E} \times \mathbf{B} \) Drift Velocity

[16] Figures 2a and 2b show the induction and potential electric fields in the equatorial plane at 0657 UT, during the
5-min interval when the model magnetic field is dipolarizing. (Here the potential electric field is computed by mapping potentials to the magnetic equatorial plane from the ionosphere. For more details about our definition of “induction” and “potential,” see section 3 of Paper 1.)

[17] During the magnetic field dipolarization, the induction electric field is westward in the midnight sector. It is stronger than the potential electric field for $X < -12$ but comparable in the nearer-Earth region that is of primary interest for this study. The potential electric field near midnight, though more structured because it was computed self-consistently, is also predominantly westward for $X > -12$. The induction electric field was computed from our time-varying magnetic field model, as described in section 3.3 of Paper 1. For $X > -12$, the induction and potential electric fields tend to be of roughly comparable size during the dipolarization. Inside geosynchronous orbit the potential electric field, which maps to the ionosphere, is directed mainly in the dusk-to-dawn direction while the induction electric field, which does not map to the ionosphere, is westward.

Figure 2. Components of the equatorial electric field at 0657 UT, during the dipolarization. Arrows show directions, while colors show strength, in mV/m. (a) Induction electric field, (b) potential field in a frame that rotates with Earth, (c) total electric field in that frame, and (d) total electric field in a nonrotating frame are shown. XMIN and YMIN refer to the $X$ and $Y$ coordinates of the point where the field strength on the field line has a minimum, which in this run is in the equatorial plane.
directed oppositely, i.e., dawn to dusk. When the two electric fields are combined (Figure 2c) a rather complicated pattern is obtained. It is important to note that these results indicate that the standard practice of using a potential electric field to represent the inner magnetospheric electric field is untenable when the magnetic field is dipolarizing near substorm onset.

Figure 3 shows the total electric field, analogous to Figure 2d, but for 0704 UT, a time after the imposed dipolarization. At this time there is no induction electric field and the potential electric field has changed in an interesting way, with the development of a narrow region of enhanced westward drift (a so-called SAID event) in the premidnight sector at \( L \approx 7 \).

There is scant observational evidence concerning inner magnetospheric flows in response to substorms. However, Nishimura et al. [2008] recently reported a rapid increase in westward flow in the premidnight inner magnetosphere within 30 s after a substorm onset, which seems to be consistent with the electric fields shown in Figure 3, although in our simulation the flow peaked a bit outside geosynchronous orbit, and their CRRES observations were at \( L = 5–6.4 \). The difference may be due to the fact that our simulated event occurred in quieter conditions than the substorms reported by Nishimura et al. [2008]. However, Nishimura et al. [2008] cited only one event with quick response to substorm onset, so it is certainly not convincing confirmation of the simulation results.

3.2. RCM Limitations and Validity Considerations

For completeness, some discussion is needed concerning the validity of RCM-calculated equatorial electric fields for substorm conditions. Although the potential electric field is calculated carefully and self-consistently within the RCM, the induction field depends on an input model of the substorm current wedge. As discussed in Paper 1, parameters of the substorm current wedge were chosen to fit measurements at one point (Geotail), at \( X \approx -9 \), \( Y \approx 0 \). Thus, calculated induction electric fields far from that point lack substantial observational or theoretical support.

Additional validity concerns also arise because of the high flow speeds calculated by the simulations (hundreds of km/s). The Vasyliunas equation, which the RCM uses to calculate field-aligned current from magnetospheric plasma pressure gradients, assumes that the magnetic force on the plasma balances the pressure gradient force, an assumption that is valid if (1) the flow speed is much less than the sound speed and (2) the motional time scale is much greater than the Alfvén wave travel time from the equatorial plane to the ionosphere. Figure 4 displays the local sonic Mach number of the RCM-computed flows within the modeling region, specifically the ratio of the \( E \times B \) drift speed to \((5P/3\rho)^{1/2}\); Figure 4 indicates that the flow speeds exceed the sound speed in much of the region beyond \( X = -15 R_E \).

We estimate that the Alfvén wave travel time from the equatorial plane to the ionosphere and back is \( \sim 2 \) min, which is not that short compared to the 5-min duration of the magnetic field collapse. Legitimate questions can therefore be raised about the validity of applying the RCM under these conditions.

Because the Chen and Wolf [1999] simulations are based on full MHD calculations, with no neglect of inertial terms, we can use them to provide insight into the validity of the RCM results. The Chen and Wolf [1999] simulations imply that, when some physical process out in the plasma sheet substantially reduces \( PV^{5/3} \) on a flux tube, the equatorial region of the tube moves earthward at a speed that is comparable to the Alfvén speed. Because of the sharp curvature of the magnetic field near the equatorial plane, a wave that resembles a transverse Alfvén wave in the equatorial plane (where \( v \perp B \)) immediately mode converts into a combination of two earthward traveling waves: an Alfvén wave and also a slow mode wave that rapidly steepens into a shock. The waves propagate to the ionosphere, reflect, and then propagate back to the point where the rapidly shortening field line crosses the equatorial plane, where they reflect again, etc. Eventually, the flux tube comes to rest at an equilibrium position where the Vasyliunas equation is satisfied. Because of finite MHD wave travel time, the filament calculation shows a time delay of \( \sim 1 \) min between the time

\[
\text{Figure 4. Sonic Mach number } v[\gamma P/\rho]^{1/2} \text{ in the equatorial plane at 0657 UT.}
\]
the equatorial crossing point of the field line starts moving earthward and the time when the ionospheric end starts moving toward the equator. In the filament simulation, it takes 3–4 min for the ionospheric end to fully "catch up" with the magnetospheric end. Naive use of the Vasyliunas equation would imply a faster motion of the ionospheric end of the field line. However, use of that equation gets the total motion and \( \int E\,dt \), integrated over ~3–4 min, right. This means that it should also get the time-integrated Birkeland currents approximately right. For that reason, even though it cannot properly describe the evolution on a 1-min time scale, the RCM can still provide valuable insight into the problem of substorm expansion.

The RCM shows ionospheric motions occurring simultaneously with motions in the equatorial plane, whereas there should actually be a time delay of a minute or so. The code is also unable to describe oscillations with periods of ~2 min which are observed in the Geotail data during dipolarization. (See, e.g., \( V_y \) and \( E_y \) in Figure 4 of Paper 1.) Still, however, the approximations used in the RCM allow it to get the most important time integrals correct. Specifically, for modeling injection into the inner magnetosphere, the key parameters are the total amount of magnetic flux in the injected bubble and the distribution function \( f(\lambda) \) of plasma in the bubble. Our estimates of those parameters are highly constrained by Geotail measurements and are therefore not dependent on precise modeling of the rapid reconfiguration of the plasma sheet at the beginning of the expansion phase. Specifically, Geotail measures \( \int E\,dt \), which differs from the flux in the bubble by an effective width \( \Delta \), which must be estimated from other observations. In addition, Geotail measures particle pressure and density, which can be used to estimate \( f(\lambda) \) using a magnetic field model and assuming isotropy.

Our assumption of bounce equilibrium could become inaccurate during the dipolarization. Nonadiabatic heating would cause the entropy to increase. To get a rough estimate of the seriousness of that effect, we calculated the effects of rapid compression of an ideal gas in a cylinder with a piston that is compressing the gas. There is no change in the entropy function \( PV^\gamma \) when the piston velocity is less than the sound speed, and it increases rather slowly as the Mach number rises above the value 1. Mach numbers 1.5 and 2.0 lead to increases of only about 4% and 20%, respectively, in \( PV^\gamma \).

Use of the RCM equations becomes more and more dubious as one moves further out in the tail. Although we are most interested in what happens in the inner magnetosphere, earthward of Geotail at \( \sim 9 R_E \), we placed the outer boundary of the simulation at \( \sim 20 R_E \) on the night side for the following two reasons: (1) Placing the boundary further out in the tail allows the flow channel/bubble to take the longitudinal width that is the natural result of the reduction of \( PV^\gamma /3 \) in the bubble and the ionospheric conductance, rather than being controlled by the longitudinal width of the bubble as specified on the tailward boundary, which is highly uncertain. (2) In the simulation, the period when high flow velocities are observed (and consequently the period when the RCM equations are not valid) is limited to the interval from 0655 to 0700 UT, when the magnetic field is dipolarizing. In that interval, the electric field in the midnight region is dominated by the inductive electric field, which is a data-driven input to the RCM and not the result of any self-consistent calculation.

3.3. Auroral and Midlatitude Trough Electric Fields Associated With Substorm Expansion

Figure 5 shows computed electric equipotentials and Birkeland currents in the nightside ionosphere. As magnetic field dipolarization proceeds, the location of the RCM boundary near local midnight, which is fixed at about \( X = -20 R_E \) in the equatorial plane, moves poleward in the ionosphere. The collapse of the midnight region field lines causes there to be more magnetic flux at \( X > -20 \), which necessitates the poleward expansion of the ionospheric modeling region.

\[ \text{Figure 5.} \quad \text{Birkeland currents (colors) and equipotentials in the northern ionosphere, for the same six times as in Figure 1. The Sun is to the left. Birkeland currents are in mA/m}^2, \text{and positive values indicate downward current. Contour spacing is 5 kV. Dashed equipotentials are negative.} \]
Before substorm onset, region 1 currents all lie poleward of the RCM modeling region, and region 2 currents are weak. After 0655 UT, region 1 sense currents form on the eastern and western edges of the bubble. Ionospheric closure of these currents produces a strong westward potential electric field across the bubble. In that field, the region 2 currents move earthward near midnight and strengthen. Those strong region 2 currents produce an eastward prompt penetration electric field at low ionospheric latitudes. Thus, in the ionosphere, we have the convergence of two flows near the equatorward edge of the aurora at midnight: equatorward $\mathbf{E} \times \mathbf{B}$ drift in the auroral zone inside the bubble, and poleward $\mathbf{E} \times \mathbf{B}$ drift in the subauroral region. The exhaust from this convergence flows eastward east of the bubble and

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**Figure 6.** (a) Potentials and Birkeland currents near local midnight at 0657 UT, near the beginning of the expansion phase. Contour spacing is 2 kV, and negative potentials are dashed; colors indicate Birkeland current, and red arrows show direction of $\mathbf{E} \times \mathbf{B}$ drift. The $xi$ and $yi$ coordinates are $\sin \theta \cos \phi$ and $\sin \theta \sin \phi$, respectively, where $\theta$ is colatitude in degrees and $\phi$ is a local time angle that is equal to zero at local noon, $\pi/2$ at dusk, $\pi$ at midnight, etc. Thus the Sun is to the left. (b) Radar-measured velocities and inferred equipotentials (3 kV spacing, adapted from Grocott et al. [2006]). (c) IMAGE/FUV data superimposed on the same equipotential pattern (adapted from Grocott et al. [2006]). Figures 6b and 6c show the 1800–2400 MLT sector.
westward west of it. Figure 6a provides a closer look at the electric equipotentials and Birkeland currents in the midnight region for 0657 UT.

[28] One clear feature of the midnight region potential pattern is an increased westward potential electric field inside the bubble. A similar increase was also apparent in the idealized RCM substorm simulation of Zhang et al. [2008].

[29] The physical reason for the increased westward field in the bubble is clear. From Vasyliaunas’ equation, the reduced value of entropy inside the bubble gives rise to downward Birkeland current on the eastern side of the bubble and upward current on the western side. The completion of that current through the ionosphere requires an enhanced westward electric field in the auroral ionosphere footprint of the bubble.

[30] What is the observational evidence for the existence of enhanced westward electric field in the auroral ionosphere near the center of the substorm current wedge? The Super Dual Auroral Radar Network (SuperDARN) data for the modeled period show a region of equatorward flow in a narrow range of local time near local midnight, in rough agreement with the model, although the local time range may have been limited to some extent by the field of view of the radars. The equatorward flow began much earlier in the observations than in the model, which suggests that the model, which was driven by observations of the solar wind and of a bubble at a single magnetospheric spacecraft and not by any ionospheric data, does not accurately represent what actually happened globally on 22 July 1998, particularly with regard to the strange “growth phase” which occurred in a period of northward IMF.

[31] The literature describes several efforts at observational definition of electric field changes in the auroral ionosphere during a substorm expansion phase. For example, Provan et al. [2004] used SuperDARN radar data in a statistical study of 67 substorms. On the whole, however, the ionospheric-electric field signature of substorm expansion has been difficult to pin down, because it is far less dramatic than substorm effects on the electrojet currents and the aurora and far less dramatic than the equatorial electric field signature. (The electric field effect of the plasma bubble looks particularly dramatic in our simulation, because the modeled expansion phase occurred in a period of weak convection.) Because substorms vary greatly, localized features tend to blur in a statistical study. However, a number of case studies have been conducted for individual events using SuperDARN radars to define potential patterns in the substorm region along with both satellite auroral images and ground magnetometer data used to pin down other features. Figures 6b and 6c shows an observational plot from Grocott et al. [2006], based on Tasman International Geospace Environment Radars (TIGER)/SuperDARN HF radars and Imager for Magnetopause-to-Aurora Global Exploration (IMAGE)/FUV auroral photos. For this event there is a clear indication of equipotential bunching. (Note that this was not the event we modeled.) Additional evidence of the same type of behavior can be found in the SuperDARN-based data presented by Brustow et al. [2001]. Of course, observational plots tend to be substantially more complex than what can be seen in the simulations. At the present time we cannot state with confidence that equipotential pinching, a characteristic feature of the simulations we have done so far, is typical of observed substorm onsets.

[32] As noted in Paper 1, we forced RCM pressures to approximately match pressures measured by Geotail’s LEP instrument, which is limited to particles below about 40 keV. This may have caused us to underestimate the particle pressure after dipolarization by ~20%, while underestimating the growth-phase pressure by a much smaller percentage.

The computed disturbance in the Birkeland current and potential electric field during and after onset are roughly proportional to the difference in $P_B$, outside and inside the bubble. We may well have overestimated this difference by 30–40% and may have underestimated the disturbance electric fields by about the same percentage.

[33] A second feature of the computed $E_y$ field is a westward flow to the west of the bubble. Figure 7 shows some detail of this feature, which represents nonbubble flux tubes getting out of the way of the Equatorward-moving bubble. At 0657 UT, the westward flow is spread across the modeled part of the auroral zone, but by 0700 UT, the bubble’s footprint has moved Equatorward, and the westward flow is concentrated in the midlatitude-trough region just Equatorward of the auroral conductance enhancement.

The pattern at 0700 resembles a polarization jet (PJ) or subauroral ion drift (SAID) event. After 0700 UT the rapid westward flow gradually decreases with time.

[34] PJ/SAID and SAPS events are well-established features of RCM runs during times of strong convection [e.g., Harel et al., 1981b; Garner et al., 2004]. Here, however, the calculated SAID event occurred during a period of weak overall convection and was associated with the injection of a plasma sheet bubble into the inner magnetosphere. The PJ/SAID event that appeared in this simulation was extremely brief, just a few minutes. PJ/SAID and SAPS events that appeared in previous simulations, caused by enhanced convection, lasted much longer. The present simulation indicates that a SAID-like signature can occur briefly an expansion phase onset. This source of SAIDs is very minor compared to the convective source, but might occasionally be observable.

[35] The association between PJ/SAID and SAPS events is well-established features of PJ/SAID and SAPS events is well-established. Many observers have tried to determine the time relationship between PJ/SAID and SAPS events. Nishimura et al. [2008] found a SAID-like fast westward subauroral flow event in close coincidence with a substorm onset. Parkinson et al. [2003] found a region of high-speed flow within the auroral zone that was also in close coincidence with another substorm onset. Miyashita et al. [2008] found that SAPS activity increased very shortly after the onset of one substorm, though it decreased at the time of a second substorm onset two hours later. Others have found that SAIDs occur significantly after substorm onset [e.g., Anderson et al., 1993; Koutsov et al., 2006, 2008]. Makarevich and Dyson [2007] found a variety of timing differences. On the basis of CRCM simulations that did not include reduced entropy bubbles or substorm associated $B_y$ field stretching or dipolarization, Ebihara et al. [2009] predicted that a time lag between a substorm onset and the appearance of the westward flow depends on the distance between the onset region and the observatory. Also, for the event of 22 July 1998, the DMSP spacecraft happened to pass through the trough region at about 20 magnetic local time and observed a classic SAID event, which agrees with the theoretical prediction within a few
minutes. However, there is no observational way to determine whether the duration of that observed SAID was only a few minutes, as predicted by the model. It is interesting that the two-vortex flow pattern that one expects from a bubble has been clearly observed in association with bursty bulk flows \cite{Kauristie et al., 2000; Grocott et al., 2006; Nakamura et al., 2005}, but the situation for substorm expansion phases, which can cover a wider range of local time, is less clear.

3.4. Prompt Penetration Electric Fields Associated With Substorm Onset

\cite{36} We use the term “prompt penetration electric field” to refer to electric field effects that occur in the low-
midlatitude ionosphere (Equatorward of SAPS/SAID) as a happens in the magnetosphere. The RCM simulation for the auroral zone and for (q and subauroral ionosphere near local midnight. Figure 6 concentrated on the night side than the pattern found in ZHANG ET AL.: RCM BUBBLE INJECTION, 2

AE may be correlating positively with convection sense electric fields below the auroral zone, particularly at mid-latitudes on the nightside. In the simulation the bubble injection pushes the equatorward edge of the plasma sheet to lower latitudes ahead of the bubble, which increases region 2 currents in that area. The strengthened region 2 currents give rise to an eastward (overshielding) electric field more than 2–3° equatorward of the region 2 currents. The bubble creation mechanism for overshielding is very closely related to the magnetic reconfiguration mechanism suggested by Fejer et al. [1990]. That paper emphasized that the reduction in plasmalobe magnetic flux observed following a northward turning of the interplanetary magnetic field leads to a deformation of the plasma sheet inner edge, and consequent overshielding. That overshielding mechanism was developed after RCM simulations showed that reduction of the cross-polar-cap potential drop, which was the traditional explanation for overshielding [Kelley et al., 1979], was insufficient to explain the duration of overshielding following a northward turning of the IMF [Spiro et al., 1988]. When a northward turning of the IMF triggers a substorm, the process that creates the plasma bubble also reduces the tail lobe magnetic flux. Although the substorm of 22 July 1998 was not convincingly triggered by a northward turning, simulation of it provides insight into the early phase of overshielding in substorms associated with northward turnings.

[37] Statistical studies based on Jicamarca radar data indicate that an increase in AE produces undershielding-type prompt penetration electric field [Fejer and Scherliess, 1997], in seeming contradiction to the model’s prediction that the substorm-associated bubble injection leads to overshielding. However, AE correlates positively with convection strength as measured by the cross-polar-cap potential drop, and, of course, the injection of a bubble in a substorm should be associated with an increase in AE. Statistically, the prompt penetration response to an increase in AE may be more closely linked to an increase in polar cap potential than to injection of a bubble. Individual substorm event studies are clearly needed to resolve the apparent discrepancy. To date, none have been done using Jicamarca data, as far as we know. However, Sastri et al. [1992, 2001, 2003] have used low-latitude ionosondes and ground magnetograms to get an idea of the low-latitude electric field signature of substorm expansion. In most of the substorms studied, there is evidence of overshielding sense electric fields in qualitative agreement with the simulation results. However, some of the substorms studied may have been triggered by northward turning, which makes it hard to distinguish the bubble injection effect from the effects of overshielding because of a decrease in polar cap potential drop and the large-scale reduction of tail lobe flux. Another problem with observational testing of the model is that the model predicts only consequential overshielding. That overshielding mechanism leads to a deformation of the plasma sheet inner edge, and consequent overshielding. That overshielding mechanism was developed after RCM simulations showed that reduction of the cross-polar-cap potential drop, which was the traditional explanation for overshielding [Kelley et al., 1979], was insufficient to explain the duration of overshielding following a northward turning of the IMF [Spiro et al., 1988]. When a northward turning of the IMF triggers a substorm, the process that creates the plasma bubble also reduces the tail lobe magnetic flux. Although the substorm of 22 July 1998 was not convincingly triggered by a northward turning, simulation of it provides insight into the early phase of overshielding in substorms associated with northward turnings.

[38] Figure 8 shows the prompt penetration electric potential pattern obtained in our substorm onset simulation. This is an overshielding-type RCM pattern, but more concentrated on the night side than the pattern found in standard RCM runs, where the overshielding is caused by a poleward potential drop decrease [e.g., Spiro et al., 1988].

[39] Figure 9 shows the temporal growth and decay of the local time profile of eastward ionospheric electric fields at two latitudes (the Equatorward boundary of the RCM (≈10°, Figure 9 (top)) and at midlatitude (45°, Figure 9 (bottom))). The strongest fields are confined to the nightside and terminator regions and the fields are weaker near the equator than at mid-latitudes.

[40] Our simulation suggests that substorm onset may cause short-duration overshielding-type prompt penetration electric fields below the auroral zone, particularly at mid-latitudes on the nightside. In the simulation the bubble...
proportional to $\eta$.) Figure 10 shows the evolution of the $H^+$ distribution function through the bubble injection at the same six times as Figure 1, for three different RCM invariant energy channels. Black contours show the effective potential, defined by

$$\Phi_{\text{eff}} = \Phi_{\text{ion}} + \Phi_{\text{cor}} + \frac{\lambda_i V^{-2/3}}{e}.$$  

Figure 10 clearly shows that gradient/curvature drift has greater effects on the drift path of particles with higher energies. The inner magnetospheric injection of $H^+$ with kinetic energy at geosynchronous orbit of 700 eV in the depleted channel is almost entirely controlled by the $E \times B$ drift, which is charge independent. (There is no $O^+$ in this simulation.) The flow channel of the low-energy $H^+$ is close to the midnight meridian (see Figures 10a–10f). However, for more energetic $H^+$, the effects of gradient/curvature drift, which is both charge and energy dependent, becomes more important. As shown in Figures 10g–10r, more energetic particles in the depleted channels gradient/curvature drift westward and reach the inner magnetosphere through drift paths that are highly tilted across the premidnight sector. At 0730 UT, 35 min after the bubble boundary condition is imposed, the centers of the flow channels for $H^+$ ions with 33- and 130-keV geosynchronous energy extend far into the afternoon sector on the dayside. By 0730 UT, the highest-energy channel shows a narrow tongue of high-$\eta$ plasma drifting westward in the afternoon sector just earthward of...
the depletion channel. This tongue represents higher-energy plasma sheet ions that were just earthward of the bubble at onset. Dipolarization of the magnetic field carried them earthward, and they subsequently moved to the west as gradient/curvature drift began to dominate. [44] Figure 11 shows the proton pressure distribution ($P_p$) along the midnight meridian on the equatorial plane at the same six times as Figures 1 and 10. The inner localized $P_p$ peak at $X = -2.9 R_E$ represents the center of the quiet time ring current, which was installed as an initial condition and

![Figure 10](image)

Figure 10. Format is similar to Figure 1, but color snapshots of $\eta_p$, which is number of particles per unit magnetic flux per invariant energy channel, and effective equipotentials (black contours) for $H^+$ with energy invariants $\lambda_1 = (a-f) 0.1$, (g-l) 4.7, and (m-r) 18.6 keV($R_E$/nT)$^{2/3}$, corresponding to approximate energies at geosynchronous orbit of 700 eV, 33 keV, and 130 keV, respectively. (The distribution function is proportional to $\eta_p$.) Note that the $\eta_p$ scales of the color bar are different by a factor of 10 or 100. Corotation is included in the effective potential. Equipotentials have the same 5-kV spacing.

\begin{center}
\begin{tabular}{c}
\begin{tabular}{l}
\textbf{$\eta_c [10^{11}]$} \\
0.5 & 1.0 & 1.5 & 2.0 & 2.5 & 3.0 & 3.5 & 4.0 & 4.5 & 5.0 & 5.5
\end{tabular}
\end{tabular}
\end{center}
changes very little during the simulated bubble event. At the end of the growth phase (i.e., at 0655 UT), the outer \( P_P \) peak, due to the particles that have entered the RCM modeling region through the tailward boundary, is located at \( X_{GSM} = -8.4 R_E \) and has a value of only 1.4 nPa. Over the next three minutes, the peak value more than triples and moves \( \sim 1 R_E \) closer to the Earth. After the dipolarization and strong bubble injection are complete, the peak gradually declines. The results shown in Figure 11 (top) resemble those of Zhang et al. [2008], but with the following two differences: (1) the present event is much weaker, so the pressure peak shown in Figure 11 is weaker and further from Earth and (2) the new results give a more realistic pressure profile overall, because a quiet time ring current was included in the initial condition. The dual peak configuration of the pressure is consistent with observations during individual substorm events [e.g., Kistler et al., 1992] and at various times in a magnetic storm [Lui et al., 1987], although the statistical pressure profile is generally monotonic [e.g., Spence and Kivelson, 1993].

[45] It may seem odd that the early evolution of the bubble shows up as a decrease in the distribution function (as shown in Figure 10, characterized by \( \eta \) values), while Figure 11 indicates an increase in pressure beyond \( \sim 12 R_E \). \( PV^{5/3} \) is two-thirds the sum of \( \eta \lambda \) (equation (6) of Paper 1). It is possible for all of the \( \eta \)'s to decrease but for \( P \) to increase, providing that the flux tube volume decreases sufficiently, as is the case here. Figure 11 (bottom) shows how the equatorial magnetic field increases in the dipolarization process.

[46] Figures 12 and 13 provide a close-up view of how the bubble and the dipolarization work together in the injection process. Figures 12 and 13 show a well-defined plasma sheet inner edge at 0654 UT, just before onset. By 0656 UT, the field dipolarization has begun in the model, bringing the plasma sheet inner edge earthward. However, the bubble (yellow region in Figure 13) has not yet entered the plotted region \( (X > -10) \). Physically, the reduction in westward cross-tail current provides a northward magnetic field perturbation earthward of the bubble. By 0658 UT, dipolarization is up to 60\% of its maximum value, and the plasma sheet inner edge nearly touches geosynchronous orbit. The bubble has now pushed its way in to \( X \sim -7 \). However, the pressure peak is located earthward of that and consists of flux tubes with high \( PV^{5/3} \) that were pushed earthward ahead of the bubble. These high-content pushed flux tubes clearly play an important role in particle injection. Their earthward motion is due to a combination of the westward induction electric field caused by the dipolarization and the westward potential electric field needed to provide the ionospheric connection between oppositely directed Birkeland currents flowing on either side of the bubble. By 0700 UT, dipolarization is complete, and the pressure enhancement has been forced inside geosynchronous orbit, but only over a narrow range of local time. The bubble has now reached the inner edge of the plasma sheet. After 0700 UT, \( P \) and \( PV^{5/3} \) gradually decline near the inner edge because of the energy-dependent gradient/curvature drift of the injected particles. It should be noted that the highest values of the pressure at \( L = \sim 7 \) in Figures 11 and 12 probably represent an overestimate, because the inputted magnetic field does not inflate in response to the locally increased particle pressure. Geosynchronous spacecraft observed no significant flux increases associated with this substorm. However, since there were no spacecraft in the narrow local time range where the simulation indicated that the bubble penetrated to geosynchronous orbit, there is no clear inconsistency between the model and the data.

[47] One might wonder why the pressure-bearing ions that penetrated inside geosynchronous orbit by 0700 UT, as shown in Figures 12 and 13, didn’t just drift west, staying inside geosynchronous orbit. The answer is that, because of the overshielding (eastward) electric field, they subsequently moved away from the Earth as they drifted west. Of course, this simulation assumed a very weak polar cap potential drop through the late growth phase and early expansion. They might not have drifted away from the Earth if convection had been stronger.

[48] It is interesting that the inner edge of the high plasma pressure region shows a clear earthward protrusion limited...
to a small range of local times near midnight. Its shape resembles the injection boundary (Figure 14) originally proposed many years ago to explain the substorm-associated dispersion patterns observed from locations at, and some- times earthward of, geosynchronous orbit [McIlwain, 1974; Konradi et al., 1975; Mauk and Meng, 1983]. In our simulation, the dented-in shape of the inner edge results from the superposition of the induction electric field and the westward potential electric field associated with the Birkeland currents flowing on the edges of the bubble. While the original modeling that introduced the injection boundary concept [e.g., McIlwain, 1974] assumed that potential electric fields transported particles away from the region of the original injection, the possible importance of induction electric fields was pointed out by Moore et al. [1981]. Modeling with the RCM has finally advanced to

![Figure 12.](image_url)  

The injection process viewed in terms of equatorial particle pressures near local midnight at six different times.
the point where it can incorporate reasonably realistic time-
dependent induction fields with self-consistently computed
potential electric fields.

3.6. Bubble-Free Run

[49] It is natural to ask, at this point “To what extent do
the ionospheric and inner magnetospheric effects discussed
in sections 3.3–3.5 result from the bubble (specifically the
region of reduced plasma sheet $PV^{5/3}$) and to what extent
do they result from the dipolarization of the magnetic field”? This question implies a physical inconsistency, because the dipolarization of the midnight region field lines is really possible only if their $PV^{5/3}$ values are reduced. A model that computes the magnetic field self-consistently with RCM-computed $PV^{5/3}$ could not address the question, but the RCM can, because its magnetic field is inputted and

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**Figure 13.** The injection process viewed in terms of equatorial $PV^{5/3}$. The format is the same as Figure 12.
not computed self-consistently. We did an RCM run that was identical to the main one described in this paper, except that we did not reduce the midnight region $PV^{5/3}$ on the RCM boundary at onset and did not correspondingly change the distribution of potential along that boundary. The results differed from those presented earlier in several ways. There were no region 1 currents within the RCM modeling region during the early expansion phase. Birkeland currents were very weak tailward of the inner edge region, because $PV^{5/3}$ was nearly uniform there. Consequently there was no concentration of westward ionospheric electric field in the center of the substorm. The peak eastward prompt penetration electric fields were 2–3 times stronger than the ones shown in Figures 8 and 9, because there were no strong region 1 sense currents on the sides of the wedge region, to partly balance out the strengthened region 2. Since there was no Equatorward-moving bubble, there was no need for plasma to move out of the way, and consequently there was no SAID. By the end of the dipolarization, plasma sheet pressures were higher in the midnight region beyond $\sim 7 R_E$ than in the main run (because of the lack of depletion). The pressure peak had about the same magnitude but was not highly concentrated near local midnight and was further tailward ($\sim 7.5 R_E$ rather than $\sim 6.3 R_E$). Compare Figure 15 with Figure 12d. The overall conclusion is that the reduction in $PV^{5/3}$ that was enforced in the main run had a major effect on the earthward injection of plasma and an even stronger effect on the ionospheric electric fields and Birkeland currents.

4. Discussion and Conclusions

This paper has described an RCM simulation focused on quantitative modeling of the injection of particles into the inner magnetosphere during a modest substorm. An attempt has been made to take account of both the inductive and potential electric fields. The model induction fields were not computed self-consistently but were constructed using a substorm current wedge model developed by Tsyganenko [1997], adjusted to fit measurements by Geotail at $X \approx -9$. A bubble (region of reduced $PV^{5/3}$) was introduced into the modeling region through the tailward boundary, using Geotail measurements to estimate $PV^{5/3}$ and $TV^{2/3}$. The simulation results provide insight into the strong Birkeland currents in the current wedge and the corresponding electric fields, as well as the relative roles of potential and induction electric fields. Some interesting features of the simulation are as follows:

1. Closure of the oppositely directed Birkeland currents on either side of the RCM-computed current wedge led to a concentration of westward electric field in the auroral ionosphere, near the center of the wedge. Ionospheric observations provide modest observational evidence for this model-predicted feature.

2. The injection of the bubble produced a short-lived SAID event.

3. The simulations indicate the existence of an over-shielding (eastward) electric field at subauroral latitudes on the night side. The present simulation represents a specific case of the magnetic reconfiguration effect on penetration electric fields [Fejer et al., 1990].

4. At onset, the model-computed inner edge of the plasma sheet displays a dent near midnight that resembles the shape of the injection boundary suggested many years ago on observational grounds by McIlwain [1974] and Konradi et al. [1975].
[55] 5. Flux tubes that are pushed earthward ahead of the bubble play a significant role in the injection process.

[56] By combining data-driven magnetic field changes with self-consistent calculation of the magnetospheric electric potential and plasma distribution, the present simulations represent an important step toward accurate physical representation of particle injection in a substorm. However, the processes involved are extremely complex, and the present models are far from providing a full and accurate picture. Additional work that we need to do in the future includes the following:

[57] 1. We need to simulate a substorm for which geosynchronous spacecraft observed a classic injection signature. Los Alamos particle detectors showed no significant substorm signatures for the 22 July 1998 substorm that we have modeled, and the RCM predicted significant injection to geosynchronous orbit only briefly and only for about one hour of local time, which was less than the separation of the two spacecraft nearest midnight. Thus the model and measurements were basically consistent, but there was no real quantitative test.

[58] 2. The Tyaganenko [1997] substorm current wedge model employed in this study was quite simple and should be modified for greater consistency with RCM-computed pressures. Zaharia [2008] showed cases where the field-aligned currents were greatly modified by letting the magnetic field and pressure distributions relax to equilibrium. However, that does not mean that RCM simulations, which have always been based on inputted magnetic fields, give completely unrealistic Birkeland currents. When we start the RCM from an empirical pressure distribution, the initial computed Birkeland currents are usually meaningless, as are the electric fields. However, those electric fields rearrange the plasma and Birkeland currents, which typically settle down to a classic pattern in a fraction of an hour. In a short period of time, the ionosphere-magnetosphere coupling sets up region 2 currents for any reasonable magnetic field model.

[59] 3. The substorm current wedge and bubble need to expand in local time after the initial onset, for realistic representation of an expansion phase.

[60] 4. Field-aligned potential drops need to be included in the simulations.

[61] 5. We need to determine the sensitivity of the conclusions to the form assumed for the potential on the RCM’s tailward boundary.

[62] 6. We have used a version of the RCM that assumes that the Earth’s dipole is perpendicular to the solar wind velocity and Earth-Sun line, which necessitated a coordinate change that relates measurements made on a real spacecraft to our idealized magnetosphere. (See Paper 1.)

[63] 7. Account should be taken of the possibility that substorm-associated dipolarization may be fast enough to cause some nonadiabatic ion heating.

[64] In setting the RCM’s particle boundary conditions, we need to include the contributions from ions above the cutoff energy of the low-energy particle instrument in our estimate of the total ion pressure. This may have caused our calculated substorm-associated Birkeland currents and electric fields to be larger than the real ones, as discussed in section 3.3.

[65] We essentially drove the RCM with bubble observations made by a single magnetospheric spacecraft on 22 July 1998. Of course, the result was not an accurate representation of what actually happened globally on that day. Our idealized simulation has illuminated some of the physical processes that accompany the injection of a bubble into the inner magnetosphere. To achieve actual realism, we will have to develop a methodology for utilizing a much wider range of observational data to set the boundary conditions that drive the model, including, at least, several THEMIS spacecraft, SuperDARN, and ground magnetometers. The reader should also bear in mind that the our whole approach, which is based on bounce-averaged drift equations and on the neglect of inertial terms, cannot describe variations on time scales shorter than the typical ion bounce time or, equivalently, the time for an MHD wave to travel from cross-tail current sheet to ionosphere and back.

Acknowledgments. We are grateful to the reviewers for very helpful comments. Work at Rice University has been supported by the National Space Weather Program under NSF grant ATM-0720309, NASA Guest Investigator grant NNG05G06G, and the NASA Heliophysics Theory Program under grants NNG05G09G and NNX07AF44G. Work at Prairie View A & M University was supported by NASA Geospace Science grant NNG06H72G. Computational support was provided in part by the Rice Terascale Cluster funded by NSF under grant EAR-0216467 and a partnership between Rice University, Intel, and Hewlett-Packard and in part by the Rice Computational Research Cluster funded by NSF under grant CNS-0421109 and a partnership between Rice University, AMD, and Cray.

Zuyin Pu thanks the reviewers for their assistance in evaluating this paper.