Contribution of convective transport to stormtime ring current electron injection

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[1] Significant increases in electron fluxes and energy densities at energies from 200 eV to ∼1 MeV have been observed during magnetic storms to L values as low as 2. To investigate the processes responsible for these flux increases of ring current electrons, we simulate the guiding-center drift and loss of electrons from the plasma sheet to the inner magnetosphere during storms. We use a dipole field plus a constant southward interplanetary magnetic field as our magnetic field model. Over this magnetic field model we impose corotation, quiescent Stern-Volland, and storm-associated enhancements in the convection electric field. We perform phase-space mapping simulations with imposed initial (theoretical results or Combined Release and Radiation Effects Satellite (CRRES) observations) and boundary (averaged Los Alamos National Laboratory/multiple-particle analyzer or CRRES observations) conditions for hypothetical and real storm events, respectively. Wave-particle interactions are the dominant loss process for ring current electrons. Wave activity outside the plasmapause is enhanced during storms due to the particle injection from the plasma sheet to the inner magnetosphere during active times. Our loss model takes such enhanced losses into account. We compare our simulated electron fluxes with previously reported fluxes observed by Explorer 45 for hypothetical storms and with in situ fluxes from CRRES/low-energy plasma analyzer (LEPA) (∼100 eV to ∼20 keV) and CRRES/medium-energy sensor A (MEA) (153 keV to 1.582 MeV) for two storm events (26 August 1990 and 10 October 1990). We find that direct injection from the plasma sheet by enhanced convection can account for increases in the stormtime ring current electron fluxes from 10 to ∼50 keV. Our simulations quantitatively reproduce the enhanced low-energy (∼10 keV) electron fluxes observed by CRRES/LEPA at equatorial radial distances of ∼3 to 6.6R_E. Our simulated electron fluxes at intermediate energies (∼50 keV) overestimate the corresponding fluxes observed by Explorer 45 at L ∼ 3–5, suggesting that the loss model that we are currently using underestimates the actual electron losses at energies of ∼50 keV. We find that transport via enhanced convection cannot account for the rapid filling of the slot region at 3–5R_E for ≥100 keV electrons when we apply linearly interpolated Data Acquisition and Processing Program (DMSP) cross-polar-cap potentials in our simple electric field model. However, when we superimpose stormtime fluctuations of the cross-tail potential drop over linearly interpolated DMSP potentials, we find that the fluxes of electrons are enhanced up to energies of ∼150 keV at L ∼ 3–5R_E during the October 1990 event because radial diffusion of the high-energy electrons during the 22-hour main phase can be significant. However, it still cannot account for the stormtime flux increases of E ≥ 200 keV at L ∼ 3–5. This may be in part because the simple electric field model that we are using underestimates the electric field intensity in the slot region. Local acceleration mechanisms, which we have not included in our model, may also play an important role.

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1. Introduction

The stormtime ring current consists of ions and electrons with energies of ~10 to ~200 keV that drift westward to form the stormtime ring current. Much work, e.g., [Frank, 1967] and [Williams and Smith, 1965; Williams and Lyons, 1974] has been done to account for the observed stormtime enhancement of ring current ions. Although it has been reported that electrons contribute ~25% of the stormtime energy content of protons for energies from 200 eV to 50 keV at 1 ≤ L ≤ 8 [Frank, 1967], the stormtime ring current electrons have been largely neglected in the past. It is thought that the storm-associated time-varying enhancement of the magnetospheric convection electric field is mainly responsible for transporting charged particles from the plasma sheet inward to the region of stormtime ring current, and then the magnetic field and curvature gradient drift cause ions to drift westward to form the stormtime partial or closed ring current [e.g., Chen et al., 1993; 1994; Fok et al., 1996, 1999, 2001; Jordanova et al., 1997]. While this concept has been successfully applied to ring current ions, the stormtime enhancements of electron fluxes have not been explained. Furthermore, the contribution of electrons to the total energy content of the ring current has not yet been quantified definitively through either observations or modeling.

Let us first examine the general kinematic features of ions and electrons. In the inner magnetosphere, electrons and ions have the same $E \times B$ drift, but the gradient and curvature drift depend on charge and energy. As a result, in the ring current energy range (10–200 keV), electrons drift eastward while ions drift westward. Moreover, electrons conserving the first invariant $\mu$ also have a drift separatrix marking the innermost location that electrons from the plasma sheet can gain access along open trajectories and the outermost location that they are trapped on closed trajectories [e.g., Kavanagh et al., 1968; Chen, 1970; Ejiri, 1978]. For a given cross-polar-cap potential, this drift separatrix moves closer to the Earth with decreasing $\mu$. Additionally, the drift separatrix moves inward with increasing cross-polar potential drop or convection electric field. Thus except at low $\mu$ values where corotation and magnetic drift can negate each other for ions, electrons should penetrate as deep as protons with the same magnitude of the electric field and $\mu$ value.

An important difference between the dynamics of the ring current ions and electrons is that the loss of stormtime ring current electrons occurs on timescales that can be much shorter than that of stormtime ring current ions. This is one of the reasons why electrons should contribute less to the total energy content of the stormtime ring current. Theoretical electron lifetimes of Lyons and Thorne [1973] show that, within the plasmasphere, lifetimes against wave-particle interactions are significantly shorter than those against Coulomb scattering. For example, 3 MeV $G^{-1}$ electrons at $L \geq 4$ have a lifetime against Coulomb collisions of a few 100 days. In contrast, the lifetimes against pitch angle scattering by plasmaspheric hiss during quiet times are typically several days for ring current electrons [Lyons et al., 1972]. Albert [1994] refined Lyons et al.'s [1972] results by including higher harmonics of plasmaspheric hiss. Abel and Thorne [1998] computed the electron-scattering rates due to lightning-induced whistlers and very low frequency (VLF) waves in addition to Coulomb collisions and plasmaspheric hiss. Their calculations show that the lifetime of 100 keV electrons at $L = 4$ is reduced by a factor of about 3 from ~17 to ~6 days after the inclusion of whistler and VLF waves. The studies mentioned above are valid within the plasmapause. However, the plasmasphere shrinks significantly during the main phase of the storm, and ring current enhancements occur primarily outside the stormtime plasmapause. It is thus important to include losses outside the plasmapause when evaluating the formation of the stormtime ring current electrons. Wave activity outside the plasmapause is significantly enhanced during magnetically active times due to injections from the plasma sheet. The electron lifetime against wave-particle interactions at $L \geq 4$ during disturbed times could be as short as that for strong pitch angle diffusion, which is ~1 hour for 3 MeV $G^{-1}$ electrons at geosynchronous orbit. Unfortunately, there are not many observational studies of electron lifetimes in the inner magnetosphere at ring current energies, and currently one needs to rely heavily on theoretical models of electron loss.

Wave-particle interactions can result in not only electron loss by pitch angle scattering, but also electron acceleration. Summers and Ma [2000] investigated the acceleration of electrons via cyclotron resonance with whistler waves. The timescale that they found to accelerate ~100 keV electron to >1 MeV is several days. This timescale is longer than the typical duration of a storm main phase. Horne and Thorne [2003] recently found that whistler-mode chorus outside $L = 3$, their assumed active time plasmapause location, tends to scatter 10–60 keV electrons into the loss cone. This scattering leads to significant wave growth, consistent with the observations of enhanced whistler-mode chorus waves outside the plasmapause during magnetically disturbed periods [e.g., Meredith et al., 2001]. The enhanced chorus also resonates with higher-energy electrons and cause significant acceleration of electrons up to approximately mega electron volt energies. The corresponding timescale of energy diffusion from whistler-mode chorus can be on the order of a few hours for ~100 keV electrons at $L = 3.5$ during storms (R. M. Thorne, personal communication, 2003). Thus such energization may help in explaining the $\geq$100 keV electron enhancements outside the plasmapause during storms. Its importance to the stormtime enhancements of ring current electron will be assessed in our simulations indirectly. Another possible mechanism that has been proposed for accelerating high-energy electrons in the inner magnetosphere is through drift resonance of electrons with ultralow frequency (ULF) waves [Elkington et al., 1999, 2003]. This interaction conserves the first invariant $\mu$, and the acceler-
ation/deceleration occurs as electrons diffuse radially. Elkington et al. [1999, 2003] have simulated the drift-
resonant acceleration by Pc-5 ULF waves while conserving \( \mu \). Their results show that 1-MeV electrons at \( L = 6.6 \) can have radial diffusion rates of \( D_{\text{LL}} = 4.34 \times 10^{-2} \text{ h}^{-1} \) (radial diffusion scale time \( \tau_{\text{LL}} = 23 \) hours). Timescales are expected to be significantly longer at lower \( L \), leading to timescales for acceleration to 1 MeV that are significantly longer than the duration of a storm main phase.

[5] In this study, we evaluate the extent to which radial transport by enhanced electric fields can account for the stormtime ring current electron enhancements. We simulate ring current electrons with the same magnetic and electric field models and simulation method as used by Chen et al. [1994] for protons. An electron loss model is developed based on previous theoretical and observational studies of electron lifetimes. We evaluate our loss model by comparing our simulated electron fluxes with observations. Local acceleration by plasma waves is not included in the current model. However, we can still assess the possible importance of local acceleration to ring current electrons by studying the discrepancies between our simulation results and observations. We first simulate hypothetical storms to evaluate the fundamental processes affecting stormtime ring current electron and compare the simulated electron fluxes with previously reported [Lyons and Williams, 1975] fluxes measured by Explorer 45. Then we further simulate two storm events (26 August 1990 and 10 October 1990) and compare the simulated electron fluxes with in situ Combined Release and Radiation Effects Satellite (CRRES) fluxes.

2. Model Description

[7] In this section, we describe our ring current simulation model, which is an adaptation of the simulation model of Chen et al. [1993, 1994, 1998] for ring current ions, and that of Chen and Schulz [2001a, 2001b] for diffuse aurora electrons. We trace equatorially mirroring electrons with constant \( \mu \) values that are representative of ring current electrons in a model magnetosphere under storm-associated enhancements in the convection electric field. We map phase-space distributions by invoking Liouville’s theorem modified by particle loss along the simulated trajectories as \( f(t + \Delta t) = f(t) \exp(-\Delta t/\tau) \), where \( f \) is the phase-space density, \( t \) is time, \( \Delta t \) is a short enough time, and \( \tau \) is electron lifetime.

2.1. Magnetic Field Model

[8] The magnetic field model that we are using consists of the geomagnetic dipole field plus a uniform southward field [Dungey, 1961, 1963]. The field intensity at the equatorial plane is given by

\[
B_0(r) = \frac{\mu_E}{r^3} - \Delta B,
\]

(1a)

where \( \mu_E = 3.05 \times 10^4 \text{ nT} \) is the geomagnetic dipole moment, \( R_E \) is the radius of the Earth, \( r \) is the geocentric distance, and \( \Delta B \) is the magnitude of the uniform southward field. This field model is quite reasonable for \( r \leq 6R_E \), where the ring current forms, though it does not include the effects of the ring current itself [see Figure 1 in the work of Chen et al., 1993]. The equation of a magnetic field line in this model is

\[
r = La \left( 1 + \frac{1}{2b^4} \right) \sin^2 \varphi.
\]

(1b)

where \( r \) is the geocentric radial distance, \( L \) is the dimensionless label of the field line, \( a \) is the Earth’s radius, \( \theta \) is the magnetic colatitude, and \( b \) is the radius of the equatorial neutral line. We have taken the constant \( b = 12.82R_E \) so that the last closed field line (denoted as \( L^* \)) in this model maps to a colatitude \( \theta^* = 20^\circ \) on the Earth’s surface. The \( \Delta B \) in this case equals 14.474 nT, and the field model is axisymmetric and time independent.

[9] We choose to first use this analytical magnetic field model because it preserves essential features of the relevant physical processes while allowing us to represent the results of needed subsidiary calculations in terms of analytic functions.

2.2. Electric Field Model

[10] In our studies we consider a simple electric potential function

\[
\Phi_E(L, \varphi) = -\frac{V_\Omega}{L} + \frac{V_0}{2} \left( \frac{L}{L^*} \right)^2 \sin \varphi + \frac{\Delta V(L, \varphi; t)}{2} \left( \frac{L}{L^*} \right) \sin \varphi,
\]

(2)

where \( \varphi \) is the angle of the magnetic local time (MLT), and the three respective terms on the right-hand side correspond to corotation (\( V_\Omega = 90 \text{ kV} \)), steady quiescent Stern-Volland [Volland, 1973; Stern, 1973] convection (the quiescent cross-tail potential drop \( V_0 = 25 \text{ kV} \)), and a storm-associated convection potential [Nishida, 1966; Brice, 1967]. In our electric field model, the steady and stormtime-enhanced convection electric fields are assumed to be proportional to \( (L/L^*)^\gamma \), where \( \gamma \) is called shielding factor. The steady convection is assumed to be well shielded with \( \gamma = 2 \). However, the stormtime-enhanced convection has no shielding with \( \gamma = 1 \). We model the time-varying cross-tail potential drop \( V(t) \) using either (1) a superposition of random impulses as in the work of Chen et al. [1993] for a hypothetical storm [Figure 1 in the work of Chen et al., 1994] (Figure 1a), (2) a linear interpolation of cross-polar-cap potentials inferred from DMSP measurements for real storms (solid curve in Figure 1b or dashed curve in Figure 1c), or (3) a superposition of random impulses over a linear interpolation of cross-polar-cap potentials inferred from DMSP (solid curve in Figure 1c). We calculate cross-polar-cap potential drop from the DMSP ion drift measurements. The procedures for calculating the in-track potential from ionospheric electric field or ion drift measurements are well known and have been used in a number of the ionospheric convection pattern and magnetospheric electric field studies [e.g., Hairston and Heelis, 1990; Rich and Hairston, 1994; Weimer, 1995].

2.3. Particle Dynamics

[11] We consider only equatorially mirroring electrons in this study and assume that \( \mu \) is conserved. The relativistic
Hamiltonian function for an equatorially mirroring particle is given by

\[
H = \left( p^2 c^2 + m_0^2 c^4 \right)^{1/2} - m_0 c^2 + U
= \left( 2 \mu_0 m_0 c^2 + m_0^2 c^4 \right)^{1/2} - m_0 c^2 + q \Phi_E,
\]

where \( m_0 \) is the particle’s rest mass, \( c \) is the speed of light, \( q \) is the particle charge, and \( \Phi_E \) is the electric potential given by equation (2). The equations for the guiding-center drift of particles are easily derivable from the Hamiltonian function and are given by

\[
\frac{dL}{dt} = \frac{e L^2 a}{q \nu_E} \frac{\partial H}{\partial \nu},
\]

\[
\frac{d\nu}{dt} = -\frac{e L^2 a}{q \nu_E} \frac{\partial H}{\partial \nu},
\]

Figure 1. Three types of electric field potential used in this study. (a) The cross-tail potential drop for a hypothetical storm with random impulsive enhancements in the storm main phase. (b) The cross-polar-cap potential drop measured by DMSP for 25–27 August 1990. Plus signs mark the actual data points. The black lines are linear interpolation of those data points. (c) The potential profile we use to estimate the effects of fluctuation for 9–10 October storm.
times are contaminated by the background from penetrating high-energy electrons [Friedel and Korth, 1995]. In each of the two storm events, CRRES passed the region $6 \leq L \leq 7$ three times on the morning side. We use the three measurements to specify the simulation boundary conditions for each of the storm events. Notice that the time resolution of this kind of boundary condition is poor since we use measurements at three time points to construct boundary conditions to cover the entire main-phase period, which, for example, is 16 hours for the 26 August 1990 storm. In addition, the boundary conditions are assumed to be independent of MLT. In Figure 3, we compare the CRRES spectra with the averaged geosynchronous LANL/MPA electron spectra for the corresponding observed $Kp$ values and MLT bins. The CRRES data in the top two panels are taken from the August 1990 storm, in which CRRES was around 0700 MLT at $6 \leq L \leq 7$. The CRRES data in the bottom two panels are taken from the October 1990 storm, in which CRRES was around 0500 MLT at $6 \leq L \leq 7$. We find that boundary conditions from the CRRES data agree quite well with the averaged LANL/MPA data between $\sim 0.2$ and 10 keV. However, the CRRES spectra tend to be lower than the LANL spectra below $\sim 0.2$ keV (2 keV at $L = 3$ with the same $\mu$ value), which is generally lower than the typical stormtime ring current energy.

2.5. Initial Conditions

2.5.1. Hypothetical Storm

[18] For the hypothetical storm, we use the numerical solutions of the steady state transport equation that balances radial diffusion with loss due to precipitation in the limit of weak pitch angle diffusion [Albert, 1994] to obtain initial conditions. The numerical solutions give the phase-space density for electrons with fixed $\mu$ values ($1 \sim 200$ MeV G$^{-1}$) from $r_0 = 1.2\sim5.5R_E$, where pitch angle diffusion is important. We linearly extrapolate the logarithm of the phase-space density from $5.5R_E$ to geosynchronous orbit and then renormalize the initial distributions using the quiet time boundary conditions. Figure 4 shows the initial phase-space density profiles for electrons with $\mu = 1$, 5, 30, and 50 MeV G$^{-1}$. The dotted curves are the extrapolation, and the crosses correspond to the averaged LANL/MPA data (the one for 50 MeV G$^{-1}$ is calculated from the extrapolation of LANL/MPA data mentioned in section 2.4) at $Kp = 3$, which is a representative stormtime $Kp$ value. The initial conditions based on the numerical solutions of the steady state transport equation are useful when observed spectra are not available.

2.5.2. Storm Events

[16] When observed flux spectra profiles are available, it is desirable to base our initial distributions on them. For the two storm events of interest, we use one pass of prestorm observations from CRRES to construct the initial conditions for the simulations of storm events, assuming no MLT-dependence for initial conditions. We note that the use of observed prestorm spectra avoids introducing discrepancies inherent in the initial conditions based on the theoretical model.

2.6. Loss Model for Electrons

[17] Electron loss is not negligible during the storm main phase. In fact, losses seem to play an important role in the

Figure 2. The boundary spectra of $Kp = 3$ at midnight, dawn, noon, and dusk. The solid curves are the interpolation of the actual averaged LANL/MPA data, while the dashed curves are extrapolated results. The boundary spectra have minimum around dusk.

[12] We set up a grid of final positions in the equatorial plane that are spaced every $0.2R_E$ from 2.0 to $6.6R_E$ (geosynchronous altitude) and every $5^\circ$ in MLT. We follow representative particle trajectories backward in time from the final positions to either their initial positions or when they cross geosynchronous altitude, which we take as our outer boundary. Then we invoke Liouville’s theorem modified by particle loss to map the stormtime phase-space density distribution. This mapping requires knowledge of the boundary and initial phase-space distribution.

2.4. Boundary Conditions

2.4.1. Hypothetical Storms

[13] For the simulations of hypothetical storms, we apply a boundary spectrum at geosynchronous orbit based on averaging 12 years of geosynchronous Los Alamos National Laboratory/multiple-particle analyzer (LANL/MPA) electron data that are parameterized by $Kp$ and binned in 0.5-hour increments of MLT [Korth et al., 1999]. The LANL/MPA covers electron energies from a few electron volts to 40 keV (from $\sim 0$ to 40 MeV G$^{-1}$). However, we simulate the electrons having $\mu$ up to 200 MeV G$^{-1}$. Thus we linearly extrapolate the logarithm of the LANL/MPA electron flux data from 40 to 200 MeV G$^{-1}$. Figure 2 shows the boundary spectra of $Kp = 3$, which corresponds to the representative stormtime $Kp$ value of our hypothetical storm at midnight, dawn, noon, and dusk. This figure illustrates MLT dependence in the boundary spectra.

2.4.2. Storm Events

[14] For the two storm events of interest, we obtain the boundary spectra at $6.6R_E$ directly from CRRES/LEPA and CRRES/MEA data by averaging the fluxes from 6 to $\sim 7R_E$. CRRES/LEPA [Hardy et al., 1993] covers electron energies from $\sim 100$ eV to $\sim 20$ keV (attenuated mode), while CRRES/MEA [Vampola et al., 1992] covers from 153 keV to 1.582 MeV. There is an instrument on board CRRES called EPAS [Korth et al., 1992] that covers the energy gap between 21 and 153 keV, but its measurements in the range of $L \sim 3$–5 during geomagnetically active
formation of the stormtime ring current electrons. During a geomagnetic storm, the plasmasphere shrinks from its quiet time size as charged particles from the plasma sheet drift closer to the Earth due to enhanced convection. During storms, there is also enhanced wave activity. In order to reflect the enhanced losses outside the plasmapause, our loss model includes electron lifetimes that depend not only on energy and $L$ but also on whether an electron is within or outside the plasmapause.

[18] Earthward of the plasmapause, we use the electron lifetimes calculated by Albert [1994] based on pitch angle scattering by plasmaspheric hiss. In his calculations, the wave amplitude of plasmaspheric hiss is taken as the representative quiet time value. Smith et al. [1974] found that the plasmaspheric hiss intensity varies little from quiet time to storm initial and main phase. Thus it is reasonable to assure the loss rates inside the plasmapause to be independent of time. Albert’s calculations terminate at 5.5$R_E$, his assumed plasmapause location. When the simulated plasmapause location is beyond 5.5$R_E$, we extrapolate the logarithm of his results linearly from 5.5 to 6.6$R_E$, our simulation boundary. The solid curves in Figure 5 illustrate lifetime profiles for electrons with different $\mu$ values inside $R_E$.

Figure 3. Comparison of storm event boundary conditions with averaged LANL/MPA data. Solid diamonds are averaged CRRES data from 6 to 7$R_E$ on labeled orbits (dates). Plus signs are averaged LANL/MPA data for labeled $K_p$ and MLT.

Figure 4. Initial conditions for electrons with $\mu = 1, 5, 30, \text{and } 50 \text{ MeV G}^{-1}$. The solid curves are the interpolations of numerical results by Albert [1994]. The dotted curves are the extrapolations to our simulation boundary (6.6$R_E$) where initial conditions have the same values as the MLT-averaged LANL/MPA data of $K_p = 1$. The cross sign points correspond to the MLT-averaged LANL/MPA data of $K_p = 3$, which always have higher phase-space densities.
the plasmapause. For example, an electron with 5 MeV G\(^{-1}\) at 4\(R_E\) would have a lifetime of \(\sim 28\) days.

[19] By comparing diffuse aurora spectra around 65° latitude [e.g., Lyons and Fennell, 1986] with spectra of electrons with 90° pitch angle at geosynchronous orbit (6.6\(R_E\)), we find that electrons with energies up to 2 keV have approximately isotropic pitch angle distributions. Thus we specify a critical energy, \(E_c = 2\) keV, and assume that electrons outside the plasmapause with kinetic energy below \(E_c\) have lifetimes against strong pitch angle diffusion (dotted curves in Figure 5). This is a reasonable upper energy limit for strong pitch angle diffusion due to electron interactions with plasma waves observed outside the plasmasphere [Lyons, 1974]. For electrons outside the plasmapause with kinetic energy above \(E_c\), we assume that their lifetimes are proportional to \(L^{-1/3}\) (dashed curves in Figure 5), which is derived from formula (14) given by Lyons [1974]. In the derivation, we assume that the lifetimes are inversely proportional to the diffusion coefficients.

[20] During a storm the plasmapause location varies. We determine the plasmapause location by finding the drift separatrix of cold (0 MeV G\(^{-1}\)) electrons in our model at

**Figure 5.** An illustration of how our loss model calculates electron lifetimes. The vertical and horizontal dash-dotted lines correspond to a representative plasmapause location (3.5\(R_E\)) and 6 hours, respectively. Solid curves are electron lifetimes calculated by Albert [1994], which are applied to electrons within the plasmapause. Dashed curves are lifetimes for electrons with energy above the critical energy \((E_c)\), 2 keV, and outside the plasmapause based on the work by Lyons [1974]. Dotted curves correspond to the lifetimes against strong pitch angle diffusion [Schulz, 1998], which are applied to electrons with energy \(<E_c\), and outside the plasmapause.
time intervals of 30 s. For illustrative purposes, we consider a representative plasmapause location of $3.5R_E$ and mark this location by a vertical dash-dotted line in all the panels of Figure 5. For radial distance below the plasmapause location, we would use the solid curves for the electron lifetimes. For radial distance greater than the plasmapause, we would use the dashed curves if the energy exceeds $E_c$ or the dotted curves if the energy is below $E_c$.

3. Simulation Results and Comparison With Observations

[21] In this section, we present simulation results of a hypothetical storm and two real storms. We compare qualitatively the simulation results of the hypothetical storm with previous observations. This will help us to evaluate some basic mechanisms for the formation of the stormtime electron ring current. Real parameters (e.g., measured cross-polar-cap potential drops and measured initial and boundary conditions) are applied to simulate the two storm events. We make detailed comparisons of the simulation results with in situ CRRES observations.

3.1. Hypothetical Storm

[22] We model a hypothetical storm using the simple model of convection electric field derived from the potential given by equation (2) in which enhancements in the cross-tail potential $\Delta V(t)$ are a superposition of nearly random

![Figure 6. The simulated phase-space distributions for electrons with $\mu = 1$, 3, and 5 MeV G$^{-1}$. The first, second, and third columns correspond to $t = 0$ (initial conditions), 6, and 9 hours. The black solid and dotted curves are trajectories, which start from diamonds to plus signs. See color version of this figure at back of this issue.](image-url)
impulses. The cross-tail potential drop of steady quiescent convection, $V_0$, taken to be 25 kV, and the time average cross-tail potential of impulsive convection over the main-phase time $T$, $\langle \Delta V(t) \rangle$, is 125 kV. $T$ is defined as the time during which the impulsive enhancements of the electric field are allowed to occur. In the hypothetical storm considered here, $T = 3$ hours. The total simulation time $t$ is 9 hours. The main phase occurs at $t = 0$–3 hours. We apply the initial conditions calculated by Albert [1994]. We choose the boundary conditions based on the averaged geosynchronous LANL/MPA data for $Kp = 3$, which we take as a representative stormtime $Kp$ value (see Figure 2). We map the phase-space density distributions at $t = 6$ and 9 hours.

Figure 7. The simulated phase-space distributions for electrons with $\mu = 10, 30, \text{ and } 50$ MeV G$^{-1}$. The first, second, and third columns correspond to $t = 0$ (initial conditions), 6, and 9 hours, respectively. See color version of this figure at back of this issue.

[21] The simulated phase-space distributions for electrons of $\mu = 1, 3, \text{ and } 5$ MeV G$^{-1}$ and $\mu = 10, 30, \text{ and } 50$ MeV G$^{-1}$ are shown in Figures 6 and 7 (color plots at the back plate section), respectively. The columns correspond to the phase-space density distributions at simulation time $t = 0$ (the beginning of the storm main phase), $t = 6$ and 9 hours, respectively. There are significant stormtime enhancements in the phase-space density for $\mu \leq 10$ MeV G$^{-1}$. The enhancements for electrons with $\mu = 1, 3, \text{ and } 5$ MeV G$^{-1}$ (Figure 6) can occur to as low as $3R_E$. From the plots, we can see that the loss of 1-MeV G$^{-1}$ electrons as very significant. Freshly injected low-energy electrons undergo significant loss as they drift to the morning side, which agrees well with
a recent statistical survey of CRRES/LEPA data by N. Meredith (private communication, 2003). Stormtime enhancements of the phase-space density for electrons with \( \mu = 10 \text{ MeV G}^{-1} \) (Figure 7c) occur as low as 4\( R_E \). However, for electrons with \( \mu = 30 \) and 50 MeV G\(^{-1}\) (Figure 7) phase-space density enhancements occur only to \( \sim 5 R_E \). A sharp boundary between high phase-space densities associated with electrons directly transported along open trajectories from the outer boundary and low phase-space densities associated with electrons that were initially trapped on closed trajectories leads to a “spiral structure” in the phase-space density plots. The spiral structures are apparent in phase-space density distributions of low \( \mu \) electrons. Comparing the results at \( t = 9 \) hours with the results at \( t = 6 \) hours shows that the spiral structures tend to extend further around the Earth with time. Two representative trajectories are superimposed over the phase-space density distributions of 1, 3, and 5 MeV G\(^{-1}\) electrons at \( t = 6 \) hours in Figure 6. The open diamonds represent the initial positions, while the plus signs are the final positions (\( t = 6 \) hours). The black dotted curves show representative trajectories originating from the nightside boundary. The black solid curves show representative trajectories of electrons that had been on a closed trajectory prior to \( t = 0 \). These trajectories illustrate that the spiral structures in the phase-space distribution result from the slow magnetic gradient drift speed of low \( \mu \) electrons. The enhanced phase-space distributions for high \( \mu \) values (Figure 7) are fairly circular because of the relatively fast magnetic gradient drift speed of high \( \mu \) electrons.

[24] We compare our simulation results at \( t = 6 \) hours with observed electron flux profiles from Explorer 45 observations during the December 1971 storm (minimum Dst = \(-171\) nT) reported by Lyons and Williams [1975]. We first convert simulated phase-space density profiles to differential flux profiles at the same energies as data reported by Lyons and Williams [1975]: 50, 90, 180, and 340 keV. Next, we plot the simulated flux profiles along the orbit of the satellite to compare the simulated and observational flux profiles, as shown in Figure 8. In these plots the solid curves correspond to the fluxes at the end of the main phase, and the dashed curves correspond to the fluxes during the prestorm quiet time. The gray curves correspond to the Explorer 45 data for the December 1971 storms. At that
time, Explorer 45 traveled from 2030 MLT at 5.2\(R_E\) to 0200 MLT at 2.0\(R_E\) (inbound). The diamonds are the actual simulation data points, while the black curve is a cubic spline interpolation of the points. The simulated stormtime fluxes are considerably larger than the observed fluxes at \(3 \leq L \leq 4.5\) for 50 keV. In contrast, the simulated stormtime fluxes are considerably smaller than the observed fluxes at \(L \leq 5.5\) for 90, 180, and 340 keV electrons. The slot region (\(3 \leq L \leq 5\) in this particular storm) of high-energy electrons is not filled in our simulation results, while the observed slot region is filled. In fact, the simulation results show no significant stormtime enhancements for electrons at 340 keV. The discrepancies at low energies (50 keV) may result from our underestimation of the stormtime electron loss for tens of kilo electron volt electrons although our loss model generates significant loss for lower energy (~10 keV) electrons. One reason that we do not reproduce the enhancements in the slot region for high-energy electrons could be that our simple electric field model underestimates the real electric field in the slot region. In addition, some other process, such as local acceleration by plasma waves may also be responsible for the enhancements of high-energy electrons around the slot region. We discuss this issue further in section 4.

3.2. Storm Events

[25] In this section, we apply our simulations to two storm events. Meredith et al. [2001] have reported the flux changes of radiation-belt electrons during three storms with CRRES/MEA [Vampola et al., 1992] data, which covers electron energies from 153 keV to 1.582 MeV, and CRRES/LEPA [Hardy et al., 1993] data, which covers electron central energies from ~100 eV to ~20 keV. We select two of the three storms for our studies. One occurred in August 1990 while the other in October 1990. For these storm event studies, the polar-cap potential drop measured by one DMSP satellite is used to calculate the storm-associated enhancements of the cross-tail potential drop \(\Delta V(t)\) in the simulations. The \(\Delta V(t)\) is obtained by linearly interpolating the DMSP cross-polar-cap potential and subtracting an assumed quiet time convection value of 25 kV. We use the initial and boundary conditions directly obtained from CRRES data. We compared our simulation results with data measured from CRRES/MEA and CRRES/LEPA.

[26] Figure 9 presents Dst, \(K_p\), and DMSP polar-cap potential data for the August 1990 storm. The different shades of gray in the Dst trace correspond to different orbit numbers of CRRES. The solid curves are for outbound, and the dotted curves are for inbound. We will use the same shades of gray- and line-type coding in Figures 9–11. Each shade of gray corresponds to a CRRES orbit as labeled. The solid parts represent outbound, while the dotted parts correspond to inbound. We will use the same shades of gray in Figures 10 and 11.

Figure 9. Dst, \(K_p\), and polar-cap potential of August 1990 storm. The Dst trace is coded with different shades of gray. Each shade of gray corresponds to a CRRES orbit as labeled. The solid parts represent outbound, while the dotted parts correspond to inbound. We will use the same shades of gray in Figures 10 and 11.

[27] Figure 11 shows a comparison between the simulated and observed flux profiles. CRRES data from orbits 75 (solid gray curves) and 77 (solid black curves) correspond to the prestorm and post main-phase flux profiles, respectively. The simulated fluxes are compared with orbit 77 data and are plotted along the corresponding portion of CRRES orbit (black open diamonds). The black dash-dotted curves are a cubic spline interpolation of the simulated data points. For low-energy (12.3-keV) electrons, our simulation results agree well with observations. However, the observed sharp flux decrease at \(\sim 3R_E\) cannot be reproduced. We think that our electric field may be too strong in that region. We investigate this issue by comparing simulated and observed plasmapause locations since the plasmapause location is controlled by the convective electric field.
Figure 12 shows CRRES electron number density, $N_e$, and radial distance, $R$, versus universal time (UT) for orbit 77. We determine from Figure 12 that the plasmapause at that time was at $\sim 3R_E$, where CRRES also observed a sharp decrease of 12.3 keV electron flux. Figure 13 is the comparison of simulated plasmapause locations with statistical plasmapause locations based on CRRES electron number density data [Moldwin et al., 2002] at three different times during the 26 August 1990 storm. The solid curves are the separatrix of cold (0 MeV G) electrons in our model, while the dashed curves represent the plasmapause location determined by $5.39 - 0.382K_p$ (max) [Moldwin et al., 2002]. For the three times selected, the total cross-polar-cap potentials are 55, 90, and 190 kV, and $K_p = 1.7, 3.3,$ and $6.7$, respectively. We show only the nightside of the magnetosphere because both the statistical and simulated plasmapauses are symmetric about the dawn-dusk meridian. The comparison shows that our simulated plasmapause agrees well with the statistical results at the dusk side but is much closer to the Earth at the midnight and dawn side. Since the plasmapause location is strongly determined by the electric field, Figures 12 and 13 suggest that our electric field model is too strong from the midnight to dawn to noon side at $L \sim 3$.

For electrons with energies of 153, 214, and 271 keV, our simulation reproduces the observed enhancements at $\sim 3.5R_E$, although the simulated fluxes are a little bit higher than the observed ones. This could result from not including Dst effects and/or poor time resolution of our boundary conditions. Note that since the slot region was already filled before this storm, the good match we find within the slot region simply reflects the fact that slot-region enhancements did not occur.

Next we simulated the stormtime ring current electrons for the October 1990 storm. Figure 14 shows the Dst, $K_p$, and DMSP polar-cap potential of this storm. Figure 15 shows the observational data from CRRES. Enhancements of 12.3-keV electrons are observed from $\sim 3.5R_E$ to the outer boundary. The slot region ($3 \leq L \leq 5$) in high-energy electron profiles was well formed before the storm onset since there was quite a long period of quiet time before this storm. However, enhancements at $L > 3$ fill the slot at the end of the storm main phase. As shown in Figure 16, our simulated fluxes agree fairly with observed ones at $L > 4$ for low-energy electrons (12.3 keV). However, the simulated enhancements are larger than the observed enhancements at $L < 4$. One possible reason is that our loss model may
underestimate the enhanced stormtime loss rates at this energy. Again, the sharp decrease of 12.3-keV electron flux is not simulated. Simulated enhancements of 12.3 keV electrons can be seen at radial distance within 3.5 \( R_E \).

[31] For high-energy electrons (153, 214, and 271 keV), our model cannot simulate the filling of the slot region that is seen in CRRES data. This is similar to what we found in the comparison of the hypothetical storm results with the Explorer 45 data. The decreases of high-energy electron flux at \( L/2/C^2 \gtrsim 5.5 \) region cannot be reproduced either. An adiabatic response to decreasing magnetic field and some other loss processes could be responsible for this decrease. Brautigam and Albert [2000] simulated the phase-space density of high-energy electrons during the same storm using the Fokker-Planck equation. Their simulation results at CRRES orbit 186 show deeper (\( L < 4 \)) penetration of 100-MeV G^{-1} (~270 keV at \( L = 4.5 \) according to their magnetic field model) electrons. In their model they included the radial diffusion from fluctuating convection electric field.

[32] To investigate the effect of electric field fluctuation on the ring current transport, we superimpose random impulses over the linearly interpolated cross-polar-cap potential profile measured by DMSP for the October storm (Figure 1c). The solid curve in Figure 1c shows the impulsive cross-tail potential drop. The amplitudes of the impulses are generated randomly to create a Gaussian distribution with an average of the interpolated DMSP measurements (the dashed curve in Figure 1c). More details about the way in which we generate the random impulses can be found in the work of Chen et al. [1993]. The diamonds are 1-hour time averages of the impulsive potential. We performed a simulation in which the impulsive convection electric field and simulated flux profiles are compared with the CRRES flux profiles in Figure 17. With the impulsive electric field, there are significant flux enhancements at \( L \sim 3-5 \) for 153-keV electrons although the averaged magnitude of those simulated enhancements is still smaller than what CRRES observed. This shows that fluctuations in the convection electric field can help enhance the fluxes of higher-energy (~150 keV) electrons for this storm that had a main phase of \( \sim 22 \) hours. Chen et al. [1994] had found that the radial diffusion of higher-energy ring current ions could enhance the fluxes at \( L \sim 3-5 \).
for storms that had main phases that were longer than the typical convective transport times. However, for higher energies (214 and 271 keV), there are only some small enhancements in the slot region \( (L \sim 3–5) \) due to fluctuation of electric field. Larger flux enhancements occur at \( L \sim 5–5.5 \) for these energies because enhancements due to radial diffusion should have the most dramatic effect near the open-closed drift separatrix. For example, during the last 5 hours’ simulation (cross-polar-cap potential is \( \sim 150 \) kV), the separatrix of 33 MeV G\(^{-1}\) (~153 keV at \( 4R_E \)) electron is located at \( 4.3R_E \) at dawn and \( 4.9R_E \) at midnight (CRRES is at postmidnight sector at that time). However, the separatrix of 46 MeV G\(^{-1}\) (~214 keV at \( 4R_E \)) electron is at \( 4.8R_E \) at dawn and \( 5.5R_E \) at midnight. Thus the fluctuation of electric field can help ~153 keV electrons fill the slot region \( (L \sim 3–5) \) but is ineffective in enhancing radial transport of higher energies (214 and 271 keV) in that region on the timescales of the storm main phase.

4. Summary and Discussion of Simulation Results

[33] Our model reproduces qualitatively observed stormtime enhancements of 10–50 keV electrons from 2.2 to \( 6.6R_E \). That is, radial transport by enhanced convection alone can account for stormtime enhancements of electrons with these energies, although our model tends to overestimate the observed fluxes at these energies at \( \sim 3 \) to \( 4.5R_E \). This suggests that our loss model underestimates stormtime loss rates for electrons for these energies. The losses outside the plasmapause in the current paper are based on calculations for electrostatic waves, which more strongly affect

![Figure 12.](image-url) Electron number density data by CRRES and its radial distance as function of UT. The sharp decrease of electron number density occurred \( \sim 3R_E \), where observed 12.3-keV electrons also show a sharp decrease in flux.

![Figure 13.](image-url) Comparison of 0 MeV G\(^{-1}\) electron separatrix location (solid curves) and plasmapause location (dashed curves) determined by \( 5.39 - 0.382Kp \) (max) [Moldwin et al., 2002] at three different time (0200 UT, 0700 UT, and 0900 UT on 26 August 1990).
\( \leq 10 \) keV electrons \([\text{Lyons}, 1974]\) than higher-energy electrons. However, whistler-mode chorus waves, which are known to be enhanced outside the plasmapause during magnetically disturbed periods \([\text{e.g., Meredith et al., 2001}]\), can result in significant loss of electrons with energies \( \sim 10 \) to 60 keV \([\text{Horne and Thorne, 2003}]\). Thus loss due to whistler chorus should be considered in the future.

While our simulation can explain the stormtime enhancements of lower energy \((10–50 \) keV\) electrons, it cannot reproduce the filling of the slot regions \((L \sim 3–5)\) by high-energy electrons \((100–300 \) keV\). To estimate how large a cross-polar-cap potential we would need to achieve the high-energy electron enhancements in the slot region, we calculated the drift separatrix for high-energy electrons in our electric field model. Conceptually, the separatrix marks the innermost location that electrons from the plasma sheet can gain access along open trajectories. Figure 18 illustrates the separatrix locations of 33 MeV G\(^{-1}\) \((E \approx 153 \) keV at 4\(R_E\)) electrons as a function of constant storm-associated convection, \(\Delta V\). In Figure 15c, CRRES/MEA data show that 153-keV electrons have enhanced flux at \(R_0 = 4\). From Figure 15a, we can see that CRRES was between midnight and dawn at \(R_0 = 4\). Thus according to Figure 18, it requires more than a 200-kV potential drop of storm-associated convection to get enhanced fluxes of 153-keV electrons in the postmidnight region of 4\(R_E\). The corresponding electric field in the equatorial plane is \(\sim 2.3 \) mV m\(^{-1}\). A total of 225 kV \((25 V_0 + 200 \Delta V)\) of cross-polar-cap potential drop is larger than that observed by DMSP in the October storm (Figure 14c). However, our modeled electric potential has a simple spatial distribution with day-night asymmetry. In reality, an electric potential can be distributed so that we may obtain a \(\sim 2.3 \) mV m\(^{-1}\) electric field in a localized region at 4\(R_E\) with a total cross-polar-cap potential drop that is smaller than 225 kV. For instance, the electric field instrument on CRRES \([\text{Wygant et al., 1992}]\) observed dawn-to-dusk-directed electric field components as high as 10 mV m\(^{-1}\) at the region \(3 < L < 5\) during main phases of the two storm events considered here (outbound orbits 77 and 186). Another example is that \textit{Burke et al.} [1998] reported a \(\sim 2.0 \) mV m\(^{-1}\) electric field intensity near the equatorial plane at \(L = 4\) while DMSP measured \(\sim 110 \) kV cross-polar-cap potential drop for a storm. Other observations \([\text{Wygant et al., 1998; Rowland and Wygant, 1998; Anderson et al., 2001}]\) and recent simulation studies \([\text{Fok et al., 2001; Chen et al., 2003}]\) also show that the storm-associated electric field can be larger in certain MLT regions at low \(L\) values than does the simple electric field model that we have used. In highly disturbed times \((Kp > 5)\), \textit{Rowland and Wygant} [1998] reveal that the electric field intensity peaks at \(L \sim 4\) or even closer to the Earth. This may help electrons penetrate more deeply. On the other hand, realistic distribution of electric potential may also result in a weaker electric field intensity than what the simple electric field model predicts. This could explain why our simulated fluxes of low-energy \((\sim 10 \) keV\) electron have no sharp decreases at \(L \sim 3\) as observed by CRRES. Although it may be possible to achieve filling of the slot region for 153-keV electrons by using a more realistic electric field, it is less likely that convection alone can account for the filling of slot region for 214- and 271-keV electrons. The cross-polar-cap potential we need to inject them into the slot region would be unrealistically large \((\sim 300 \) kV\). Later, we intend to further investigate how much more the realistic electric field model can affect the formation of ring current.

[35] We have estimated the effect of fluctuation of electric field on stormtime ring current formation during the October 1990 storm event. We find that the fluctuating convective electric field can enhance the radial transport of 153-keV electrons to partially fill the slot region. However, the fluctuations are not so effective for enhancing fluxes of electrons with \(E > 214 \) keV at \(L \sim 3–5\).

[36] Acceleration processes via wave-particle interactions may also play an important role in producing stormtime flux enhancements of higher-energy \((E \geq 150 \) keV\) ring current electrons. \textit{Elkington et al.} [1999, 2003] reported that 1 MeV electrons at \(L = 6.6\) can have a radial diffusion rate of \(D_{\perp LL} = 4.34 \times 10^{-2} \) h\(^{-1}\) (radial diffusion scale time \(\tau_{\perp LL} = 23\) hours) by resonating with Pe-5 ULF waves. However, the timescale for such radial diffusion is expected to increase strongly with decreasing radial distance and decreasing electron energy, and thus it seems unlikely that such diffusion can account for the rapid (within several hours) filling of the slot that is shown by the observations.
Figure 15. Orbit and fluxes measured by CRRES during October 1990 storm. The flux profiles for each CRRES orbit are distinguished by the shades of gray used in Figure 14.
Figure 16. Comparison of our simulation results with observations. Black solid curves are CRRES data for orbit 186. Gray solid curves are for orbit 184. The open diamonds are our simulation data points. Black dashed-dotted curves are interpolations of the data points. Black dashed lines are our initial conditions.
presented here. Summers and Ma [2000] found that it is possible to accelerate $\sim 100$ keV electrons to $\sim 1$ MeV in several days by whistler chorus. However, the recent results by Horne and Thorne [2003] suggest that the energization by chorus at energies of 100–300 keV may have timescales of several hours, and thus should be considered as possible means for filling the slot region during the short time of a storm main phase.

[37] The observed decrease of fluxes for high-energy electrons at $L > 5$ can be explained by an adiabatic process referred to as the Dst effect [Kim and Chan, 1997]. The stormtime magnetic field intensity decreases significantly due to the injection of energetic particles. In order to keep the first invariant conserved, electrons decrease kinetic energy and move outward. Those responses result in decreases of fluxes of high-energy electrons near geosynchronous orbit. The higher the energy, the more the fluxes of electrons decrease. We plan to simulate this phenomenon in the future after we include the disturbed magnetic field by the ring current itself. Besides the Dst effect, other loss mechanisms (e.g., electron losses due to whistler waves [Horne and Thorne, 2003]) may also result in the flux decrease of high-energy electrons at $L > 5$.

Figure 17. In the same pattern of Figure 16, we show the results of simulation with electric potential described in Figure 1c.

Figure 18. The separatrix locations of 33-MeV G$^{-1}$ electrons at midnight and dawn as a function of storm-associated cross-polar-cap potential drop. Notice that total cross-polar-cap potential is the sum of quiet time potential drop, $V_0$, and storm-associated potential drop, $\Delta V$. 


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Figure 6. The simulated phase-space distributions for electrons with $\mu = 1, 3,$ and $5 \text{ MeV G}^{-1}$. The first, second, and third columns correspond to $t = 0$ (initial conditions), 6, and 9 hours. The black solid and dotted curves are trajectories, which start from diamonds to plus signs.
Figure 7. The simulated phase-space distributions for electrons with $\mu = 10$, 30, and 50 MeV G$^{-1}$. The first, second, and third columns correspond to $t = 0$ (initial conditions), 6, and 9 hours, respectively.