

1 **Self-Consistent Model of Magnetospheric Electric Field, Ring**
2 **Current, Plasmasphere, and Electromagnetic Ion Cyclotron**
3 **Waves: Initial Results**

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Abstract.

17 Further development of our self-consistent model of interacting ring current
18 (RC) ions and electromagnetic ion cyclotron (EMIC) waves is presented. This model
19 incorporates large scale magnetosphere-ionosphere coupling and treats self-consistently
20 not only EMIC waves and RC ions, but also the magnetospheric electric field, RC,
21 and plasmasphere. Initial simulations indicate that the region beyond geostationary
22 orbit should be included in the simulation of the magnetosphere-ionosphere coupling.
23 Additionally, a self-consistent description, based on first principles, of the ionospheric
24 conductance is required. These initial simulations further show that in order to model
25 the EMIC wave distribution and wave spectral properties accurately, the plasmasphere
26 should also be simulated self-consistently, since its fine structure requires as much
27 care as that of the RC. Finally, an effect of the finite time needed to reestablish a
28 new potential pattern throughout the ionosphere and to communicate between the
29 ionosphere and the equatorial magnetosphere cannot be ignored.
30

31 1. Introduction

32 Electromagnetic ion cyclotron (EMIC) waves are a common and important feature
 33 of the Earth's magnetosphere. The source of free energy for wave excitation is provided
 34 by the temperature anisotropy of ring current (RC) ions, which naturally develops during
 35 inward convection from the plasmashet. The EMIC waves have frequencies below the
 36 proton gyro-frequency, and they are excited mainly in the vicinity of the magnetic
 37 equator with a quasi field-aligned wave normal angle [*Cornwall, 1965; Kennel and*
 38 *Petschek, 1966*]. These waves were observed in the inner [*LaBelle et al., 1988; Erlandson*
 39 *and Ukhorskiy, 2001*] and outer [*Anderson et al., 1992a, 1992b*] magnetosphere, at
 40 geostationary orbit [*Young et al., 1981; Mauk, 1982*], at high latitudes [*Erlandson et al.,*
 41 *1990*], and at ionospheric altitudes [*Iyemori and Hayashi, 1989; Bräysy et al., 1998*].

42 Feedback from EMIC waves causes nonadiabatic pitch-angle scattering of the RC
 43 ions (mainly protons) and their loss to the atmosphere, which leads to the decay of RC
 44 [*Cornwall et al., 1970*]. This is especially important during the main phase of storms,
 45 when RC decay is possible with a time scale of around an hour or less [*Gonzalez et al.,*
 46 *1989*]. During the main phase of major storms RC O^+ may dominate [*Hamilton et al.,*
 47 *1988; Daglis, 1997*]. These ions cause damping of the He^+ -mode EMIC waves, which
 48 may be very important for RC evolution during the main phase of the greatest storms
 49 [*Thorne and Horne, 1994; 1997*]. Obliquely propagating EMIC waves interact well with
 50 thermal plasmaspheric electrons due to Landau resonance [*Thorne and Horne, 1992;*
 51 *Khazanov et al., 2007b*]. Subsequent transport of the dissipating wave energy into the

52 ionosphere causes an ionospheric temperature enhancement [*Gurgiolo et al.*, 2005]. This
53 wave dissipation is a mechanism proposed to explain stable auroral red arc emissions
54 present during the recovery phase of storms [*Cornwall et al.*, 1971; *Kozyra et al.*, 1997].
55 Measurements taken aboard the Prognoz satellites revealed a so-called “hot zone”
56 near the plasmapause, where a temperature of plasmaspheric ions can reach tens of
57 thousands of degrees [*Bezrukikh and Gringauz*, 1976; *Gringauz*, 1983; 1985]. Nonlinear
58 induced scattering of EMIC waves by thermal protons [*Galeev*, 1975] was used in the
59 RC-plasmasphere interaction model by *Gorbachev et al.* [1992] in order to account for
60 these observations. An extended analysis of thermal/suprathermal ion heating by EMIC
61 waves in the outer magnetosphere was presented by *Anderson and Fuselier* [1994],
62 *Fuselier and Anderson* [1996] and *Horne and Thorne* [1997]. Relativistic electrons
63 (≥ 1 MeV) in the outer radiation belt can also strongly interact with EMIC waves
64 [*Thorne and Kennel*, 1971; *Lyons and Thorne*, 1972]. Data from balloon-borne X-ray
65 instruments provides indirect but strong evidence that EMIC waves cause precipitation
66 of outer-zone relativistic electrons [*Foat et al.*, 1998; *Lorentzen et al.*, 2000]. These
67 observations stimulated theoretical and statistical studies, which demonstrated that
68 EMIC wave-induced pitch-angle diffusion of MeV electrons can operate in the strong
69 diffusion limit with a time scale of several hours to a day [*Summers and Thorne*, 2003;
70 *Albert*, 2003; *Meredith et al.*, 2003]. This scattering mechanism is now considered to
71 be one of the most important means for relativistic electron loss during the initial and
72 main phases of storm. All of the above clearly demonstrates that EMIC waves strongly
73 interact with electrons and ions of energies ranging from ~ 1 eV to ~ 10 MeV, and that

74 these waves strongly affect the dynamics of resonant RC ions, thermal electrons and
75 ions, and the outer radiation belt relativistic electrons. The effect of these interactions is
76 nonadiabatic particle heating and/or pitch-angle scattering, and loss to the atmosphere.

77 The rate of ion and electron scattering/heating in the Earth's magnetosphere is not
78 only controlled by the wave intensity-spatial-temporal distribution but also strongly
79 depends on the spectral distribution of the wave power. Unfortunately, there are still
80 very few satellite-based studies of EMIC waves, especially during the main phase of
81 magnetic storms, and currently available observational information regarding EMIC
82 wave power spectral density (mainly from the AMPTE/CCE and CRRES satellites)
83 is poor [Engebretson *et al.*, 2008]. Ideally, a combination of theoretical models and
84 available-reliable data should be utilized to obtain the power spectral density of EMIC
85 waves on a global magnetospheric scale throughout the different storm phases. To
86 the best of our knowledge, there is only one model that is able to self-consistently
87 simulate a spatial, temporal and spectral distribution of EMIC waves on a global
88 magnetospheric scale during the different storm phases [Khazanov *et al.*, 2006]. This
89 model is based on first principles, and explicitly includes the wave generation/damping,
90 propagation, refraction, reflection and tunneling in a multi-ion magnetospheric plasma.
91 The He^+ -mode EMIC wave simulations based on this model have showed that the
92 equatorial wave normal angles can be distributed in the source region, i. e. in the region
93 of small wave normal angles, and also in the entire wave region, including those near
94 90° . The occurrences of the oblique and field-aligned wave normal angle distributions
95 appear to be nearly equal with a slight dominance of oblique events [Khazanov and

96 *Gamayunov, 2007*]. This theoretical prediction is supported by a large data set of the
97 observed wave ellipticity [*Anderson et al., 1992b; Fraser and Nguyen, 2001; Meredith et*
98 *al., 2003*]. The observation of a significant number of linearly polarized events near the
99 equator suggests that waves are often highly oblique there. Using the more reliable wave
100 step polarization technique, *Anderson et al. [1996]* and *Denton et al. [1996]* analyzed
101 data from the AMPTE/CCE spacecraft, presented the first analysis of near linearly
102 polarized waves for which the polarization properties were determined. They found a
103 significant number of wave intervals with a wave normal angle $\theta > 70^\circ$, the highest θ
104 ever reported. Compared to field-aligned waves, such highly oblique wave normal angle
105 distributions can dramatically change the effectiveness (by an order of magnitude or
106 more) of both the wave-induced RC proton precipitation [*Khazanov et al., 2007b*] and
107 relativistic electron scattering [*Glauert and Horne, 2005; Khazanov and Gamayunov,*
108 *2007*]. Strong sensitivity of the scattering rates to the wave spectral characteristics,
109 and the wide distribution of EMIC wave normal angles observed in the magnetosphere,
110 suggests that in order to employ EMIC waves for heating and/or scattering of the
111 magnetospheric particles in a model, the wave spectral distribution will require special
112 care, and should be properly established.

113 The resulting EMIC wave power spectral density depends on the RC and cold
114 plasma characteristics. On the other hand, the convective patterns of both RC ions
115 and the cold plasmaspheric plasma are controlled by the magnetospheric electric field,
116 determining the conditions for the interaction of RC and EMIC waves. Therefore, this
117 electric field is one of the most crucial elements necessary to properly determine the

118 wave power spectral density. The region 2 field-aligned currents (FACs) couple the
119 magnetosphere and ionosphere. This large scale coupling determines and maintains a
120 self-consistent dynamic of the electric field and RC [*Vasyliunas, 1970; Jaggi and Wolf,*
121 *1973; Garner et al., 2004; Fok et al., 2001; Khazanov et al., 2003b; Liemohn et al.,*
122 *2004*]. A self-consistent simulation of the magnetosphere-ionosphere system should
123 provide, at least in principle, the most accurate theoretical electric field. The EMIC
124 waves resulting in the magnetosphere are not only a passive element in the coupled
125 RC-ionosphere system but also may influence the electrodynamics of coupling. During
126 storm times, the wave-induced RC proton precipitation not only changes the FAC
127 distribution, but can potentially modify the conductance and/or the neutral gas velocity
128 in the ionosphere-thermosphere system [*Galand et al., 2001; Galand and Richmond,*
129 *2001; Fang et al., 2007a, 2007b*]. Both of these characteristics are crucial elements
130 in the magnetosphere-ionosphere electrodynamics. Such wave-induced modification
131 can be especially important equatorward of the low-latitude edges of the electron and
132 proton auroral ovals where the wave-induced RC ion precipitation may be a dominant
133 energy source. In addition, electrons and protons do not interact in the same way with
134 the atmosphere. One should keep in mind that energetic protons ionize more efficiently
135 than electrons do because their energy loss for each produced electron is smaller than
136 that of energetic electrons [*Galand et al., 1999*]. Therefore, even if the proton energy
137 flux is smaller compared to the electron flux, the response of the atmosphere to protons
138 can be significant. The above arguments suggest that a self-consistent model of the
139 magnetospheric electric field, RC, plasmasphere, and EMIC waves is needed to properly

140 model wave spectral distribution and to improve the modeling of the large scale
141 magnetosphere–ionosphere electrodynamics.

142 In this study, we present a new computational model that is a result of coupling
143 two RC models developed by our group. The first model deals with the large scale
144 magnetosphere–ionosphere electrodynamic coupling and provides a self–consistent
145 description of RC ions and the magnetospheric electric field [*Liemohn et al.*, 2001;
146 *Ridley and Liemohn*, 2002; *Liemohn et al.*, 2004]. The second model is governed by a
147 coupled system of the RC kinetic equation and the wave kinetic equation. This model
148 self–consistently treats a mesoscale electrodynamic coupling of RC and EMIC waves,
149 and determines the evolution of the EMIC wave power spectral density [*Khazanov et*
150 *al.*, 2006; *Khazanov et al.*, 2007a]. The RC–EMIC wave model explicitly includes the
151 wave growth/damping, propagation, refraction, reflection, and tunneling in a multi–ion
152 magnetospheric plasma. Although RC ions and EMIC waves in the second model are
153 treated self–consistently, the electric field is externally specified. So far, the above two
154 models were used independently. As such, the main purpose of this paper is to present
155 a new self–consistent model of the magnetospheric electric field, RC, plasmasphere, and
156 EMIC waves along with initial results from the model simulations. The results presented
157 in this study were obtained from simulations of the May 2–4, 1998 geomagnetic storm,
158 that we previously analyzed using an analytical formulation of the Volland–Stern electric
159 field [*Khazanov et al.*, 2006; *Khazanov et al.*, 2007b].

160 This article is organized as follows: In section 2 we present a complete set
161 of the governing equations, and formulate the approaches used in the model

162 simulations. In the same section, we specify the initial/boundary conditions, and the
 163 interplanetary/geomagnetic characteristics, which drive our model. In section 3 the
 164 initial results from these simulations and discussion are provided. Finally, in section 4
 165 we summarize.

166 2. RC–EMIC Wave Model and Magnetosphere–Ionosphere

167 Coupling

168 2.1. Governing Equations

169 To simulate the RC dynamics we solve the bounce–averaged kinetic equation for
 170 the phase space distribution function of the major RC species (H^+ , O^+ , and He^+),
 171 as originally suggested in the models of *Fok et al.* [1993] and *Jordanova et al.* [1996].
 172 The distribution function, $F(r_0, \varphi, E, \mu_0, t)$, depends on the radial distance in the
 173 magnetic equatorial plane r_0 , geomagnetic east longitude, kinetic energy E , cosine of
 174 the equatorial pitch angle μ_0 , and time t . For the He^+ –mode EMIC waves we also
 175 use the bounce–averaged kinetic equation. This equation describes a physical model of
 176 EMIC waves bouncing between the off–equatorial magnetic latitudes, which correspond
 177 to the bi–ion hybrid frequencies in conjugate hemispheres, along with tunneling across
 178 the reflection zones and subsequent strong absorption in the ionosphere (for the
 179 observational and theoretical justifications of this model see [*Gamayunov and Khazanov,*
 180 2008; *Khazanov et al., 2007a*]). The bounce–averaged wave kinetic equation was derived
 181 in our previous paper [*Khazanov et al., 2006*], and it explicitly includes the EMIC wave

182 growth/damping, propagation, refraction, reflection, and wave tunneling in a multi-ion
 183 magnetospheric plasma. In the present study, following *Khazanov et al.* [2006], we
 184 ignore the azimuthal and radial drifts of the wave packets during propagation, we do not
 185 include the wave tunneling across the stop zone, and consequently use a truncated wave
 186 kinetic equation. The resulting system of equations to drive RC–EMIC wave coupling
 187 takes the form:

$$\begin{aligned}
 188 \quad \frac{\partial F}{\partial t} &+ \frac{1}{r_0^2} \frac{\partial}{\partial r_0} \left(r_0^2 \left\langle \frac{dr_0}{dt} \right\rangle F \right) + \frac{\partial}{\partial \varphi} \left(\left\langle \frac{d\varphi}{dt} \right\rangle F \right) \\
 189 \quad &+ \frac{1}{\sqrt{E}} \frac{\partial}{\partial E} \left(\sqrt{E} \left\langle \frac{dE}{dt} \right\rangle F \right) + \frac{1}{\mu_0 h(\mu_0)} \frac{\partial}{\partial \mu_0} \left(\mu_0 h(\mu_0) \left\langle \frac{d\mu_0}{dt} \right\rangle F \right) \\
 190 \quad &= \left\langle \left(\frac{\delta F}{\delta t} \right)_{loss} \right\rangle, \tag{1}
 \end{aligned}$$

$$191 \quad \frac{\partial B_w^2(r_0, \varphi, t, \omega, \theta_0)}{\partial t} + \langle \dot{\theta}_0 \rangle \frac{\partial B_w^2}{\partial \theta_0} = 2 \langle \gamma(r_0, \varphi, t, \omega, \theta_0) \rangle B_w^2. \tag{2}$$

193 On the left–hand side of equation (1), all the bounce–averaged drift velocities are
 194 denoted as $\langle \dots \rangle$ and may be found in many previous studies [e. g., *Khazanov et al.*,
 195 2003a]. The term on the right–hand side of this equation includes losses from charge
 196 exchange, Coulomb collisions, RC–EMIC wave scattering, and ion precipitation at low
 197 altitudes [e. g., *Khazanov et al.*, 2003a]. Loss through the dayside magnetopause is
 198 taken into account, allowing a free outflow of the RC ions from the simulation domain.
 199 In equation (2), B_w is the EMIC wave spectral magnetic field, ω and θ_0 are the wave
 200 frequency and equatorial wave normal angle, respectively, $\langle \dot{\theta}_0 \rangle$ is the bounce–averaged
 201 drift velocity of the wave normal angle, and $\langle \gamma \rangle$ is a result of averaging the local
 202 growth/damping rate along the ray phase trajectory over the entire wave bounce period.
 203 The factor $\langle \gamma \rangle$ takes into account both the wave energy source due to interaction with

204 the RC ions and the energy sink due to absorption by thermal and hot plasmas.

205 To perform bounce averaging in equation (2), the ray phase trajectory should
 206 be known, and we obtain it by solving the set of ray tracing equations. For a plane
 207 geometry these equations can be written as [e. g., *Haselgrove, 1954; Haselgrove and*
 208 *Haselgrove, 1960; Kimura, 1966; Khazanov et al., 2006]*

$$209 \quad \frac{dr}{dt} = -\frac{(\partial G/\partial \mathbf{k})_r}{\partial G/\partial \omega}, \quad (3)$$

$$210 \quad r \frac{d\lambda}{dt} = -\frac{(\partial G/\partial \mathbf{k})_\lambda}{\partial G/\partial \omega}, \quad (4)$$

$$211 \quad \frac{dk_r}{dt} = k_\lambda \frac{d\lambda}{dt} + \frac{(\partial G/\partial \mathbf{r})_r}{\partial G/\partial \omega}, \quad (5)$$

$$212 \quad \frac{dk_\lambda}{dt} = -\frac{k_\lambda}{r} \frac{dr}{dt} + \frac{(\partial G/\partial \mathbf{r})_\lambda}{\partial G/\partial \omega}. \quad (6)$$

216 In equations (3)–(6), the Earth–centered polar coordinate system is used to characterize
 217 any point P on the ray trajectory by length of the radius vector, r , and magnetic
 218 latitude, λ . Two components, k_r and k_λ , of the wave vector are given in a local Cartesian
 219 coordinate system centered on the current point P with its axes oriented along the
 220 radius vector and magnetic latitude direction, respectively. The function $G(\omega, \mathbf{k}, \mathbf{r})$ has
 221 roots for EMIC eigenmodes only, i. e., $G = 0$ at any point along the EMIC wave phase
 222 trajectories. Equations (3)–(6) are also used to obtain the off–equatorial power spectral
 223 density distribution for EMIC waves, which is needed to calculate the bounce–averaged
 224 pitch angle diffusion coefficient in the right–hand side of equation (1). (For more details
 225 about the system of equations (1)–(6) and its applicability please see our previous
 226 papers [*Khazanov et al., 2003a; Khazanov et al., 2006; Khazanov et al., 2007a*].)

227 The bounce-averaged pitch angle diffusion coefficient on the right-hand side
 228 of equation (1) is a functional form of the EMIC wave power spectral density, and
 229 $\langle \gamma(r_0, \varphi, t, \omega, \theta_0) \rangle$ in equation (2) is a functional form of the phase space distribution
 230 function. So, there is a system of coupled equations, and the entire set of equations
 231 (1)–(6) self-consistently describes the interacting RC and EMIC waves in a quasilinear
 232 approximation. Compared to our previous RC–EMIC wave studies, which are based
 233 on equations (1)–(6) only [Khazanov *et al.*, 2006; 2007b], we are now going to take
 234 into account the magnetosphere–ionosphere coupling by self-consistently treating the
 235 current closure between RC and the ionosphere.

236 *Vasyliunas* [1970] mathematically formulated a self-consistent model of the
 237 magnetosphere–ionosphere coupling by providing the basic equations governing the
 238 system. He outlined a logical chain of the model as follows: (1) the magnetospheric
 239 electric field determines the distribution of RC ions and electrons and, particularly,
 240 the total plasma pressure at any point; (2) from the plasma pressure gradients, the
 241 electric current perpendicular to the magnetic field can be calculated; (3) because the
 242 total current density should have zero divergence under magnetospheric conditions, the
 243 divergence of the perpendicular current density must be canceled by the divergence
 244 of FAC density, and so the divergence of the perpendicular current integrated along
 245 the entire field line gives the total FAC flowing into/out of the conjugate ionospheres;
 246 (4) from the requirement that FAC is closed by the horizontal ohmic currents in the
 247 ionosphere, the distribution of the electric potential in the ionosphere can be found;
 248 and (5) the ionospheric potential can be mapped back into the magnetosphere along

249 geomagnetic field lines, and the requirement that this “new” magnetospheric electric
 250 field agrees with the “initial” magnetospheric field closes the magnetosphere–ionosphere
 251 system.

252 To quantify the above logical chain, *Vasyliunas* [1970] used the following equations:

$$253 \quad \mathbf{J}_\perp(r_0, \varphi, s) = \frac{\mathbf{B}}{B^2} \times \left(\nabla P_\perp + \frac{P_\parallel - P_\perp}{B^2} (\mathbf{B} \cdot \nabla) \mathbf{B} \right), \quad (7)$$

$$254 \quad J_{\parallel,i}(\lambda(r_0), \varphi) = -B_i(\lambda(r_0), \varphi) \int_{s_S}^{s_N} \frac{\nabla \mathbf{J}_\perp}{B(r_0, \varphi, s)} ds, \quad (8)$$

$$255 \quad \nabla \mathbf{I}_i = j_{\parallel,i} \sin \chi, \quad \mathbf{I}_i = \Sigma \left(-\nabla \Phi_i + \frac{\mathbf{V}_n}{c} \times \mathbf{B}_i \right), \quad (9)$$

258 where P_\perp and P_\parallel are the total plasma pressure (we neglect the electron pressure in the
 259 current study) perpendicular and parallel to the external magnetic field \mathbf{B} , respectively,
 260 and \mathbf{J}_\perp is the perpendicular current density. The FAC density at the ionospheric level
 261 is $J_{\parallel,i}$ (positive for current flowing into the ionosphere), B_i is the magnetic field in
 262 the ionosphere, and integration in equation (8) is done along the entire magnetic field
 263 line between foot points s_S and s_N . The coordinates $(\lambda(r_0), \varphi)$ are the corresponding
 264 ionospheric latitude and MLT for the magnetic field line crossing the equatorial plane at
 265 (r_0, φ) (assuming that φ is the same at the equator and at the ionospheric altitude). In
 266 equations (9), \mathbf{I}_i and Σ are the height integrated horizontal ionospheric current density
 267 and conductivity tensor, respectively, and χ is an inclination of the magnetic field (dip
 268 angle). The electric potential at the ionosphere level is Φ_i , and \mathbf{V}_n is the velocity of the
 269 neutral gas in the ionosphere. Following many previous studies, in the present study we
 270 assume that the neutral gas corotates with the Earth and neglect the potential drop
 271 between the ionosphere and the equatorial magnetosphere [e. g., *Ebihara et al.*, 2004].

272 Finally, it should be noted that, in general, equation (9) is written for the northern and
 273 southern ionospheres with the corresponding FAC $j_{\parallel,i}$, while equation (8) gives only
 274 the total FAC flowing into/out of the conjugate ionospheres but the obvious equation
 275 $J_{\parallel,i} = j_{\parallel,i}(s_S) + j_{\parallel,i}(s_N)$ is held.

276 The set of equations (1)–(9) drives the RC, the EMIC waves, and the magnetospheric
 277 electric field in a self-consistent manner if all the initial and boundary conditions are
 278 specified and the ionospheric Hall and Pedersen conductances are known. A block
 279 diagram of the self-consistent coupling of the RC, EMIC waves, plasmasphere, and
 280 ionosphere is presented in Figure 1. The system characteristics in orange boxes are
 281 externally specified, and the dashed lines connect the model elements, which are
 282 currently not linked.

Figure 1

283 2.2. Approaches Used in Simulations

284 The geomagnetic field used in the present study is taken to be a dipole field. It is
 285 a reasonable approximation for the present study because the most important results
 286 are obtained from simulations of the May 2–3, 1998 period ($Dst = -106$ nT) when
 287 the Earth’s magnetic field is only slightly disturbed in the inner magnetosphere [e. g.,
 288 *Tsyganenko et al., 2003*]. The convection electric field is calculated self-consistently as
 289 described in subsection 2.1, and the total electric field includes both the magnetospheric
 290 convection and corotation field. The equatorial cold electron density, n_e , is obtained
 291 from the dynamic global core plasma model of *Ober et al. [1997]*. This model is basically
 292 the same as a time-dependent model of *Rasmussen et al. [1993]*, which was used in our

293 previous studies, except the Ober et al. model is linked with a self-consistent electric
 294 field obtained from the system (1)–(9), while the Rasmussen et al. model is driven by the
 295 Volland–Stern convection field [Volland, 1973; Stern, 1975] with Kp parameterization.
 296 Thus, the cold plasma density dynamics is also electrically self-consistent in our global
 297 RC–EMIC wave model. This is extremely important for a correct description of the
 298 EMIC wave generation/damping and propagation. In order to model the EMIC wave
 299 propagation and interaction with RC, we also need to know the density distribution
 300 in the meridional plane. In the present study we use a magnetic field model for the
 301 meridional density distribution, i. e., $n_e \sim B$, because a more sophisticated analytical
 302 model by Angerami and Thomas [1964] used in our previous studies [e. g., Khazanov
 303 et al., 2006] was found to give nearly the same results. The meridional model is
 304 then adjusted to the equatorial density model. So the resulting plasmaspheric model
 305 provides a 3D spatial distribution of the electron density. Besides electrons, the cold
 306 magnetospheric plasma is assumed to consist of 77% H^+ , 20% He^+ , and 3% O^+ , which
 307 are in the range of 10 – 30% for He^+ and 1 – 5% for O^+ following the observations by
 308 Young et al. [1977] and Horwitz et al. [1981]. Geocoronal neutral hydrogen number
 309 densities, needed to calculate loss due to charge exchange, are obtained from the
 310 spherically symmetric model of Chamberlain [1963] with its parameters given by Rairden
 311 et al. [1986].

312 During the main phase of major storms, RC O^+ may dominate [e. g., Hamilton et
 313 al., 1988; Daglis, 1997] and, as a result, contribute to strong damping of the He^+ –mode
 314 EMIC waves [Thorne and Horne, 1997]. Although there is no doubt that, in principle,

315 this process is important, let us evaluate the validity of excluding the He^+ -mode
 316 damping by RC O^+ in the May 2-4, 1998 storm simulation. Using the RC kinetic model
 317 of *Jordanova et al.* [1998], *Farrugia et al.* [2003] found that during the main phase
 318 of the May 4, 1998 storm the energy density of RC H^+ is greater than twice that of
 319 O^+ at all MLTs, and the contribution of He^+ to the RC energy content is negligible.
 320 This implies that the RC O^+ content does not exceed 30% during the main phase of
 321 this storm. This estimate was obtained from a global simulation, which did not include
 322 oxygen band waves. On the other hand, *Bräysy et al.* [1998] observed a very asymmetric
 323 O^+ RC during the main phase of the April 2–8, 1993 storm, which may suggest that a
 324 majority of the RC oxygen ions get lost before they reach the dusk MLT sector. This
 325 result is difficult to explain in terms of charge exchange and Coulomb scattering, and
 326 suggests that the production of EMIC waves contributes significantly to RC O^+ decay
 327 during the main and early recovery phases. In other words, due to the generation of
 328 the O^+ -mode EMIC waves, most RC O^+ might precipitate before reaching the dusk
 329 MLT sector [*Bräysy et al.*, 1998]. Therefore, to estimate the RC O^+ content correctly,
 330 the O^+ -mode should be included in the simulation, and it is likely that *Farrugia et al.*
 331 [2003] overestimated the RC O^+ content during May 4, 1998. Moreover, the calculations
 332 of *Thorne and Horne* [1997] clearly demonstrated that even the RC O^+ percentage
 333 noted above cannot significantly suppress the He^+ -mode amplification, and only slightly
 334 influences the resulting growth; inclusion of 26% O^+ in the RC population causes the
 335 net wave gain to decrease by only 20%. In addition, the most important results shown
 336 in the present study are obtained from simulations of the May 2–3, 1998 period, i. e.,

337 the first main ($Dst = -106$ nT) and recovery phases of the May 1998 large storm, when
 338 the RC O^+ content should be even smaller than the Farrugia et al. estimate for May 4,
 339 1998. It is for these reasons that we chose to exclude RC O^+ in the present simulations,
 340 and to assume that the RC is entirely comprised of energetic protons.

341 Equation (9) must be solved taking into account the contributions from both
 342 the northern and southern ionosphere. Because in the present study we assume the
 343 magnetic field lines to be equipotentials, the northern and southern ionospheres can
 344 just be replaced by an effective single ionosphere with $\Sigma = \Sigma_S + \Sigma_N$, and total FAC
 345 $J_{||,i}$ flowing into/out of it. After the resulting equation is solved, and Φ_i is found, we
 346 can easily calculate the FACs $j_{||,i}(s_S)$ and $j_{||,i}(s_N)$ flowing into/out the southern and
 347 northern ionosphere.

348 The ionospheric Hall and Pedersen conductances in our model are not calculated
 349 self-consistently but rather specified by empirical models. The resulting conductance
 350 arises from four sources: (1) direct solar extreme ultraviolet (EUV), (2) scattered solar
 351 EUV on both sides of the terminator, (3) starlight, and (4) auroral particle precipitation.
 352 The direct solar conductance is controlled by the solar zenith angle and the solar UV
 353 and EUV radiations, which correlate with the solar radio flux index $F_{10.7}$. In the present
 354 study we use the empirical model of *Moen and Brekke* [1993] for determining direct
 355 solar conductance. The scattered solar EUV and starlight conductance models are taken
 356 from the study of *Rasmussen and Schunk* [1987]. In order to specify the conductance
 357 from auroral precipitation, we use either the *Hardy et al.* [1987] statistical model or an
 358 empirical relationship between the FACs and the local Hall and Pedersen conductance

359 established by *Ridley et al.* [2001; 2004]. The Hardy et al. model is compiled from
 360 the electron precipitation patterns obtained by the DMSP satellites and gives the Hall
 361 and Pedersen conductance as a function of MLT and magnetic latitude for seven levels
 362 of activity as measured by Kp . The Ridley et al. relationship was derived using the
 363 assimilative mapping of ionospheric electrodynamics (AMIE) technique [*Richmond*
 364 *and Kamide, 1988*]. The AMIE technique was run at a one-minute cadence for the
 365 entire month of January 1997, using 154 magnetometers. This resulted in almost
 366 45000 2D maps of the Hall and Pedersen conductances and FAC. The conductance was
 367 derived from the *Ahn et al.* [1998] formulation, which relates ground-based magnetic
 368 perturbations to the Hall and Pedersen conductances. The Ridley et al. analysis showed
 369 an exponential relationship between the local FAC and the conductance [see *Amm,*
 370 *1996; Goodman, 1995*]:

$$371 \quad \Sigma = \Sigma_0 e^{-A j_{||,i}}, \quad (10)$$

372 where the constants Σ_0 and A are independent of the magnitude of $j_{||,i}$, but depend
 373 on location and whether the current is upward or downward. Although the Ridley
 374 et al. relationship is entirely empirical and not based on first principles, by using it
 375 we introduce into the model at a degree of self-consistency between the ionospheric
 376 conductance and FAC. This is a principle modification because a self-consistent
 377 description of the ionospheric conductance makes equation (9) nonlinear compared
 378 to the case of statistical conductance model. For previous use of the Ridley et al.
 379 relationship in the RC simulation see *Liemohn et al.* [2005].

380 To conclude this subsection, we note that the numerical implementations used to
 381 solve equations (1)–(6) are described in details in our previous publications [*Khazanov*
 382 *et al.*, 2003a; 2006], and to solve equation (9) a preconditioned gradient reduction
 383 resolution (GMRES) solver is used [*Ridley et al.*, 2004]. The GMRES method is robust
 384 enough to handle a wide variety of FAC and conductance patterns.

385 2.3. Initial and Boundary Conditions

386 The initial RC distribution is constructed from the statistically derived quiet time
 387 RC proton energy distribution of *Sheldon and Hamilton* [1993] and the pitch angle
 388 characteristics of *Garcia and Spjeldvik* [1985]. The night–side boundary condition
 389 for equation (1) is imposed at the geostationary distance, and it is obtained using
 390 flux measurements from the Magnetospheric Plasma Analyzer [*Bame et al.*, 1993]
 391 and the Synchronous Orbit Particle Analyzer [*Belian et al.*, 1992] instruments on the
 392 geosynchronous LANL satellites during the modeled event. Then, according to *Young et*
 393 *al.* [1982] and *Liemohn et al.* [1999], we divide the total flux measured at geostationary
 394 orbit between the RC H^+ , O^+ , and He^+ depending on geomagnetic and solar activity
 395 as measured by Kp and $F_{10.7}$ indices. Only the H^+ flux is used as a boundary condition
 396 in the simulation.

397 In the present study, the poleward boundary for equation (9) is taken at magnetic
 398 latitude $\lambda = 69^\circ$. On this boundary, we specify the electric potential using either
 399 the *Weimer* [1996] statistical model (hereinafter the W96 model), which is driven by
 400 the interplanetary magnetic field (IMF) B_Y , B_Z components and solar wind velocity,

401 or the convection model of Volland and Stern [*Volland, 1973; Stern, 1975*] with
402 *Kp* parameterization given by *Maynard and Chen [1975]* and shielding factor of 2
403 (hereinafter the VS model). The second boundary condition is specified at $\lambda = 30^\circ$, and
404 we use either the W96 model or the VS model, both of which give the potential close
405 to zero at that latitude. It should be noted that the result of calculation is insensitive
406 to the choice of the lower boundary condition, as demonstrated by *Wolf [1970]*. So, the
407 magnetospheric electric field is calculated self-consistently in the domain $30^\circ < \lambda < 69^\circ$.
408 At the same time, we should emphasize that, compared to RC, the cold electron density
409 is modeled in a more extended domain of $L \leq 10$, and in order to specify the electric
410 field in the entire $L \leq 10$ region, we use either the W96 or the VS model for the
411 magnetic latitude above $\lambda = 69^\circ$.

412 The initial RC, plasmasphere, and EMIC wave distributions are derived
413 independently and, moreover, they have nothing to do with a particular state of the
414 magnetosphere/plasmasphere system during a simulated event. Only the boundary
415 conditions provided by the LANL satellites can be considered as data reflecting a
416 particular geomagnetic situation (and, to a certain extent, the employed ionospheric
417 conductance model and an imposed cross polar cap potential drop). Therefore, before
418 the simulation of a particular geomagnetic event can occur, we first must find an
419 appropriate initial state for the RC, electric field, plasmasphere, and EMIC waves
420 that is self-consistent and reflects the particular geomagnetic situation. To obtain
421 the self-consistent initial distributions for the entire system, we first prepared the
422 plasmasphere by running the Ober model for 20 quiet days. Then, at 0000 UT on

423 1 May, 1998, a simulation of equations (1)–(10) was started using all the controlling
 424 parameters and the initial/boundary conditions along with a background noise level for
 425 the He^+ -mode EMIC waves [e. g., *Akhiezer et al.*, 1975]. We ran the model code for
 426 24 hours to achieve a quasi-self-consistent state for the system. Note that 24 hours
 427 has nothing to do with the typical time for wave amplification and instead reflects
 428 the minimum time needed to adjust the RC and waves to each other and to the real
 429 prehistory of a storm. The self-consistent modeling of the May 1998 storm period
 430 was started at 0000 UT on 2 May (24 hours after 1 May 0000 UT) using solutions of
 431 equations (1), (2), and the cold plasma distribution at 2400 UT on 1 May as the initial
 432 conditions for further simulation.

433 **2.4. Interplanetary and Geomagnetic Drivers for the Model**

434 The ionospheric boundary condition in our simulations is driven either by IMF B_Y ,
 435 B_Z components and solar wind velocity (the W96 model) or the 3-hour Kp index (the
 436 VS model). The *Hardy et al.* [1987] ionospheric conductance model is driven by Kp .
 437 All of these driving parameters are shown in Figure 2 during the May 2–4, 1998 period. Figure 2
 438 Interplanetary data are obtained from the Magnetic Field Investigation [*Lepping et al.*,
 439 1995] and the Solar Wind Experiment [*Ogilvie et al.*, 1995] instruments aboard the
 440 WIND satellite. The interplanetary configuration of May 1–5, 1998 consists of a coronal
 441 mass ejection (CME) interacting with a trailing faster stream [*Farrugia et al.*, 2003].
 442 The CME drives an interplanetary shock observed by the instruments aboard the WIND
 443 spacecraft at about 2220 UT on May 1. Three episodes of the large negative IMF B_Z

444 component were monitored. The first episode started at ~ 0330 UT on May 2 (27.5
 445 hours after May 1, 0000 UT), the second at 0230 UT on May 4 (74.5 hours after May
 446 1, 0000 UT), and the third (not shown) at ~ 0200 UT on May 5 (98 hours after May
 447 1, 0000 UT). These caused a “triple-dip” storm with the minimums $Dst = -106$ nT,
 448 $Dst = -272$ nT, and $Dst = -153$ nT (not shown). The planetary Kp index reached
 449 maximum values of $Kp \approx 7^-$ and $Kp \approx 9^-$ at the times when Dst minimums were
 450 recorded.

451 3. Results and Discussion

452 3.1. Magnetospheric Electric Field

453 The cross polar cap potential (CPCP) drop gives a rough quantitative assessment
 454 of the strength of convection in the inner magnetosphere. We calculate the CPCP drop
 455 as a difference between the maximum and minimum values of the potential at $\lambda = 67.5^\circ$
 456 (at $L \approx 7$). Results of our calculations are shown in Figure 3. The lines in red, green,
 457 and blue show results from a self-consistent simulation, while the CPCP drop shown in
 458 black is for reference purposes only. Note that the red line lies somewhat higher than
 459 the black one. This is because we do not calculate FACs between $\lambda = 69^\circ$ and $\lambda = 67.5^\circ$
 460 in the present simulations, and so there is no shielding taken into account unlike in
 461 the analytical formulation of the VS potential (black line in Figure 3). When the W96
 462 model is imposed at $\lambda = 69^\circ$, the CPCP drops are very similar for both conductivity
 463 models, and the blue line is just slightly higher than the green one. The CPCP drop

Figure 3

464 resulting from the VS model is larger during the majority of May 2–4, except for about
 465 13 hours on May 2 and 12 hours on May 4, when the CPCP drop from the W96 model
 466 is greater. It is seen that the W96 potential drop spikes to 300 kV during the main
 467 phase on May 4, whereas the VS boundary condition results in a maximum CPCP drop
 468 of only 150 kV.

469 Although the CPCP drop may serve as an overall measure of the convective
 470 strength, it does not give the morphology and strength of the electric field in the inner
 471 magnetosphere. To provide such insight, we selected six snapshots of the equatorial
 472 electric field patterns from May 2, and one snapshot at hour 77 (0500 UT on May 4).
 473 The corresponding electric potential contours are shown in Figure 4. The view is over
 474 the North Pole with local noon to the left. We present results for three runs. The
 475 equipotentials from a simulation with the VS model at the high latitude ionospheric
 476 boundary and the Hardy et al. conductance are shown in the first row. The other
 477 two runs are performed with the W96 model applied at $\lambda = 69^\circ$, and differ only by
 478 the conductance model assumed. The second row shows results for the Hardy et al.
 479 conductance model, while the third row is for a case when the Ridley et al. empirical
 480 relationship between the FAC and conductance is used. The potential configurations
 481 in Figure 4 are similar to those from the Rice Convection Model [e. g., *Garner et al.*,
 482 2004]. Overall, there are qualitatively the same large-scale potential distributions in
 483 all three models, presented in Figure 4 with a well defined large-scale dawn-to-dusk
 484 electric field. Despite this, the potential patterns reveal large differences in both the
 485 magnitude of the potential and the shape of the contours. This suggests a difference in

Figure 4

486 the fine structure of the electric field distribution since this field is proportional to the
 487 gradient of the potential.

488 One obvious feature observed in Figure 4 is a significantly enhanced electric field
 489 in the region $L \approx 3 - 4$ in the dusk–post–midnight MLT sector at hour 77 (and, not
 490 shown, at hour 76). This radially narrow intensification of the radial electric field
 491 (poleward electric field in the ionosphere) creates a westward flow channel, mainly in
 492 the dusk–to–midnight MLT sector, while a region of westward (antisunward) convection
 493 is also observed in the post–midnight sector equatorward of $L = 3$ (see Figure 4). This
 494 westward flow channel has come to be called the subauroral polarization stream (SAPS)
 495 [*Foster and Burke, 2002; Foster and Vo, 2002*]. The SAPS effect arises from the region 2
 496 FACs, which flow down into the subauroral ionosphere and close the region 1 FACs
 497 through the poleward Pedersen currents. Because of the low conductance at subauroral
 498 latitudes, the Pedersen current generates an intense poleward electric field between the
 499 region 2 FAC and the low–latitude edge of the auroral particle precipitation [*Southwood*
 500 *and Wolf, 1978; Anderson et al., 1991, 1993; Ridley and Liemohn, 2002; Mishin and*
 501 *Burke, 2005*].

502 To show the potential structure and electric field inside the SAPS region, we took
 503 two meridional cuts across the entire simulation domain and the corresponding results
 504 are shown in Figure 5. Figures 5a, b show the potential profiles on the dawn–dusk
 505 meridian for hours 33 and 77. Results for three simulations are presented along with a
 506 profile for the analytical VS model. The corresponding equatorial radial electric fields
 507 are shown in Figures 5c, d for MLT=18. Only a slight electric field intensification

Figure 5

508 (< 2.7 mV/m) is observed in the dusk sector for hour 33 (see Figure 5c), while we see
 509 an extremely developed SAPS in Figure 5d (< 13.4 mV/m). The strongest electric
 510 field intensification in Figure 5d takes place for cases when the W96 model is used
 511 in combination with either the Hardy et al. conductance model or the Ridley et al.
 512 relationship. In the latter case, we see a slightly stronger electric field in the dusk MLT
 513 sector and a developed dawnside electric field of about 5 mV/m (see Figure 5b).

514 Although the SAPS localization is correctly predicted by our model, it is likely that
 515 the SAPS electric field in Figure 5d is overestimated for the W96 boundary condition.
 516 Indeed, from the statistical model based on the electric field data measured by the
 517 Akebono/EFD instrument, *Nishimura et al.* [2007] derived the equatorial E_Y electric
 518 field component in the dusk SAPS region to be 6 mV/m during the main phase of storm.
 519 It should be noted, however, that the SAPS electric field can sometimes reach more
 520 than 10 mV/m during the main phase of geomagnetic storms [*Shinbori et al.*, 2004], and
 521 the CPCP drop derived by *Nishimura et al.* [2007] is 180 kV, whereas in our simulation
 522 it is 300 kV. The measurements taken by the double-probe electric field instrument
 523 on-board the CRRES spacecraft show a similar electric field magnitude [*Wygant et al.*,
 524 1998]. There are at least two reasons that may lead to an overestimation of the SAPS
 525 electric field in our simulations. (1) Because the W96 model was constructed from data
 526 with IMF under 10 nT, this model essentially overestimates the CPCP drop during the
 527 May 4 event when IMF was around 40 nT [e. g., *Burke et al.*, 1998]. (2) In the present
 528 simulations, we did not take into account the FACs beyond geostationary orbit, which
 529 may contribute essentially to the shielding of midlatitudes from a high latitude driving

530 convection field; the effect of FAC is proportional to the volume of the magnetic flux
 531 tube, and from the estimate by *Vasyliunas* [1972] the effect of FAC at L=6.6 is about
 532 20% of the FAC effect at L=10. Both of these issues will be addressed in future studies.

533 3.2. Plasmasphere

534 The plasmopause, and/or dayside plume, and/or detached plasma are the favorable
 535 regions for EMIC wave generation in the inner magnetosphere. This is because
 536 the density gradient there is enhanced and counteracts refraction caused by the
 537 magnetic field gradient and curvature [e. g., *Horne and Thorne, 1993; Fraser et al.,*
 538 *2005; Khazanov et al., 2006*]. As a result, the net refraction is suppressed at the
 539 plasmopause/plume edge allowing wave packets to spend more time in the phase region
 540 of amplification. Thus, the cold plasma distribution is extremely crucial for EMIC
 541 wave excitation. Both the convection and the corotation electric fields control the cold
 542 plasma dynamics. As such, we will first present the snapshots of the total electric
 543 potential obtained from our simulations. Figure 6 shows the resulting equipotential
 544 contours, that also coincide with the instantaneous cold plasma flow. The most striking
 545 reconfiguration of the potential is observed in the second and third rows in the 28 and
 546 30 hour snapshots. Referring to Figure 3, we see that starting at hour 28 the CPCP
 547 drop increases by about 100 kV during one hour for the W96 convection model. The
 548 strong convection causes a shrinking of the closed equipotential contours as shown in
 549 Figure 6 (there is stronger shrinking during hour 29). Later, an extremely developed
 550 SAPS is observed at hours 76–77 (see subsection 3.1), and the overshielding electric field

Figure 6

551 (negative E_Y) following a decrease of the CPCP difference in the W96 model is found
 552 in the inner magnetosphere at hour 79 (not shown).

553 Figure 7 shows the selected distributions of the equatorial cold plasma density for
 554 three self-consistent simulations. For each run, the plasmasphere was first prepared by
 555 running the Ober code for 20 quiet days. Then, starting at 0000 UT on 1 May, 1998,
 556 we solved the equations (1)–(10) using the initial and boundary conditions and the
 557 time series for all controlling parameters (see subsection 2.3). For the VS model (first
 558 row), a broad dayside plume is formed a few hours before hour 28. Subsequently, up to
 559 hour 39 gradual intensification of the convection (see Figures 3 and 4) causes nightside
 560 plasmaspheric erosion and the plume narrowing in the MLT extent. The latter takes
 561 place mostly in the eastward flank of the plume where the convection and corotation
 562 fields reinforce each other, while the duskside plume edge remains roughly stationary
 563 [*Spasojević et al.*, 2003; *Goldstein et al.*, 2005]. During the following storm progression,
 564 the magnetospheric convection field driven by the VS potential drop remains relatively
 565 high (see Figure 3), and the convection patterns are relatively steady (3-hour cadence).
 566 Compared to the second and third rows in Figure 7, these result in the most eroded and
 567 shrunken plasmasphere at hour 77 with a well-defined nightside plasmopause (compare
 568 these results with Figure 7 in [*Khazanov et al.*, 2006] where the entire plasmasphere was
 569 driven by the analytical formulation of the VS potential).

570 Cold plasma density distributions in the second and third rows of Figure 7 are
 571 qualitatively similar to each other, but exhibit quite a bit of difference compared to
 572 distributions in the first row. At hour 28, the plasmasphere is well-populated, and the

Figure 7

573 plasmopause is well-defined. Starting at hour 28, an increase of the CPCP drop by
 574 100 kV during one hour (see Figure 3) causes formation of the plume by hour 29 (not
 575 shown), and the presented snapshots at hour 30 are close to those at hour 29. One of the
 576 most distinguishable features observed in the second and third rows is the presence of a
 577 cold plasma on the nightside. To emphasize the existence of the recirculated detached
 578 plasma material, we show in Figure 8 the detailed plasma density evolution in the Figure 8
 579 extended domain of $L \leq 10$. It is clearly seen in Figure 8 how this recirculated detached
 580 plasma is forming and reentering the inner magnetosphere. The radial electric field for
 581 MLT=18 and 19 is also shown in Figure 9 for hours 28 and 29. The negative electric field Figure 9
 582 in the outer region in Figure 9b is resulting in plasma recirculation. However, we have
 583 to emphasize that a great care is needed to interpret these simulation results. During
 584 an extreme condition, the W96 model may predict a two-cell convection pattern with
 585 its focuses located at low latitude. The anti-sunward ionospheric plasma flow predicted
 586 by the W96 model may correspond to the lobe and the outer part of low-latitude
 587 boundary layer (LLBL) in the magnetosphere. In the dayside magnetosphere, when the
 588 plasmaspheric cold plasma is transported to LLBL, the cold plasma will flow in the
 589 anti-sunward direction [e. g., *Ober et al.*, 1998]. At the same time, reentry of the cold
 590 plasma from LLBL back to the magnetosphere may not be simple as predicted by the
 591 W96 model.

592 Although the cold plasma recirculation is seen in both the second and the third
 593 rows of Figure 7, the observed similarity is only qualitative and all the quantitative
 594 characteristics are quite different. After hour 39, the W96 CPCP drop decreased and

595 fluctuated around 50 kV except for four hours on May 4 when the CPCP drop spikes
 596 to 300 kV during the second main phase of the storm (see Figure 3). In both cases,
 597 the resulting plasmaspheres at hour 77 are extremely diffusive with shallow density
 598 gradients. This is because the anti-sunward plasma flow is especially strong during the
 599 second main phase of the storm. To demonstrate that, we show in Figure 10 the total
 600 radial electric field versus MLT for L=8, 9, and 10 at hour 77. The negative radial
 601 electric field in the afternoon-premidnight MLT sector causes a counter clockwise plasma
 602 convection. The MLT extent of the negative electric field in the afternoon-premidnight
 603 MLT sector grows with L-shell, resulting in the backward plasma flow for $MLT > 15$
 604 at L=10. This recirculation supplies the cold plasma in the nightside preventing the
 605 plasmasphere to be eroded. At the same time, as we emphasized above, a great care is
 606 needed to interpret these results.

Figure 10

607 To show the equatorial cold plasma density profiles during the periods of a
 608 well-defined and a shallow plasmopause we selected hours 33 and 77. Results of our
 609 simulations are shown in Figure 11. We see a “classical” profile of the plasmopause
 610 for hour 33, when the plasma density decreases about two orders of magnitude over
 611 $0.5 - 0.75 R_E$. The combination of the W96 model and the Ridley et al. relationship
 612 results in a detached plasma with a peak density of 20 cm^{-3} , which is clearly observed
 613 in Figure 11a (see also the third row in Figure 7). During hour 77, the plasmasphere
 614 driven by the VS CPCP drop is the most eroded and, although the plasmasphere
 615 boundary layer is wider than in Figure 11a and the plasma density drop is smaller,
 616 the plasmopause is still well-defined. For simulations with the W96 potential at the

Figure 11

617 high latitude ionospheric boundary, both density profiles shown in Figure 11b exhibit a
 618 shallow density gradient without the plasmopause while there is a clear change of the
 619 profile slope for the W96–Hardy et al. result. Note that there are also no steep density
 620 gradients outside of geostationary orbit (not shown).

621 3.3. RC Proton Precipitation

622 The convection electric field controls the global precipitating patterns of RC. As
 623 RC protons approach the Earth via the convection electric field, they precipitate into
 624 the loss cone because the equatorial loss cone angle increases with decreasing L–shell
 625 somewhat more than the equatorial pitch angle increases [e. g., *Jordanova et al.*, 1996].
 626 Note that precipitation due to Coulomb collisions with thermal plasma takes place
 627 mainly inside the plasmopause, and the wave–induced ion precipitation is organized in
 628 the radially narrow regions in the plasmasphere boundary layer [e. g., *Gurgiolo et al.*,
 629 2005; *Khazanov et al.*, 2007b]. The RC proton precipitating fluxes integrated over two
 630 energy ranges 1 – 50 keV and 50 – 400 keV are calculated as

$$631 \quad J_{lc} = \frac{1}{\Omega_{lc}} \int_{E_1}^{E_2} dE \int_{\mu_{lc}}^1 d\mu_0 j, \quad \Omega_{lc} = \int_{\mu_{lc}}^1 d\mu_0, \quad (11)$$

632 where μ_{lc} is the cosine of the equatorial pitch angle at the boundary of the loss cone,
 633 and j is the equatorial differential flux of RC protons. The snapshots of the fluxes for
 634 low and high energies are shown in Figure 12 and 13, respectively. The results from
 635 three self–consistent runs with a specified combination of the high latitude ionospheric
 636 boundary potential and conductance model are shown. For low energy, the most intense

Figure 12

13

637 precipitating fluxes near the end of the second main phase (hour 77) are observed in
 638 the second and third rows of Figure 12 when the W96 model is used. This takes place
 639 because the convection field is strongest in these two cases (see Figure 4). The spot-like
 640 spatial structure in the postnoon-midnight MLT sector is due to the wave-induced
 641 precipitation with the strongest fluxes up to $10^7 \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$.

642 The penetrating electric field driven by the W96 boundary field causes precipitation
 643 of energetic RC ions well earthward of the low energy ion precipitation. It is clearly
 644 seen in Figure 13 that the W96 boundary potential leads to a strong precipitation of
 645 the high energy ions near the inner edge of RC during the second main phase on May 4.
 646 The high energy precipitating fluxes maximize at about two times stronger magnitude
 647 than the maximal fluxes observed in the range 1 – 50 keV.

648 3.4. Energy Distribution for He^+ -Mode EMIC Waves

The coupling of the magnetosphere and ionosphere by the region 2 FACs gives a
 self-consistent description of the magnetospheric electric field. This field controls the
 convective patterns of both RC ions and the cold plasmaspheric plasma, changing the
 conditions for EMIC wave generation/amplification. The equatorial (MLT, L-shell)
 distribution of the squared wave magnetic field,

$$B_w^2(r_0, \varphi, t) = \int_{\omega_{min}}^{\omega_{max}} d\omega \int_0^\pi d\theta_0 B_w^2(r_0, \varphi, t, \omega, \theta_0),$$

649 is shown in Figure 14 for the He^+ -mode EMIC waves. As before, the results from three
 650 self-consistent simulations are presented. Comparing Figure 14 with the cold plasma

Figure 14

651 density distribution in Figure 7, we see that EMIC waves are distributed in the narrow
652 regions inside the plasmasphere boundary layer where the density gradient is enhanced.
653 Although, during hours 30–39, the spatial wave distributions in the first and second
654 rows look similar, on average, there are much more waves in a simulation with the VS
655 boundary condition than in a simulation with the W96 potential during entire May 2.
656 Moreover, there are practically no waves in the latter simulation after hour 39 (not
657 shown) while in the former case we observe the extended regions of intense waves during
658 the majority of the time up to hour 60 (not shown). This is because the plasmopause
659 is well-defined and the CPCP drop is higher in the case of the VS potential boundary
660 compared to the case of the W96 potential when the plasmasphere is highly diffusive (a
661 shallow density gradient) and RC is less intense (lower the local growth rate).

662 The density distributions in the second and third rows of Figure 7 demonstrate quite
663 a bit of difference in the after-dusk MLT sector starting at hour 33. The plasmopause
664 in the third row is located closer to the Earth, and the density gradient is shallowed
665 by the detached plasma. At the same time, we observe much less wave activity in the
666 third row of Figure 14 than in the second row. This is likely due to the effect of the
667 density distribution, because the global potential drop is even higher in the third row of
668 Figure 4 (suggesting a more intense RC) compared to the second row.

669 There are practically no waves during the second main and recovery phases,
670 except for moderate wave activity in the hour 77 snapshots in the first and third rows
671 of Figure 14. In the case of the VS–Hardy et al. combination, the plasmopause is
672 well-defined during hour 77 (see Figures 7 and 11) and waves can grow despite a less

673 intense RC in this case. On the other hand, the RC is strongly developed for the case
674 of the W96 potential, and wave growth rate is essentially higher than in the first row,
675 causing a wave generation despite the plasmasphere being extremely diffusive and the
676 density gradient being shallow.

677 3.5. Ionosphere Reconfiguration and Communication Time

678 All of the results presented above were obtained from simulations when only a
679 30 min time delay between WIND and the high latitude ionospheric boundary was
680 applied. Both the reconfiguration time needed to reestablish a new potential pattern
681 throughout the ionosphere and communication time between the ionosphere and the
682 equatorial magnetosphere were assumed to be zero. These allowed us to update the
683 equatorial electric field for each time step (a minute). However, this is not the case
684 and both the ionospheric reconfiguration time and the Alfvén propagation time are
685 essentially higher than a minute [e. g., *Ridley et al.*, 1998]. This implies that the
686 ionosphere cannot reconfigure instantly in response to change of the interplanetary
687 conditions, and that the magnetospheric electric field requires a finite time to be
688 reestablished.

689 *Ridley et al.* [1998] studied the ionospheric convection changes associated with
690 changes of the IMF. They found that the total reconfiguration time of the ionosphere is in
691 the range 3–26 min with an average of 13 min. Taking 7 min as a typical communication
692 time between the ionosphere and the equatorial magnetosphere (for example, the
693 magnetopause–ionosphere communication time is 8.4 ± 8.2 min as estimated by *Ridley*

694 *et al.* [1998]), on average, the same 13 min are needed to reestablish a new potential
 695 pattern in the magnetosphere but a 7 min delay should be applied to the ionospheric
 696 pattern. Because a great deal of scatter was reported for both time scales, below we
 697 simply adopt 20 ($= 13 + 7$) min as a time needed to reestablish a new potential pattern
 698 in the equatorial magnetosphere.

699 To assess the importance of the finite ionospheric reconfiguration and communication
 700 time effect, we reran the “W96–Hardy *et al.*” simulation. Starting at hour 24, we
 701 averaged the interplanetary parameters and FACs over a 20 min window before passing
 702 them to the ionospheric solver, and updated the equatorial electric field only once every
 703 20 min. Figure 15 shows the equatorial potential contours from this simulation along
 704 with the contours from the previous simulation, when the equatorial electric field is
 705 updated for each time step. The results during seven consecutive hours are shown
 706 (hours 35–41). The potential distributions in the first and second rows are quite a
 707 bit different suggesting that the finite ionospheric reconfiguration and communication
 708 time effect may be important, especially for the fine temporal–spatial structure of
 709 the plasmasphere–magnetosphere system. Although the “new” electric field alters the
 710 RC, wave, and cold plasma distributions, we show only the results for cold plasma
 711 density. Figure 16 demonstrates a difference in the cold plasma density distribution
 712 introduced by the effect of a finite time required to reestablish a “new” distribution
 713 of the magnetospheric electric field. Although the density distributions in these two
 714 simulations are identical at hour 24, the plasmopause/plume shapes get a visible
 715 difference in the dawn–noon MLT sector starting at hour 29 (not shown). Later, starting

Figure 15

Figure 16

716 at hour 35, an essential difference between the density distributions is observed in the
 717 night MLT sector (see Figure 16). After hour 56, the cold plasma density distributions
 718 in these two simulations are similar. This is expected after a longterm interval of system
 719 evolution, while the fine density structure still differs from time to time depending on
 720 the differences in the electric field distributions in these two simulations.

721 Although a more sophisticated methodology is required to treat and separate the
 722 effects of the finite ionospheric reconfiguration and communication time, Figures 15 and
 723 16 clearly demonstrate that the finite time effect is important, especially for the fine
 724 temporal–spatial structure of the system. This implies that the instant interplanetary
 725 parameters cannot be used in order to specify the outer ionospheric boundary condition,
 726 but rather some kind of the averaging procedure should be applied to these parameters
 727 before passing them to the ionospheric solver.

728 4. Summary

729 The scattering rate of magnetospheric RC ions and relativistic electrons by EMIC
 730 waves is not only controlled by the wave intensity–spatial–temporal distribution but
 731 strongly depends on the spectral distribution of the wave power. There is growing
 732 experimental [*Anderson et al.*, 1996; *Denton et al.*, 1996; *Anderson et al.*, 1992b; *Fraser*
 733 *and Nguyen*, 2001; *Meredith et al.*, 2003] and theoretical [*Horne and Thorne*, 1993;
 734 *Khazanov et al.*, 2006] evidence that EMIC waves can be highly oblique in the Earth’s
 735 magnetosphere. Compared to field–aligned waves, the highly oblique wave normal
 736 angle distributions can dramatically change the effectiveness (an order of magnitude

737 or more) of both the RC proton precipitation [*Khazanov et al.*, 2007b] and relativistic
738 electron scattering [*Glauert and Horne*, 2005; *Khazanov and Gamayunov*, 2007].
739 Strong sensitivity of the scattering rates to the wave spectral characteristics suggests
740 that in any effort to model EMIC wave-induced heating and/or scattering of the
741 magnetospheric particles, the wave spectral distribution requires special care and should
742 be properly established. Unfortunately, there are still very few satellite-based studies
743 of EMIC waves, especially during the main phase of magnetic storms, and currently
744 available observational information regarding EMIC wave power spectral density is poor
745 [*Engebretson et al.*, 2008]. So, a combination of comprehensive theoretical models and
746 available data should be utilized to obtain the power spectral density of EMIC waves
747 on the global magnetospheric scale throughout the different storm phases. To the best
748 of our knowledge, there is only one model that is able to simulate a spatial, temporal
749 and spectral distribution of EMIC waves on the global magnetospheric scale during the
750 different storm phases [*Khazanov et al.*, 2006]. This model is based on first principles
751 and is governed by a coupled system of the RC kinetic equation and the wave kinetic
752 equation, explicitly including the wave generation/damping, propagation, refraction,
753 reflection and tunneling in a multi-ion magnetospheric plasma.

754 The convective patterns of both the RC ions and the cold plasmaspheric plasma
755 are controlled by the magnetospheric electric field, thereby determining the conditions
756 for interaction of RC ions and EMIC waves. Therefore, this electric field is one of
757 the most crucial elements in simulating the wave power spectral density on a global
758 magnetospheric scale. Self-consistent simulation of the magnetosphere-ionosphere

759 system should provide, at least in principle, the most accurate theoretical electric
760 field [*Vasyliunas, 1970; Jaggi and Wolf, 1973*]. The need for a self-consistent model
761 of the magnetospheric electric field, RC, plasmasphere, and EMIC waves is evident.
762 In the present study we have incorporated the large scale magnetosphere-ionosphere
763 electrodynamic coupling in our previous self-consistent model of interacting RC ions
764 and EMIC waves [*Khazanov et al., 2006*]. The resulting computational model treats
765 self-consistently not only EMIC waves and RC ions but also the magnetospheric electric
766 field, RC, and plasmasphere.

767 A few runs of this new model were performed to get a qualitative assessment of
768 the effects of the high latitude ionospheric boundary condition and the ionospheric
769 conductance. The results presented in this study were obtained from simulations
770 of the May 2–4, 1998 geomagnetic storm (mostly the May 2–3 period). We have
771 performed three simulations that differ by the electric potential specified at the high
772 latitude ionospheric boundary (we used the W96 model and the VS model with Kp
773 parameterization), and/or the ionospheric conductance from auroral precipitation
774 (utilizing the Hardy et al. conductance model and the Ridley et al. relationship between
775 the FACs and the conductance). The following three combinations have been used in
776 the simulations: (1) the VS model and the Hardy et al. model; (2) the W96 model and
777 the Hardy et al. model; and (3) the W96 model and the Ridley et al. relationship. In
778 addition, one more simulation has been done: (4) the W96 model and the Hardy et
779 al. model applying a 20 min window as the time needed to reestablish a new potential
780 pattern in the magnetosphere. The RC in the present study has been simulated inside

781 geostationary orbit only, and the high latitude ionospheric boundary has been placed
782 near the ionospheric projection of this orbit. The findings from our initial consideration
783 can be summarized as follows:

784 1. Although the poleward boundary for the ionospheric potential is specified at the
785 projection of geostationary orbit in most models (probably except the Rice Convection
786 Model), we are not able to specify well the ionospheric potential there. Indeed, the
787 existing models of ionospheric electric potential (like the AMIE technique [*Richmond*
788 *and Kamide*, 1988], the *Weimer* [1996, 2001] and the *Boyle et al.*, [1997] models) are
789 much more reliable at high latitudes and give a poor representation of the potential and
790 its significant variation in the inner magnetosphere [*Foster and Vo*, 2002]. In addition,
791 the effect of FACs is proportional to the volume of the magnetic flux tube, and so
792 this effect at $L=6.6$ is about 20% of the FAC effect at $L=10$, suggesting that FACs
793 beyond geostationary orbit may produce a major shielding of midlatitudes from a high
794 latitude driving field. So the region beyond geostationary orbit should be included in
795 the magnetosphere-ionosphere coupling. An extension of the simulation domain, at least
796 to $\lambda = 72^\circ$, is vital for a truly self-consistent modeling of the magnetosphere-ionosphere
797 coupling.

798 2. Compared to the case of the Hardy et al. model, the Ridley et al. empirical
799 relationship between the FAC and conductance produces quite a bit of difference in
800 the potential distribution and, overall, stronger convection at the subauroral latitudes
801 (see Figures 4 and 5). This difference strongly affects the cold plasma distribution,
802 RC precipitation pattern, and EMIC waves (see Figures 7, 11, 12, 13, and 14). More

803 importantly, a self-consistent description of the ionospheric conductance makes equation
804 (9) nonlinear compared to the case of a statistical conductance model. This is a principle
805 point requiring that a self-consistent model, based on first principles, of the ionospheric
806 conductance should be incorporated into a simulation of the magnetosphere-ionosphere
807 coupling.

808 3. A fine density structure in the plasmasphere boundary layer, plume, detached
809 plasma etc. controls the wave propagation. This fine structure may be a more crucial
810 factor in controlling the generation of EMIC waves, than just the intensity/distribution
811 of the RC and the local plasma density. There is very large difference between the wave
812 activity in the second and third rows in Figures 14 while the density distributions in
813 the second and third rows in Figures 7 do not differ so dramatically. This suggests
814 that to model the EMIC wave distribution and wave spectral properties accurately, the
815 plasmasphere should be simulated self-consistently because its fine structure requires as
816 much care as that of the RC.

817 4. It is shown that the effect of a finite time needed to reestablish a new potential
818 pattern throughout the ionosphere and to communicate between the ionosphere and
819 the equatorial magnetosphere is important. This effect was ignored in all previous
820 simulations but it should be taken into account to model a self-consistent electric field
821 properly.

822 Concluding we would like to emphasize that in order to make significant progress
823 in developing a truly self-consistent model of the electric field, we need to considerably
824 improve our ability to accurately specify the electric field at high latitudes and

825 ionospheric conductance. Without this ability, we will not be able to accurately specify
826 EMIC wave spectra in the inner magnetosphere and correctly describe the wave-induced
827 heating and/or scattering of the magnetospheric particles.

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Figure 1. The block diagram of the RC, EMIC waves, plasmasphere, and ionosphere coupling in our model. The system characteristics in orange boxes are externally specified and the dashed lines connect the model elements that are currently not linked.

Figure 2. The interplanetary and geomagnetic characteristics during May 2–4, 1998. From the top to the bottom panels: the interplanetary magnetic field GSM B_Y and B_Z components, the solar wind velocity, 3-hour Kp index, and the measured Dst index. The hours shown are counted from 0000 UT on 1 May, 1998.

Figure 3. The cross polar cap potential drop from differently driven convection models during May 2–4, 1998. The black line, shown for reference, is the potential drop from the shielded Volland–Stern model with Kp parameterization. The red, green, and blue lines represent the self-consistent results obtained with either the VS or W96 model imposed at $\lambda = 69^\circ$, and either the Hardy et al. conductance model or the Ridley et al. empirical relationship between the FAC and conductance (see legend in the figure). In order to drive the W96 model, a 30 min time lag between WIND and the high latitude ionospheric boundary is adopted after *Farrugia et al.* [2003].

Figure 4. The equatorial potential contours in the inner magnetosphere without corotation field. The view is over the North Pole with local noon to the left. All of the indicated hours are counted from 0000 UT on 1 May, 1998. (first row) Results from a simulation with the VS model at the high latitude ionospheric boundary and the Hardy et al. conductance model. (second row) Simulation with the W96 model at $\lambda = 69^\circ$ and the Hardy et al. conductance model. (third row) The same as in the second row except that the Ridley et al. empirical relationship between the FAC and the local Hall/Pedersen conductance is used. Equipotentials are drawn every 8 kV.

Figure 5. (a, b) The potential profiles on the dawn–dusk meridian, and (c, d) the equatorial radial electric field along MLT=18 for hours 33 and 77.

Figure 6. Same as Figure 4, except that the corotation field is included.

Figure 7. The equatorial cold plasma density distributions from three self-consistent simulations. (first row) Results from a simulation with the VS model at the high latitude ionospheric boundary and the Hardy et al. conductance model. (second row) Simulation with the W96 model at $\lambda = 69^\circ$ and the Hardy et al. conductance model. (third row) The same as in the second row except that the Ridley et al. empirical relationship between the FAC and conductance is used.

Figure 8. The equatorial cold plasma density distribution in the extended domain of $L \leq 10$. The electric field is specified by the W96 model above $\lambda = 69^\circ$ but it is calculated self-consistently below this latitude using the Ridley et al. relationship between the FAC and conductance.

Figure 9. The total radial electric field (including the corotation field) in the equatorial plane. A combination of the W96 model and the Ridley et al. relationship was used to produce these results. Two profiles for MLT=18 and 19 are shown for hours 28 and 29. The positive (negative) radial electric field is considered to be parallel (antiparallel) to the radius-vector.

Figure 10. The total equatorial radial electric field versus MLT. A combination of the W96 model and the Ridley et al. relationship was used to produce these results. Three profiles for L=8, 9, and 10 are shown for hour 77. The positive (negative) radial electric field is considered to be parallel (antiparallel) to the radius-vector.

Figure 11. The equatorial cold plasma density versus L-shell for hours 33 and 77. The profiles for hour 33 are plotted along MLT=19, while the profiles for hour 77 are plotted along MLT=18.

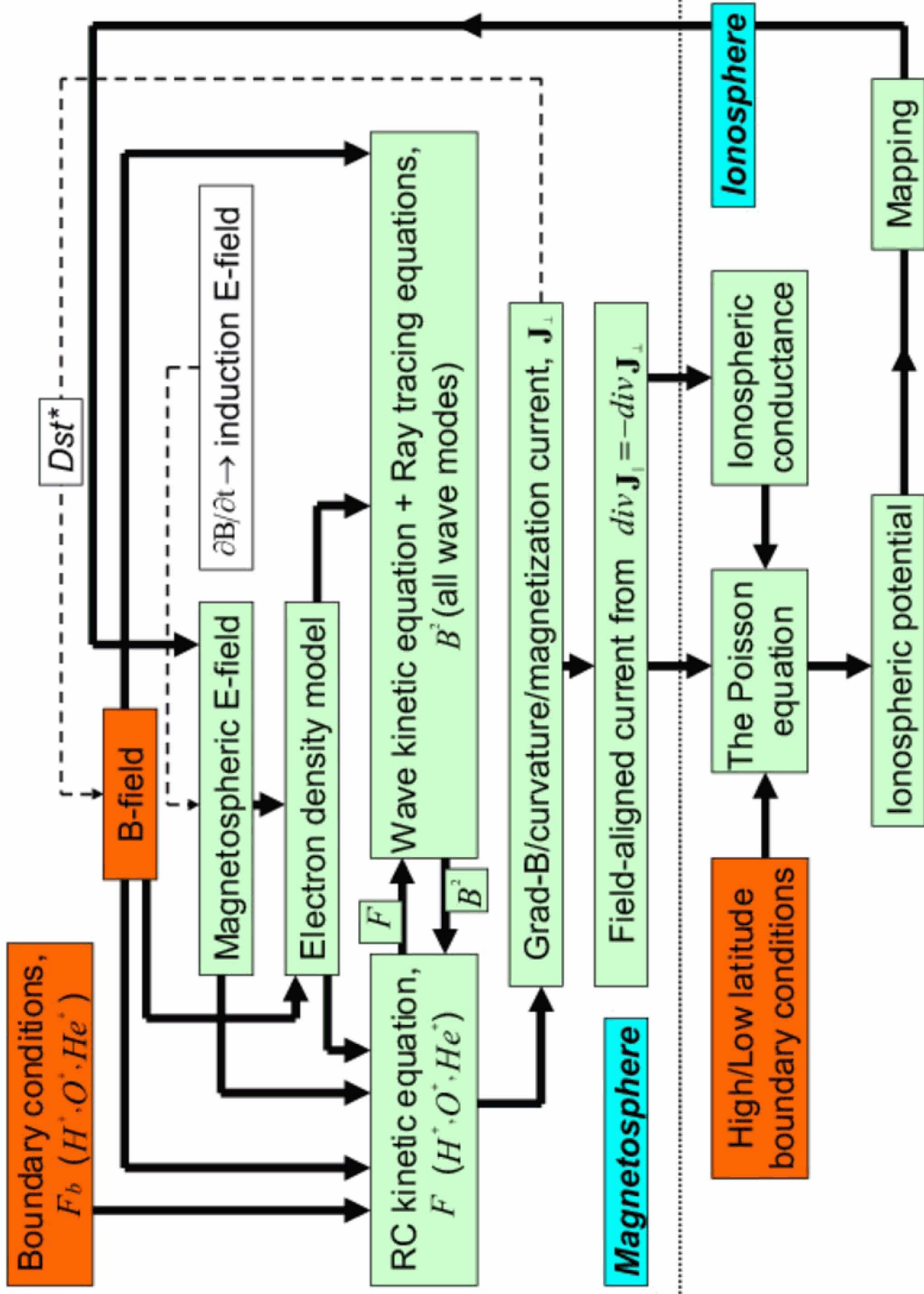
Figure 12. The RC proton precipitating fluxes averaged over the equatorial pitch-angle loss cone and integrated over the energy range 1 – 50 keV.

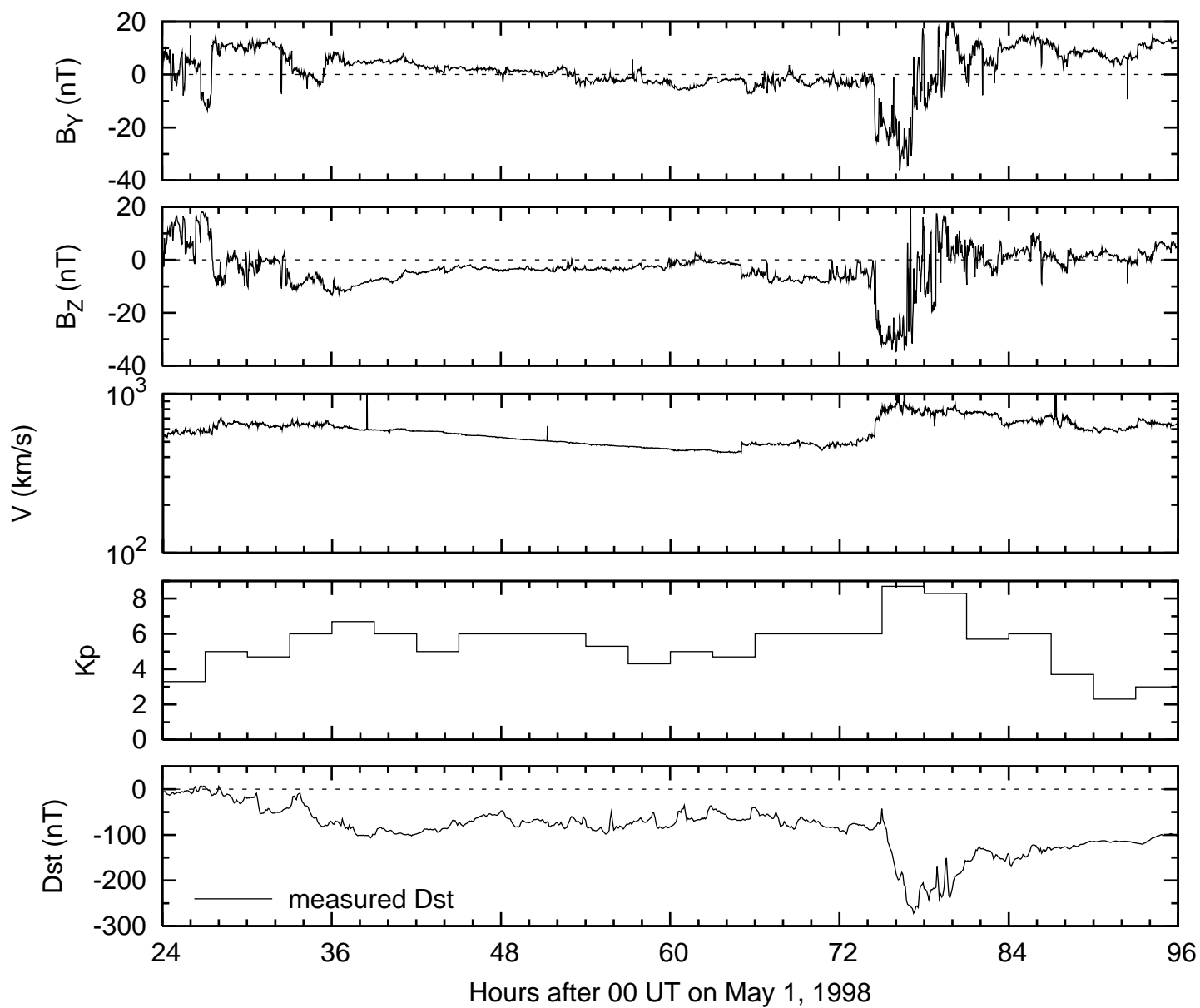
Figure 13. Same as Figure 12, except that the precipitating fluxes are integrated over the energy range 50 – 400 keV.

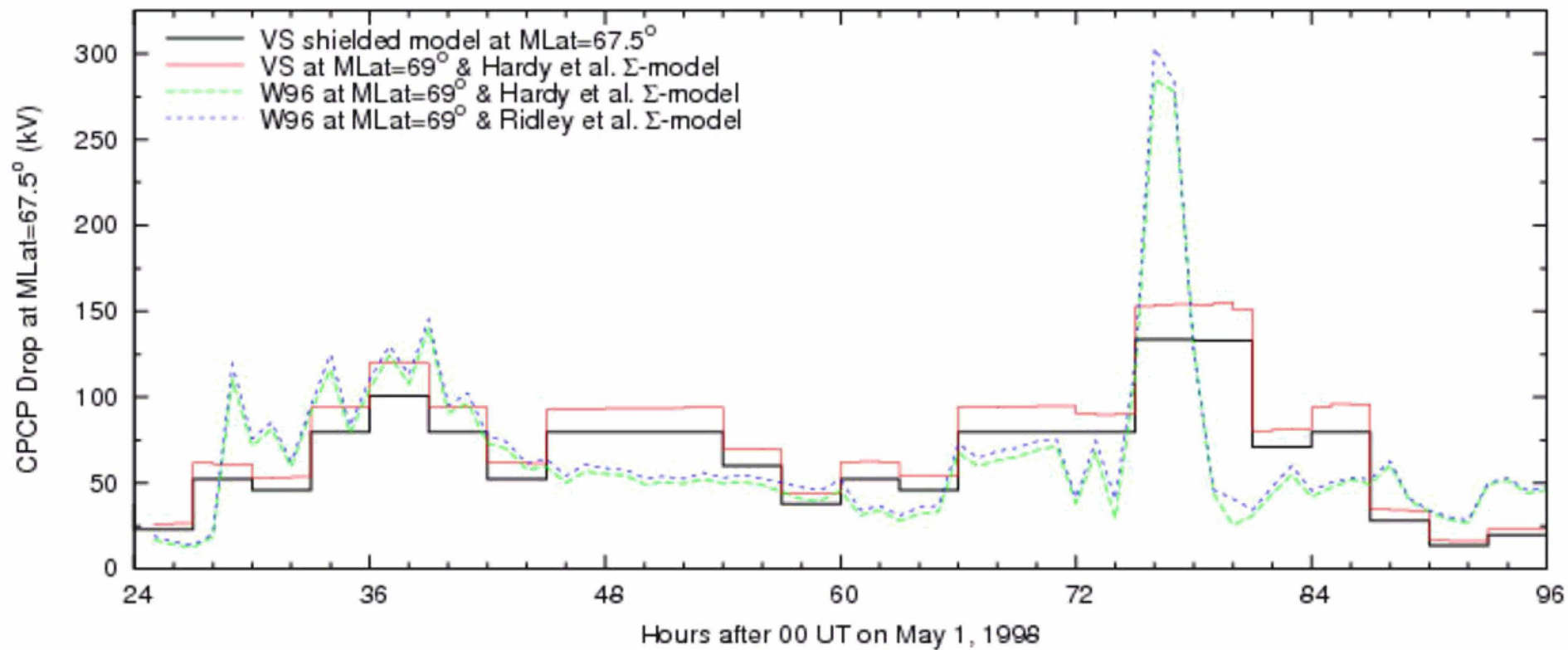
Figure 14. The distributions of squared wave magnetic field for the He^+ -mode EMIC waves. (first row) Results from a simulation with the VS model at the high latitude ionospheric boundary and the Hardy et al. conductance model. (second row) Simulation with the W96 model at the ionospheric boundary and the Hardy et al. conductance model. (third row) The same as in the second row except that the Ridley et al. empirical relationship between the FAC and conductance is used.

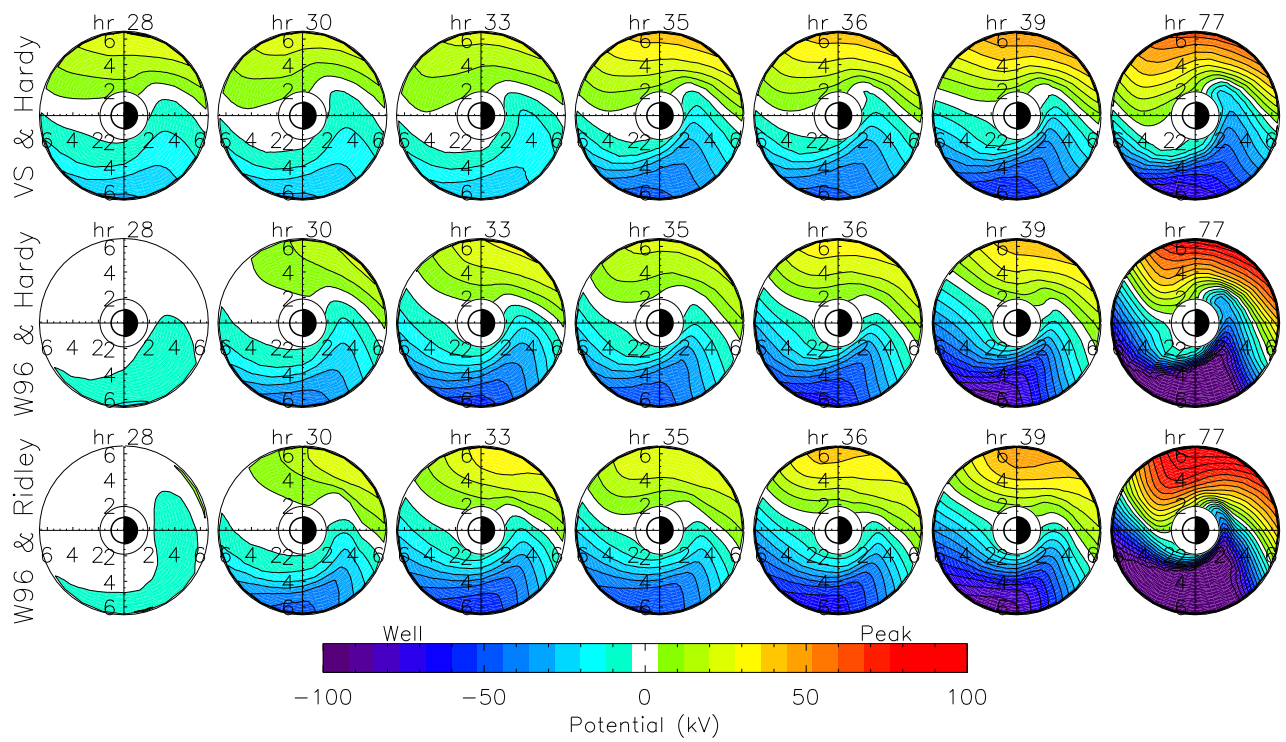
Figure 15. The equatorial potential contours in the inner magnetosphere without a corotation field. The view is over the North Pole with local noon to the left. All of the results are from simulations with the W96 potential at the high latitude ionospheric boundary and use the Hardy et al. conductance model. (first row) The magnetospheric electric field is updated each minute in accordance with the instantaneous interplanetary conditions (a 30 min time delay is applied) and FACs. (second row) The interplanetary parameters and FACs are averaged over a 20 min window prior to sending them to the ionospheric solver and the magnetospheric electric field is updated once every 20 min. Equipotentials are drawn every 8 kV.

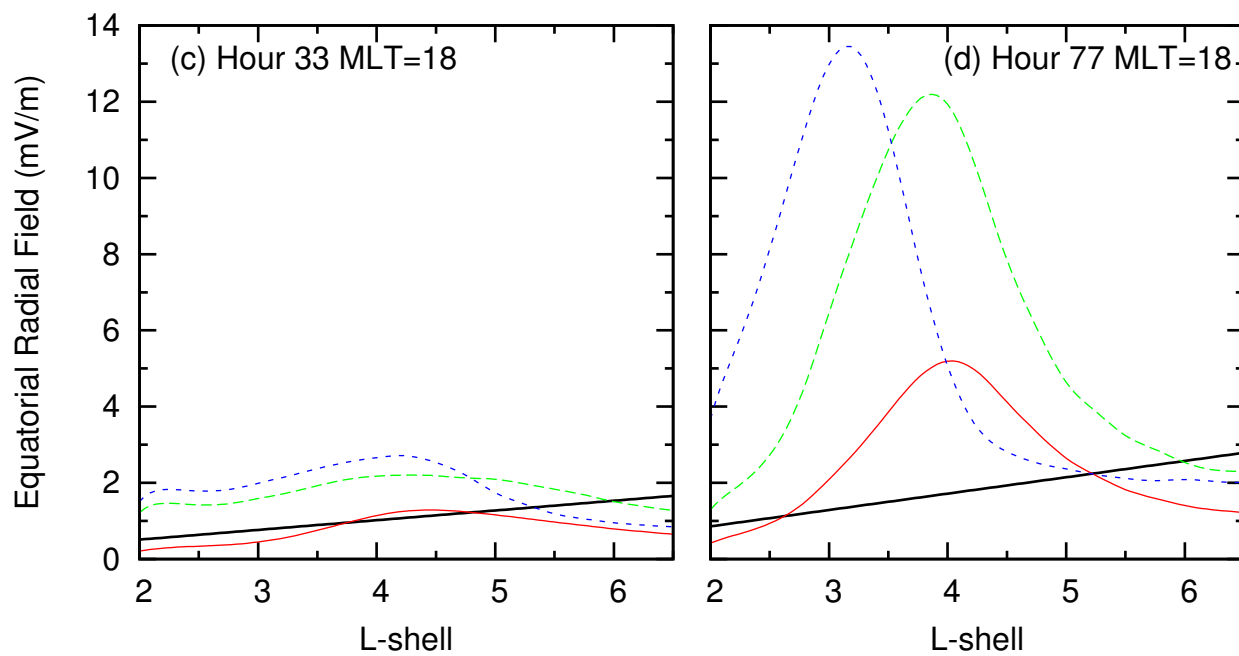
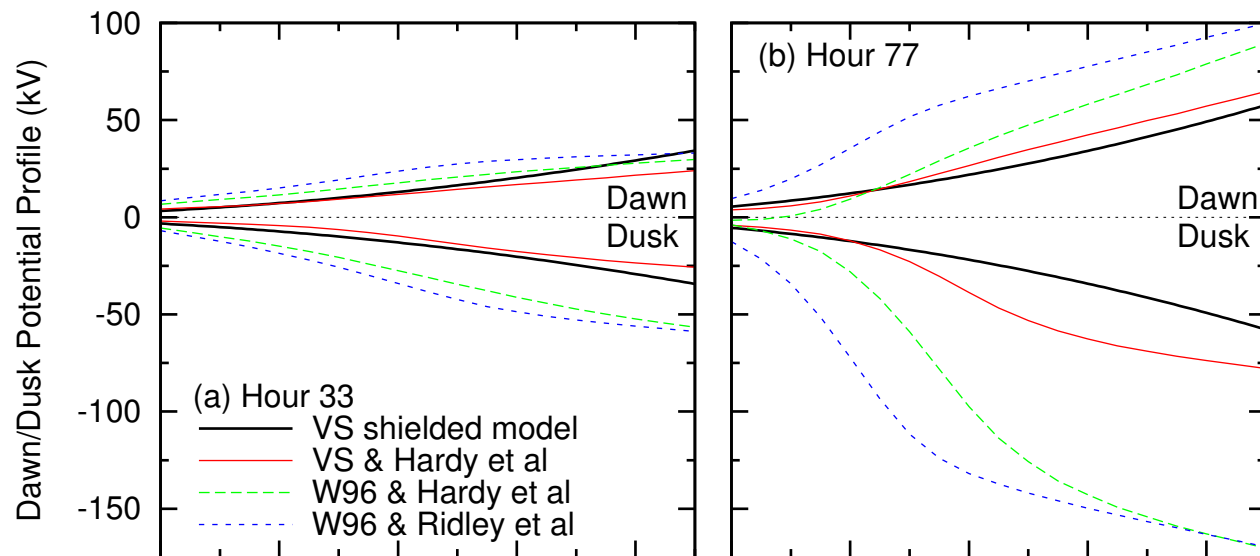
Figure 16. The equatorial cold plasma density distributions from simulations with the W96 potential at the high latitude ionospheric boundary and the Hardy et al. conductance model. (first row) The magnetospheric electric field is updated each minute accordingly to the instantaneous interplanetary conditions (with a 30 min time delay) and FACs. (second row) The interplanetary parameters and FACs are averaged over a 20 min window prior to sending them to the ionospheric solver and the magnetospheric electric field is updated once every 20 min.



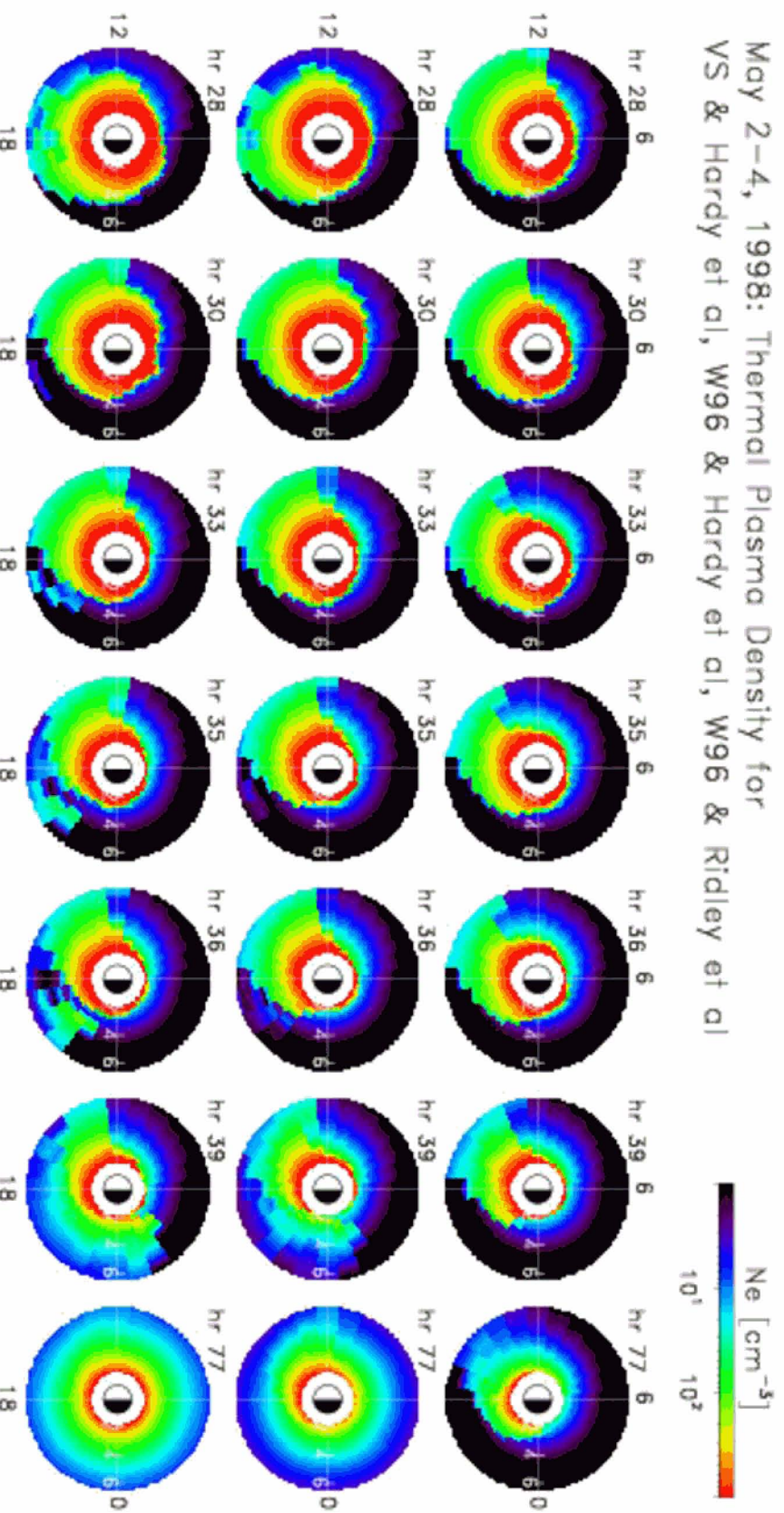


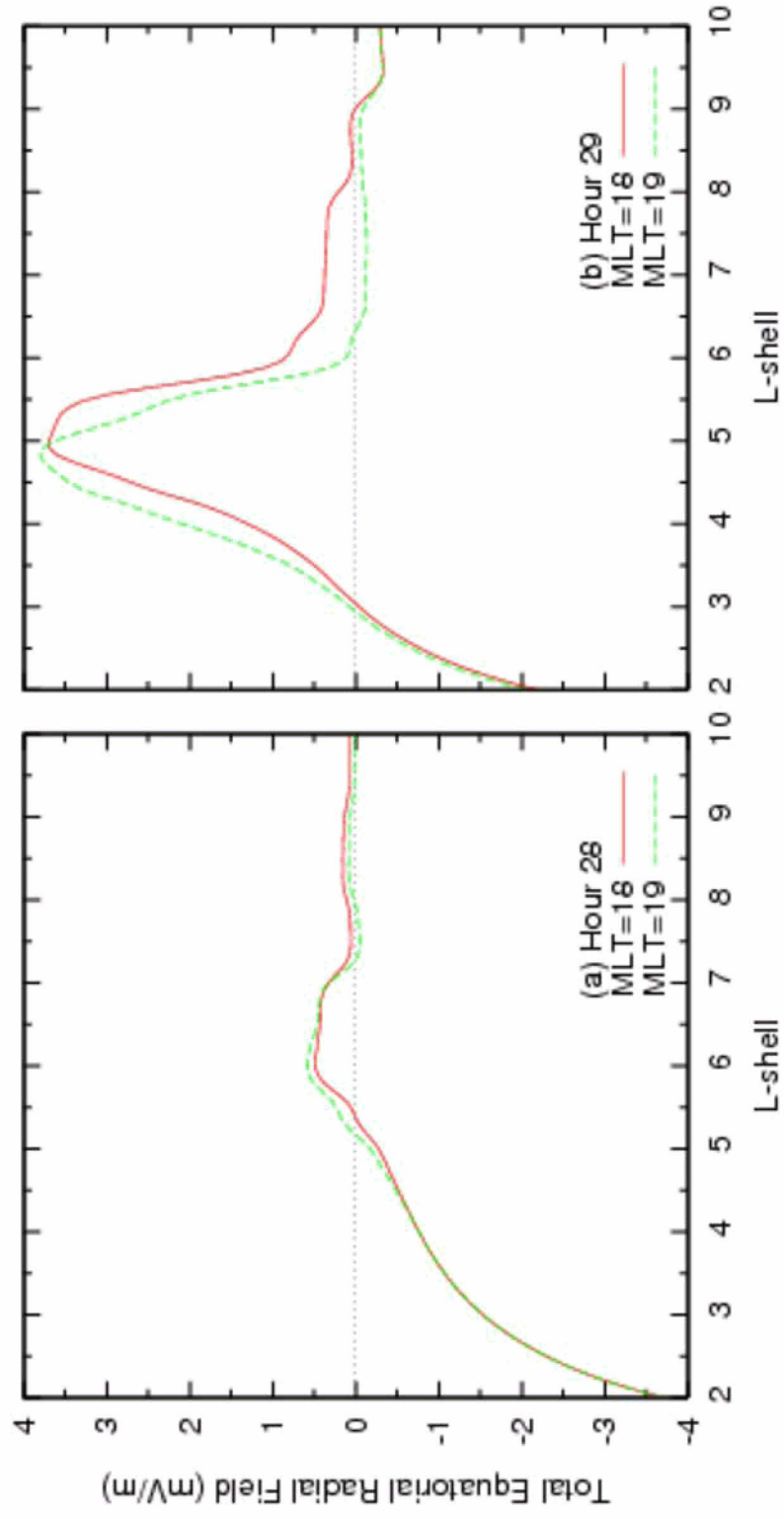


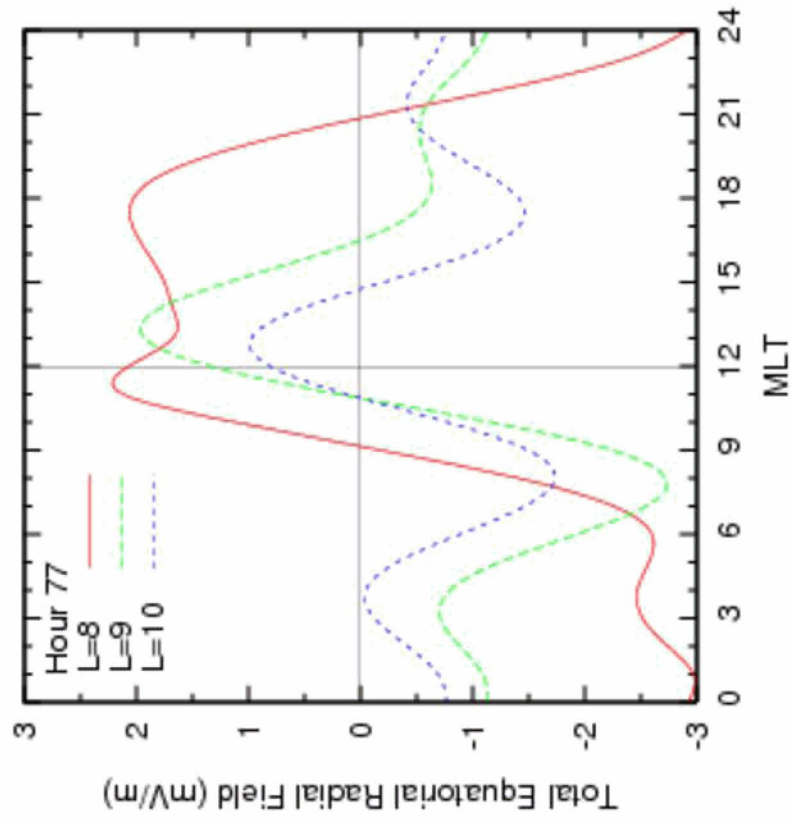




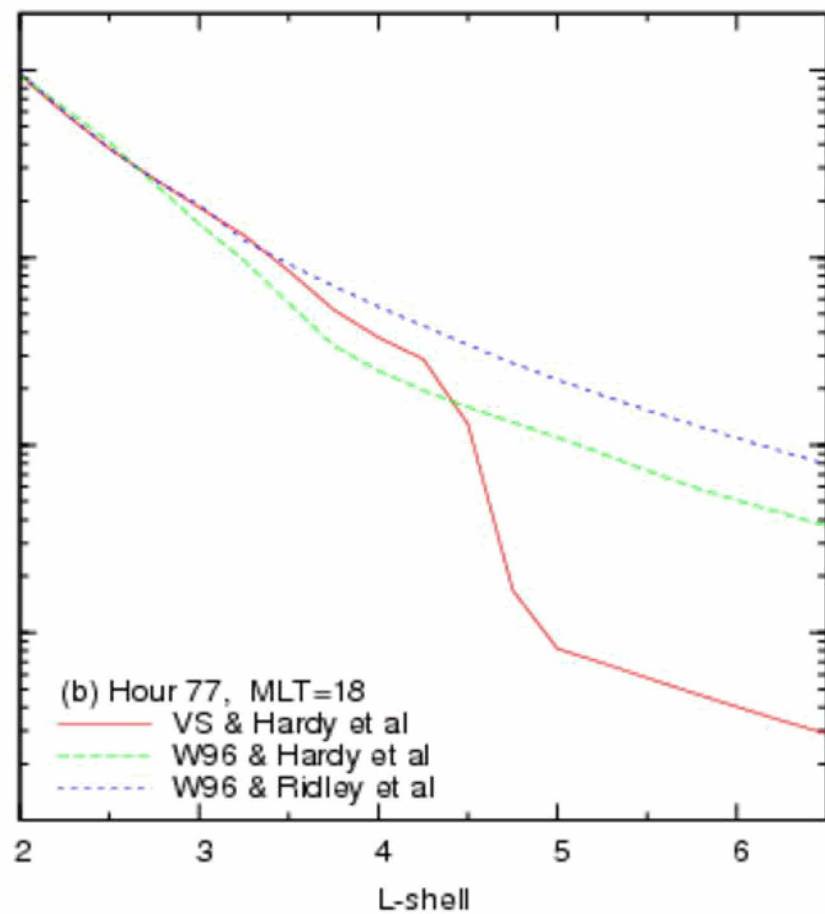
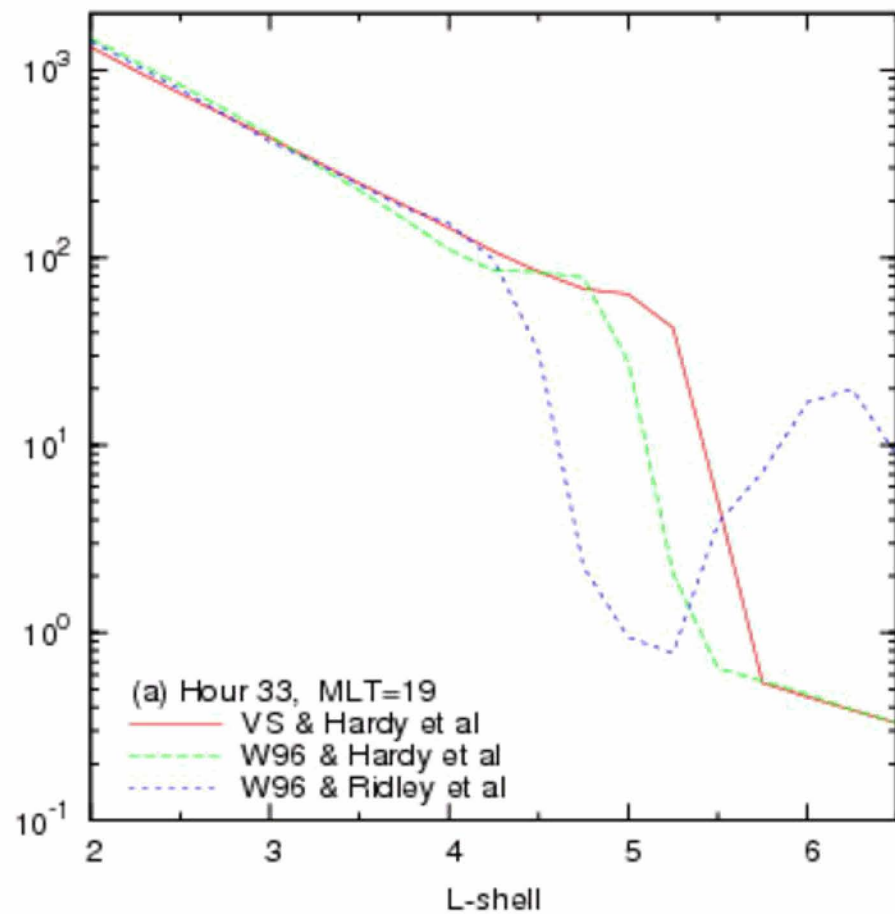
May 2-4, 1998: Thermal Plasma Density for
VS & Hardy et al, W96 & Hardy et al, W96 & Ridley et al



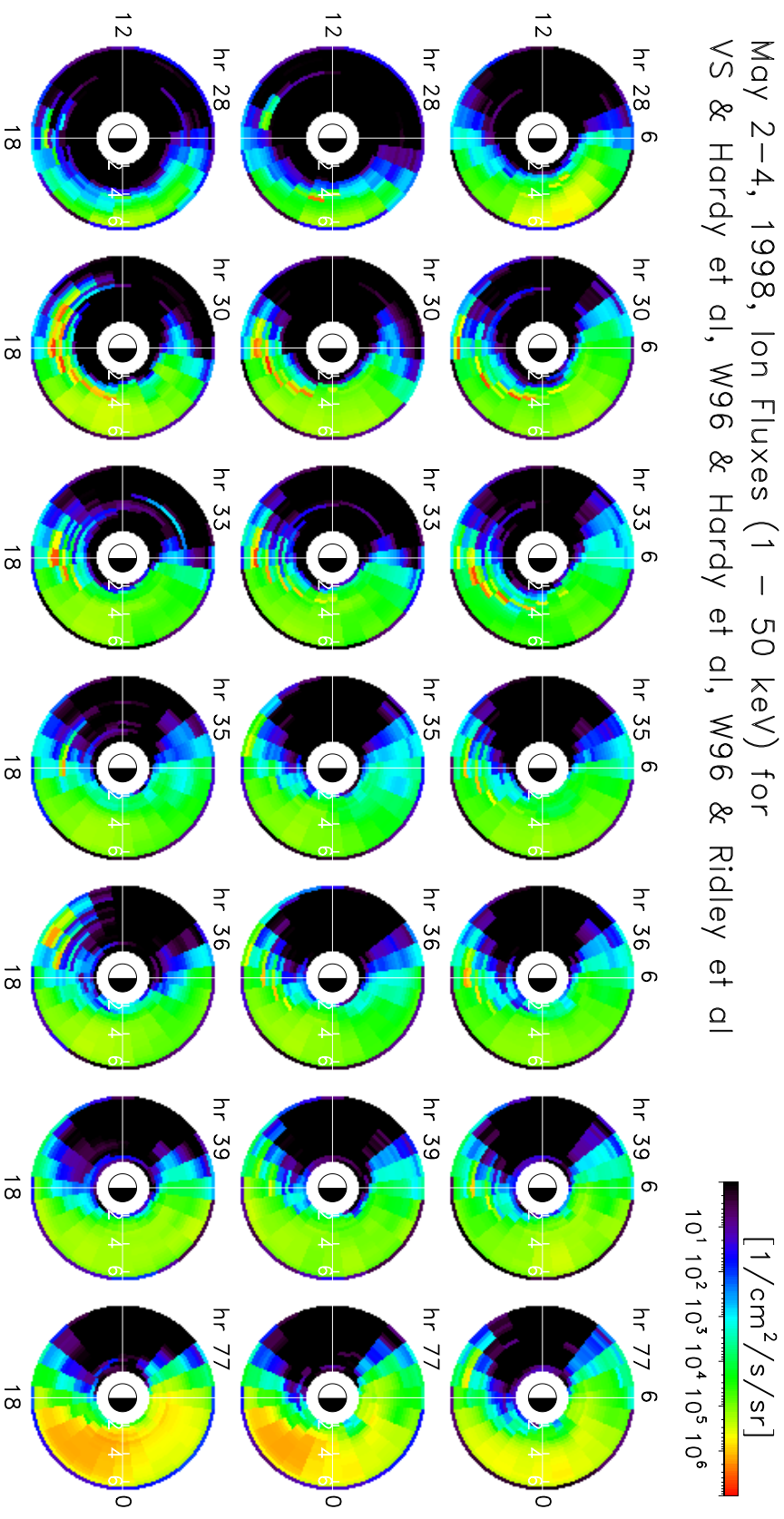




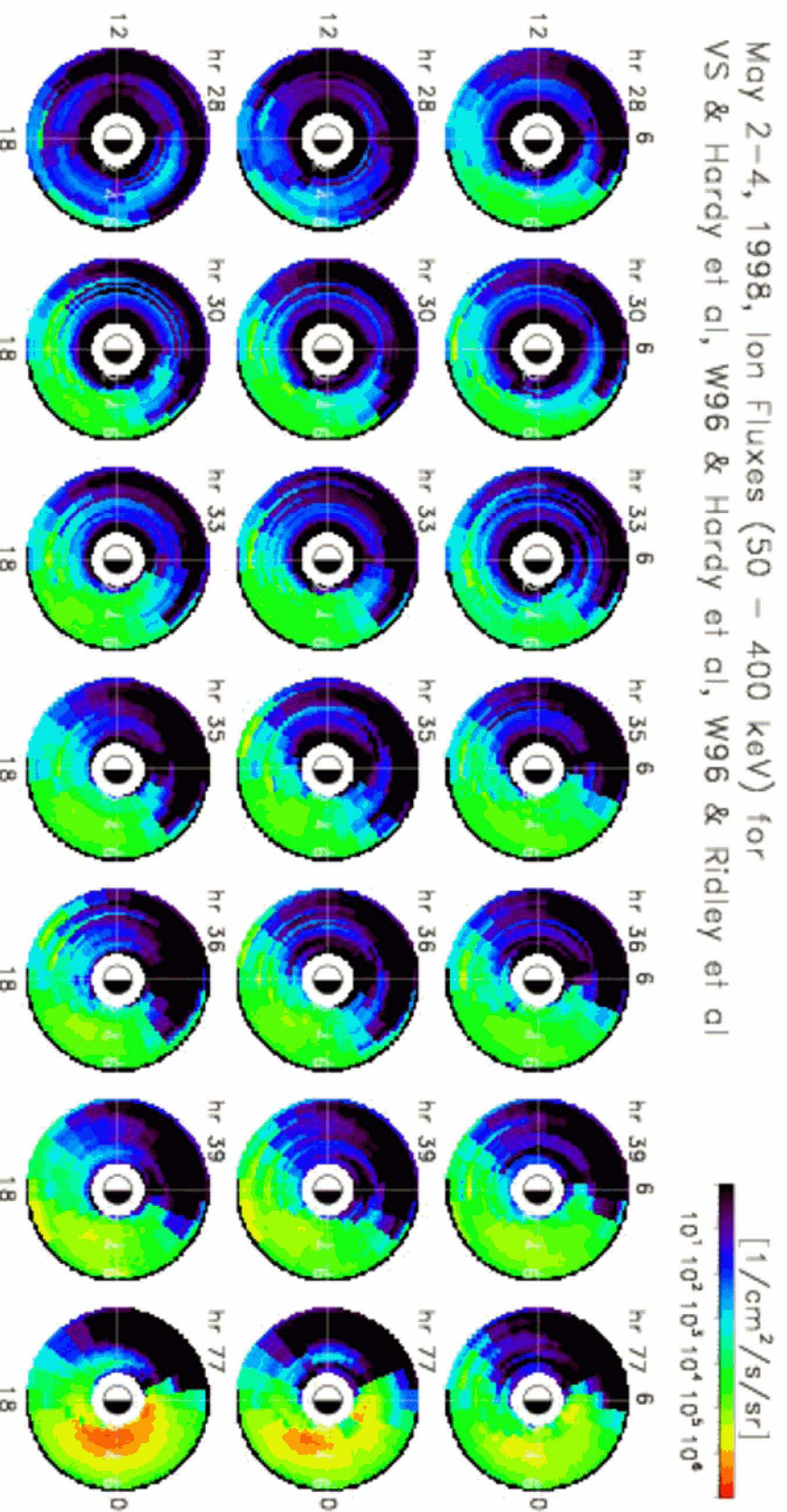
Equatorial Electron Density (cm^{-3})



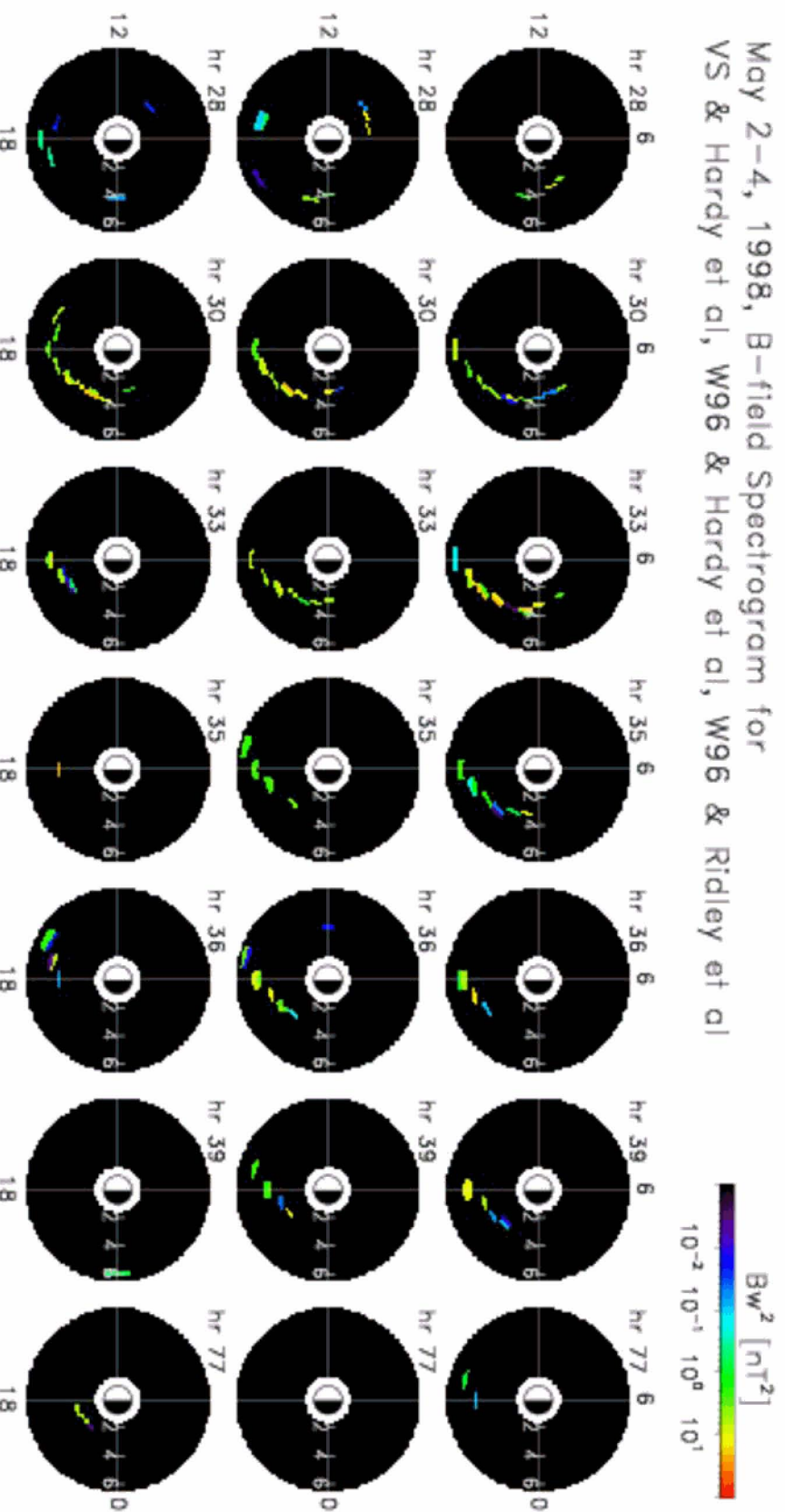
May 2–4, 1998, Ion Fluxes (1 – 50 keV) for
VS & Hardy et al, W96 & Hardy et al, W96 & Ridley et al



May 2-4, 1998, Ion Fluxes (50 - 400 keV) for
VS & Hardy et al, W96 & Hardy et al, W96 & Ridley et al



May 2-4, 1998, B-field Spectrogram for
VS & Hardy et al, W96 & Hardy et al, W96 & Ridley et al



May 2-4, 1998: Thermal Plasma Density for
Instant E-field reconfig, and 20 min reconfig time

