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Key Points:

- First self-consistent model of storm time ionosphere/ plasmasphere dynamics
- First model demonstrating connection of SED with plasmasphere plumes
- First model showing connection of TEC enhancements from middle- to high-latitude

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Storm time ionosphere and plasmasphere structuring: SAMI3-RCM simulation of the 31 March 2001 geomagnetic storm

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Abstract We present the first self-consistent modeling study of the ionosphere-plasmasphere system response to a geomagnetic storm. We use the coupled SAMI3-Rice Convention Model (RCM) of the global ionosphere and inner magnetosphere, with self-consistent electrodynamics, to simulate the 31 March 2001 magnetic storm. We find that the penetration electric fields associated with the magnetic storm lead to a storm time-enhanced density (SED) in the low- to middle-latitude ionosphere and that the separation in latitude of the Appleton anomaly peaks increases. The SED exhibits magnetic conjugacy, occurring in both the Northern and Southern Hemispheres. Moreover, mapping the boundary of the SED into the equatorial plane coincides with the development of a “plume-like” structure in the plasmasphere. These preliminary results are consistent with observations.

1. Introduction

A multitude of storm time phenomena have been observed at low-, middle-, and high latitudes as a function of the storm time, local time, and universal time (UT) that represent a complex response of the ionosphere-thermosphere-plasmasphere system to geomagnetic storms. Despite the complexity, observations indicate that the ionosphere responds to solar wind driving in several consistent ways. Among them is a prompt (within a few hours) large increase in the ionospheric Total Electron Content (TEC) at equatorial and midlatitudes [e.g., Mannucci *et al.*, 2005]. Another ionospheric response, consistently observed with incoherent radars, in situ satellite plasma probes, and global TEC maps derived from Global Positioning System (GPS) receivers, is formation of a plume or “tongue” of storm-enhanced electron density (SED) extending from middle to high latitudes [e.g., Foster, 1993, 2013]. A colocated structure in the plasmaspheric density (“plasmaspheric plume”) is often present as seen by imaging instruments [e.g., Burch *et al.*, 2001; Goldstein *et al.*, 2002] and geosynchronous satellites [Lawrence *et al.*, 1999] and is one of the indications of dramatic changes in the size and shape of the plasmasphere [Grebowsky, 1970; Burch *et al.*, 2001] during storms. An outstanding challenge that remains is identifying the sequence of physical processes that couple the ionosphere-plasmasphere system during storms [Foster *et al.*, 2002]. To this end, numerical models of the ionosphere and plasmasphere are needed that account for not only the cold plasma dynamics but the electrodynamic interaction with the magnetosphere in a self-consistent way.

In this letter we present the first self-consistent modeling study of the ionosphere/plasmasphere system in response to a geomagnetic storm. The coupled SAMI3-Rice Convention Model (RCM) is used to simulate the ionosphere-plasmasphere-ring current response to the 31 March 2001 magnetic storm. We find that a storm time-enhanced density (SED) develops in the low- to middle-latitude ionosphere and that the separation in latitude of the Appleton anomaly peaks increases during the storm. This is caused by the penetration electric field associated with the enhanced magnetospheric convection during the storm. The SED exhibits magnetic conjugacy, occurring in both the Northern and Southern Hemispheres. Finally, mapping the boundary of the SED into the equatorial plane coincides with the development of a “plume-like” structure in the plasmasphere. These findings are consistent with observations.

2. Models

The models used in this study are the National Research Laboratory (NRL) ionosphere-plasmasphere model SAMI3 [Huba *et al.*, 2000; Huba and Joyce, 2010; Huba and Krall, 2013; Krall and Huba, 2013] and the Rice

Figure 1. (a) Estimated polar cap potential (black) and SYM-H (red) as a function of time (UT), used as model inputs; (b) computed $E \times B$ drift perpendicular to the magnetic field at the magnetic equator $\theta = 0^\circ$ (red) and in the midlatitude ionosphere $\theta = 49^\circ$ (black) as a function of time (UT).

magnetosphere and of current conservation in the ionosphere [e.g., Harel *et al.*, 1981; Wolf *et al.*, 1991; Sazykin *et al.*, 2002; Toffoletto *et al.*, 2003]. The RCM modeling region in the magnetosphere typically extends close to the magnetopause on the dayside and into the middle plasma sheet ($\approx 25 R_E$) on the nightside. In this region of closed magnetic field lines, the plasma is assumed to undergo slow flow. Like SAMI3, the RCM assumes that the electric field in the ionosphere is potential (but the magnetospheric electric field includes the inductive component).

For SAMI3 to evolve the plasma, knowledge of the electric field generated by the magnetospheric convection must be specified outside the ionospheric code. The RCM, on the other hand, computes this electric field (electrostatic potential distribution) but requires knowledge of the ionospheric conductances that can only be obtained from an ionospheric model. Thus, the dominant coupling of the two models is electrodynamic—through the equation for the ionospheric electrostatic potential Φ [Huba *et al.*, 2005]

$$\nabla \cdot (\Sigma \cdot \nabla \Phi) = S(J_{\parallel}, V_n, g) \quad (1)$$

In this equation, the elements of the conductance (field line-integrated conductivity) tensor Σ are computed by SAMI3 from the ionospheric global three-dimensional solutions. The source function S contains field-aligned (Birkeland) currents $J_{\parallel}$ flowing into or out of the ionosphere [Harel *et al.*, 1981], as well as the neutral wind dynamo contributions and the gravity [Huba and Joyce, 2010]. In solving equation (1), SAMI3 provides the conductance Σ and RCM provides the high-latitude current system $J_{\parallel}$. The neutral composition and temperature are specified by NRLMSISE00 [Picone *et al.*, 2002] and the neutral winds by horizontal wind model HWM14 (D. Drob, private communication, 2014). The resulting electric field from the solution of equation (1) is then used to convect the plasma in SAMI3 and RCM. The key aspect of the coupling is that

Convection Model (RCM) [Wolf *et al.*, 1991; Toffoletto *et al.*, 2003]. SAMI3 (SAMI3 is a model of the ionosphere) is a three-dimensional, physics-based model of the ionosphere; it is based on SAMI2 [Huba *et al.*, 2000], a two-dimensional model of the ionosphere. SAMI3 models the plasma dynamics and chemical evolution of electrons and seven ion species (H^+ , He^+ , N^+ , O^+ , N_2^+ , NO^+ , and O_2^+). Ion inertia is included in the ion momentum equation for motion along the geomagnetic field. This is important in modeling the topside ionosphere and plasmasphere where the plasma transitions from collisional to collisionless. The $E \times B$ drift transports plasma transverse to the field, both “vertically” and zonally. Moreover, SAMI3 has seamless plasma transport from the geomagnetic equator to the polar regions without having to resort to different numerical formulations at low and high latitudes [e.g., Maruyama *et al.*, 2005].

The Rice Convection Model (RCM) offers a self-consistent description of the electrodynamics of the coupled inner magnetosphere-ionosphere system. The code solves the time-dependent coupled equations of plasma motion (the Vlasov equation for the bulk pressure-carrying magnetospheric plasma on closed field lines and isotropic in pitch angle) in the

Figure 2. Color-coded contours of the total electron content (TEC) and contour lines (white) of the electrostatic potential from RCM for (top) quiet and (bottom) storm time conditions. The dark black contour line is 50 TECU.

measurements and the *SYM-H* index are shown in Figure 1 during the period of the simulation study. The time dependence of the PCP is based on the models presented in *Siscoe et al.* [2002] and *Boyle et al.* [1997] and are consistent with observational results from the DMSP satellite [*Hairston et al.*, 2003]. The *SYM-H* begins to sharply decrease at 05:00 UT on day 90 (31 March 2001) and reaches a minimum at 08:00 UT. During this period the polar cap potential increases dramatically to ~ 300 kV. Figure 1b shows the $E \times B$ drift velocity perpendicular to the magnetic field at the magnetic equator $\theta = 0^\circ$ (radially upward: red) and in the mid-latitude ionosphere $\theta = 49^\circ$ (meridionally northward: black) during the same time period at local noon. At the magnetic equator the magnetic dip angle is 0° and $E \times B$ drift is upward; in the midlatitude case the dip angle is $\sim 70^\circ$ and the $E \times B$ drift is both upward and poleward. There is a significant increase in the $E \times B$ drift

rapid changes in the high-latitude current system during storm times can generate electric fields that penetrate to the low- to middle-latitude ionosphere [e.g., *Kelley et al.*, 2003]; this in turn results in significant changes in the total electron content (TEC) [*Foster*, 1993; *Mannucci et al.*, 2005] as well as the morphology of the plasmasphere [e.g., *Foster et al.*, 2002].

The geophysical parameters used in SAMI3 are $F_{10.7} = 256$, $F_{10.7A} = 172$, and $A_p = 4$. The SAMI3 ionosphere/plasmasphere ion densities are initialized with values representative of the geophysical conditions. The transients in the system relax in ≤ 8 h. SAMI3 uses the solar EUV model EUVAC [*Richards et al.*, 1994]. However, we reduced the EUV irradiance by a factor 0.75 below 400 Å because EUVAC overestimates the irradiance during solar maximum conditions as shown by *Lean et al.* [2003]. We also reduced the density of atomic O by a factor 0.93 (J. Emmert, private communication, 2014). The RCM uses the Hilmer-Voigt time-dependent magnetic field model [*Hilmer and Voigt*, 1995] and a time-varying potential on the high-latitude boundary, both estimated to vary throughout the storm interval using the NASA OMNI 5 min resolution history of solar wind and interplanetary magnetic field (IMF) parameters, as well as the *SYM-H* index. Both RCM and SAMI3 use a centered, aligned dipole magnetic field in the ionosphere.

3. Results

The time history of the cross-polar cap potential (PCP) drop estimated from the IMF and solar wind mea-

Figure 3. Plot of the (a) maximum TEC and (b) latitude of the maximum TEC in the Northern Hemisphere as a function of UT at local noon.

latitude ionosphere ($25^\circ < \theta < 60^\circ$) and peaks at $\theta \sim 20^\circ$ in the late afternoon ($\sim 16:00$ LT). Moreover, the TEC is enhanced at high latitudes ($\gtrsim 60^\circ$) in the midafternoon as the ionospheric plasma is being convected into the polar cap. This behavior is caused by the storm time penetration electric field. As shown in Figure 2 (bottom) the electrostatic potential not only intensifies in the high-latitude polar cap region but the potential extends to the equatorial region. This extension into the low- to middle-latitude ionosphere, sustained during the main phase of the storm, is responsible for the increased F region $E \times B$ drifts shown in Figure 1. (The other component of the drift velocity is also enhanced and affects plasma redistribution; here we focus on the zonal penetration electric field since it is this component that lifts the equatorial plasma and makes dramatic TEC increases.)

In Figure 3 we plot (a) the maximum TEC and (b) the latitude of the maximum TEC in the Northern Hemisphere as a function of universal time (UT) at local noon (LT 12:00). The TEC increases by $\sim 50\%$ during the storm time from 110 TECU to 165 TECU (day 90: UT 06:00). Associated with this large increase, the latitude of the peak TEC in the Northern Hemisphere increases from 10° to almost 25° so that the width of the equatorial anomaly crests more than doubles during the storm. Subsequently, the TEC relaxes to nominal levels with small increases on day 90 at 18:00 UT and day 91 at 06:00 UT which correspond to increases in the polar cap potential (see Figure 1).

We examine the relationship between structuring in the ionosphere and plasmasphere during quiet and storm times in Figures 4 (quiet) and 5 (storm). In Figures 4 (top) and 5 (top) we show color-coded contours of the electron density and contour lines of the total electrostatic potential in the magnetospheric equatorial plane (Sun is to the right). Mapping is done assuming dipolar magnetic field. The lowest level contour of the electron density is set at 30 cm^{-3} . Figures 4 (bottom) and 5 (bottom) show the global TEC (computed by integrating electron densities up to 2000 km) as well as the electrostatic potential from RCM. The contribution to the TEC from plasma above 2000 km is $\lesssim 2\%$. The black contour line in Figures 4 (bottom) and 5 (bottom) is 50 TECU; this contour level is mapped to the equatorial plane and is denoted by the red triangles in Figures 4 (top) and 5 (top). This value is chosen to match that used in Foster *et al.* [2002].

Figure 4 shows the quiet time plasmasphere and ionosphere at 15:00 UT on day 91 during the refilling phase of the plasmasphere. The equatorial electron density ($\log_{10}$) is roughly circular and is dominated

during the period of enhanced polar cap potential between 0400 UT and 0800 UT on day 90 which impacts the distribution of plasma in the low- to middle-latitude ionosphere.

The enhanced perpendicular $E \times B$ drift in the low- to middle-latitude ionosphere is associated with the zonal penetration electric field [e.g., Spiro *et al.*, 1988; Fejer *et al.*, 1990] and leads to a significant modification of the ionospheric density. This can be seen in Figure 2, which shows color-coded contours of the total electron content (TEC) and contour lines (white) of the electrostatic potential computed by the RCM. The dark black contour line is 50 TEC units ($1 \text{ TECU} = 10^6 \text{ el m}^{-2}$). Figure 2 (top) is during a quiet period (15:00 UT on day 91) and shows that the TEC is largest in the equatorial region ($\lesssim 15^\circ$), and the RCM potential is confined to the high-latitude ionosphere ($\gtrsim 60^\circ$), as expected. Figure 2 (bottom) is during the storm near the time of the peak in the polar cap potential at 06:00 UT on day 90. We note that the TEC is greatly enhanced in the mid-

Figure 4. The quiet time (top) plasmasphere and (bottom) ionosphere at 15:00 UT on day 91. Figure 4 (top) shows color-coded contours of the electron density ($\log_{10}$) and contours of the electrostatic potential. The red triangles show where the TEC = 50 TECU maps to the equatorial plane. Figure 4 (bottom) shows color-coded contours of the TEC and the black contour line is where TEC = 50 TECU.

by the corotation potential. The TEC is largest in the low-latitude ionosphere ($\theta \lesssim \pm 30^\circ$) in the day-time/early evening sector. The TEC contour level of 50 TECU maps to the equatorial plane at a distance $\lesssim 0.5 R_E$ in the morning to premidnight sector. These results are consistent with observations of the quiet time ionosphere/plasmasphere system [Huang *et al.*, 2004; Berube *et al.*, 2005; Huba and Krall, 2013].

In Figure 5 we show the model solutions at 08:00 UT on day 90 (peak of the storm main phase). Figure 5 (top) the plasmaspheric density is no longer circular in the equatorial plane: it has a pronounced plume-like structure in the afternoon sector as well as a “shoulder” in the dawn sector. Both of these features are commonly observed during storm times [e.g., Spasojević *et al.*, 2003; Goldstein *et al.*, 2005]. Additionally, the potential is no longer dominated by the corotation potential but is strongly modified by the magnetospheric convection potential. The TEC is substantially different from its quiet time morphology as shown in Figure 5 (bottom). The maximum value of the TEC has increased substantially, from 133 TECU to 206 TECU. Moreover,

Figure 5. The storm time (top) plasmasphere and (bottom) ionosphere at 08:00 UT on day 90. Figure 5 (top) shows color-coded contours of the electron density ($\log_{10}$) and contours of the electrostatic potential. The red triangles show where the TEC = 50 TECU maps to the equatorial plane. Figure 5 (bottom) shows color-coded contours of the TEC and the black contour line is where TEC = 50 TECU.

the TEC has increased in the midlatitude, afternoon sector, and a narrow plume-like structure has formed at higher latitudes ($\gtrsim \pm 60^\circ$) where the storm time convection potential has increased. This structure occurs in both the Southern and Northern Hemispheres reflecting a magnetic conjugacy effect that has been reported by *Foster and Rideout* [2007]. The TEC contour level of 50 TECU extends into the high-latitude region and demarcates the plume-like, storm time-enhanced density (SED) ionosphere structure. The contour level maps into the equatorial plane and also outlines the plasmaspheric plume structure for $R_E > 3$ and extends to $R_E \sim 6$. These results are consistent with the observations and suggested connection between ionospheric SEDs and plasmaspheric plumes reported by *Foster et al.* [2002].

4. Summary

In this letter we present the first-self consistent modeling study of a geomagnetic storm using the coupled SAMI3-RCM model. We simulate the ionosphere-plasmasphere-inner magnetosphere dynamics during one

of the largest magnetic storms (31 March 2001). We find that the storm time- and MLT-dependent penetration electric field associated with the magnetic storm leads to a storm time-enhanced density (SED) in the low- to middle-latitude ionosphere and that the separation in latitude of the Appleton anomaly peaks increases. The SED is observed to occur in both the Northern and Southern Hemispheres, exhibiting magnetic conjugacy. Moreover, mapping the boundary of the SED into the equatorial plane coincides with the development of a plume-like structure in the plasmasphere. These results are consistent with observations [Foster, 1993; Foster et al., 2002; Foster and Rideout, 2007].

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