First results using TWINS-derived ion temperature boundary conditions in CRCM

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Abstract We have integrated dynamic, spatiotemporally resolved ion temperature boundary conditions into the Comprehensive Ring Current Model (CRCM), which are based on 2-D equatorial maps derived from the Two Wide-Angle Imaging Neutral-Atom Spectrometers (TWINS) energetic neutral atom (ENA) data. The high-speed stream-driven event on 22 July 2009 is simulated and compared against an identical simulation using a statistically derived boundary condition model. ENA-derived temperatures allow users to include event-specific observations associated with a dynamic plasma sheet. This method also provides temperatures in the important region between geosynchronous orbit and the plasma sheet, a region which existing empirical models exclude. We find that the spatial and energy distributions of ion current flux and pressure have sensitive dependence on boundary conditions during this event. The coupling of boundary conditions to the time history of the convection field strength also plays an important role by throttling the influence of the boundary plasma on the inner magnetosphere. Simulated moments and spectra from our simulations are compared with remotely imaged ion temperatures from TWINS and also in situ energy spectra and temperature moments from Time History of Events and Macroscale Interactions during Substorms-D. Storm time dusk-dawn asymmetries consistent with observational data, such as Zhang et al. (2006), are reproduced well when CRCM is provided with the event-specific boundary model. A hot localized structure observed by TWINS at geosynchronous midnight during a strong northward interplanetary magnetic field interval is also reproduced with this boundary model, whereas the empirical boundary model fails to yield this feature.

1. Introduction

The plasma sheet is an important source of inner magnetospheric plasma, especially during active geomagnetic periods. Many authors have studied the connection between the state of the plasma sheet and the solar wind conditions, i.e., how the density, temperature, and pressure of the plasma sheet correlate with the state of the solar wind; see, e.g., Baumjohann et al. [1989], Borovsky et al. [1998], Tsyganenko and Mukai [2003], and Wing and Newell [1998, 2002]. Spacecraft observations indicate that the plasma sheet tends to be cold and dense during periods of prolonged northward interplanetary magnetic field (IMF) [Terasawa et al., 1997; Fairfield et al., 1981; Lennartsson, 1992]. When the IMF is southward, magnetic reconnection controls loading/unloading of the plasma sheet through the so-called Dungey cycle [Dungey, 1961], and during prolonged southward periods, the plasma sheet becomes hotter and less dense as geomagnetic activity increases [Terasawa et al., 1997; Wing and Newell, 2002]. In reality, these prolonged, steady state configurations are idealized representations of Earth’s plasma sheet, intentionally studied to shed light on simplified physical connections between the solar wind, the plasma sheet, and the inner magnetosphere. It is well-known that the solar wind-driven plasma sheet is highly dynamic during storm time and also that plasma sheet parameters exhibit strong dependence on geomagnetic activity levels. Baumjohann et al. [1989] characterized the average dependence of central plasma sheet ion temperatures on activity levels and reported that ion temperatures during active periods increase by a factor of 3–5 over those found during quiet periods. Wang et al. [2006] performed a statistical analysis using Geotail data to understand how the nightside plasma sheet structure varies under the influence of different IMF $B_z$ conditions. The $B_z$ orientation and duration are known to be the main drivers of storms, and they found that hotter nightside ion temperatures occur for shorter (longer) intervals of sustained northward (southward) $B_z$. The authors correlated dusk-dawn asymmetries with expectations from drift theory and also found that active-time plasma sheet ion temperatures increase by a factor of roughly 3–5 compared to low-activity intervals.
The spatial structure of the plasma sheet may also change on variable timescales due to substorm activity, magnetic reconnection, or dipolarizations [Ohtani, 1998; Sergeev et al., 1993]. Keese et al. [2012] used TWINS energetic neutral atom (ENA) observations to map the convection of a hot, localized structure during the main phase of the 22 July 2009 event. Those observations are apparently related to bursty bulk flows occurring in the substorm expansion phase. Large-scale magnetic reconfigurations resulting from, e.g., substorm activity are responsible for the injection of magnetic flux and plasma into the inner magnetosphere and may produce, through Faraday’s Law, intense inductive electric fields. In addition, the plasma sheet may exhibit dusk-dawn asymmetries in density and temperature [Wing and Newell, 2002; Wang et al., 2006; Keese et al., 2011 Zheng et al., 2010], further complicating the nonlinear coupling between magnetospheric regions and processes.

The underlying nonlinear coupling in magnetospheric physics presents challenges [Vasyliunas, 1970], but computational models may be used to gain insights into the fundamental physics. When performing simulations of the inner magnetosphere, it is critical to supply accurate boundary conditions since they reflect mechanisms and processes outside of the simulation domain. Models based on statistical averages of many in situ spacecraft measurements of particle distributions in the inner plasma sheet are commonly used to establish nightside boundary conditions. Thus, these models smooth out transient physics associated with phenomena including substorm processes and by-products of magnetotail reconnection. Understanding the effects caused by substorm activity or reconnection events in the storm time magnetosphere thus requires a plasma sheet boundary condition model that is tailored to a specific time frame. For simulations of a specific event, this is ideally achieved by using temporally and spatially resolved spacecraft observations for the full simulation interval. In practice, incorporating such observations into numerical simulations will be complicated by limited spacecraft coverage. This is especially the case when using in situ measurements for boundary conditions for a specific event, because of the fundamentally local nature of those measurements. Nonetheless, others have successfully used event-specific, in situ satellite measurements as boundary conditions to inner magnetospheric models in the past. Zaharia et al. [2005] used LANL MPA and SOPA data from geosynchronous orbit to supply boundary conditions for simulations of the 21–25 October 2001 event using the UNH-2D model [Jordanova et al., 1997]. The MPA/SOPA satellites are stationed at geosynchronous orbit and thus do not provide a clear picture at 8–10 Re (the Earthward edge of the plasma sheet and outer boundary in most inner magnetospheric codes), nor are MPA/SOPA data publicly available for events occurring after 2007. However, it is increasingly accepted that event-specific boundary conditions are of critical importance when performing magnetospheric simulations.

Quiet time and storm time computational studies of the inner magnetosphere have been performed in order to understand the effects of plasma sheet density and temperature on the state of the ring current. Ebihara and Ejiri [2000] found that storm time ring current buildup is insensitive to constant plasma sheet ion temperatures above 3 keV. These simulations were performed using a dipole magnetic field, a Volland-Stern convection electric field [Volland, 1973; Stern, 1974] coupled to the Boyle et al. [1997] polar cap potential, and used solar wind data provided by Wind as the model inputs. Rice convection model (RCM) simulations discussed by Garner [2003] improve on the Ebihara and Ejiri [2000] model by including a more realistic magnetic field model [Hilmer and Voigt, 1995] and a self-consistent electric field. Garner found that more intense electric shielding and stronger Region 2 currents are found when colder temperatures are provided as the plasma sheet boundary condition. Cold ion populations in the plasma sheet are dominated by the Earthward \( \vec{E} \times \vec{B} \) drift since virtually no particles in the population have high enough energy to experience substantial gradient-curvature drift. A hotter population, however, has a larger relative fraction of higher-energy ions and thus fewer ions penetrate to lower L shells, resulting in a relative decrease in pressure at low L values. This results in a weaker shielding field, a weaker ring current, and a more diffuse pressure distribution in the ring current. It is reasonable to expect that including spatial variation in the ion temperature boundary conditions would modify the azimuthal and radial structure of the ring current, the global electric field, and the distribution of energy in the inner magnetosphere.

Chen et al. [2007] presented results from magnetically self-consistent drift-loss ring current simulations using ion temperature boundary conditions determined from time-averaged Geotail measurements for two separate cases. In both cases (a cold, dense case and a hot, tenuous case), the simulations focus on ring current preconditioning, i.e., the first few hours of the main phase of a storm, during northward IMF. The boundary conditions were held constant in time but exhibited azimuthal variation and dawn-dusk asymmetry. The authors investigated the magnetic local time (MLT) dependence of the plasma sheet conditions on the...
formation of the storm time ring current. They found that cold ion populations in the post midnight quadrant produced pressure enhancements in the post midnight sector of the ring current, and that hot, tenuous boundary conditions produced a more azimuthally uniform pressure distribution on the nightside. Thus, we expect spatiotemporal dependence in the temperature boundary conditions to play an important role when simulating the full time frame of a geomagnetic storm.

In this paper we present the results of Comprehensive Ring Current Model (CRCM) simulations using ion temperature boundary conditions derived from time-resolved maps calculated from energetic neutral atom (ENA) data. Time-dependent density and temperature boundary conditions for the CRCM are typically provided by the Borovsky statistical model [Borovsky et al., 1998] or the Tsyganenko and Mukai statistical plasma sheet model [Tsyganenko and Mukai, 2003], hereafter referred to as the TM model, but the CRCM may be easily customized to admit user-defined values. For example, another unique method for determining boundary conditions involves coupling separate magnetospheric models, such as the two-way coupled BATS-R-US + CRCM model described by Gloer et al. [2013]. The BATS-R-US global MHD code is used to represent the global magnetosphere while CRCM is used to model the inner magnetosphere, and the two disparate models provide feedback to one another across the shared boundary. While this method improves upon a purely statistical approach, it cannot incorporate event-specific inner plasma sheet observations for a given simulation time frame, which is the primary focus of our current research. The ion temperature boundary conditions used in our new simulations are derived using the method described by Scime et al. [2002] and Scime and Zaniewski [2004] for the MENA instrument on the IMAGE mission and later applied to ENA measurements from the TWINS mission by Keesee et al. [2011, 2012]; note that temperatures calculated in this way are inherently isotropic, i.e., parallel and perpendicular temperatures are assumed equal [Hutchinson, 1987]. Results from these simulations are compared to otherwise identical simulations that use ion temperatures calculated from the TM plasma sheet model using the best fit coefficients found in Table 1 of that publication. To get a sense of the statistical deviation in the TM model, note that the correlation coefficient was 0.71 in their study, with the average RMS temperature and RMS deviation being 3.79 keV and 1.42 keV, respectively. Each of the 16 coefficients in the temperature equation (their equation (4)) has an associated error estimate calculated from the fitting procedure, also presented in their Table 1. The data set used in their study was provided by the LEP instrument aboard Geotail, [Mukai et al., 1994] which covered the 0–40 keV energy range. The authors note that excluding >40 keV ions may underestimate temperature moments but not by more than 5% if the calculated temperature is less than 8 keV. Results from CRCM simulations which take Borovsky et al. [1998] ion temperature boundary conditions are not compared here because that model is only valid beyond 17.5 $R_E$, far beyond the outer boundary of our simulation domain.

Boundary densities are also required to fully specify the time-dependent particle distributions in each boundary cell. For the simulations compared and discussed here (one using ENA-derived ion temperature boundary conditions and another using temperatures prescribed by the TM empirical model), we specify ion density boundary conditions with the TM model. It is necessary to keep density boundary conditions the same for both simulations to isolate the influence that each ion temperature boundary condition model has on the results. The TM model is a natural choice for boundary densities since one of our simulations uses TM ion temperatures and the models for $n_i$ and $T_i$ are calculated from the same set of Geotail data (see equations (5) and (4), respectively, in Tsyganenko and Mukai [2003]).

Using these event-specific boundary conditions in a ring current model provides a number of advantages over statistical models. One drawback of using statistical models is that these models have limitations on the parameter regimes in which the models are valid. The TM plasma sheet model, for example, is only valid for the following solar wind conditions: $-5 < B_z$ (nT) $< +5$, $300 < v_{sw}$ (km/s) $< 600$, $5 < n_{sw}$ (cm$^{-3}$ ) $< 20$. It is well-known that during active geomagnetic periods, the solar wind parameters at Earth frequently fall outside of these ranges. In addition, the TM model is valid only at distances between 10 and 50 $R_E$, which leaves an important observational gap between geosynchronous orbit and 10 $R_E$. Finally, the TM model is also solely based on data covering from late in the declining phase of solar cycle 22 through the initial phase of increasing activity during solar cycle 23, and thus, this plasma sheet model may not be representative of other solar cycles or of conditions during solar maximum. Thus, when performing numerical simulations to study the storm time coupling between the solar wind, the plasma sheet, and the inner magnetosphere, it is necessary to find a more appropriate description of the plasma at the outer boundary. Using boundary conditions that are determined using ENA measurements circumvents the formidable statistical limitations, and implementation of these new boundary conditions is not particularly challenging. In addition, these
temperature maps serve to bridge the important spatial gap between geosynchronous orbit and 10 $R_E$, a region where in situ data are sparse.

Section 2 of this manuscript primarily concerns the implementation of the ENA ion temperature data into the CRCM framework. A brief discussion of the method for determining ion temperatures from ENA data is given, along with a necessary overview of the TWINS mission. Section 3 provides an overview of the 22 July 2009 geomagnetic storm and a discussion of simulation results, with an emphasis on differences observed between temperature models. Simulation results at geosynchronous orbit are compared with remotely imaged temperatures obtained from TWINS in the beginning of section 3 and later with in situ data from the Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission. Section 4 contains a summary of this ongoing work.

2. Calculation of Ion Temperatures and Simulation Details

The Two Wide-Angle Imaging Neutral-Atom Spectrometers (TWINS) mission [McComas et al., 2009] consists of a pair of satellites (TWINS 1 and 2) in high-inclination Molniya orbits that image Earth’s magnetosphere. Each spacecraft contains a Lyman-$\alpha$ detector for geocoronal measurements, environmental sensors that measure the local charged particle environment, and an ENA imager for remote sensing of neutral atoms through charge exchange with ions. The time-of-flight resolved ENA spectrum is detected by the TWINS ENA imagers with 4° by 4° angular resolution and 1–2 min time resolution, which may be used to calculate an effective ion temperature along a given line of sight.

Given the TWINS instruments’ wide fields of view and angular resolution, a map of ion temperatures can be calculated, provided that ENA counting statistics meet significance requirements. This is accomplished by integrating measured fluxes for each instrument pixel over multiple instrument actuator sweeps. The time integration interval is adjusted to obtain good counting statistics, with a trade-off between fast imaging and lower uncertainty. Our method sets a fixed bin size at 0.5 $R_E$ by 0.5 $R_E$ in the magnetic equatorial plane (GSM coordinates) that is filled by mapping the ENA flux along the line of sight of each instrument pixel. Detailed descriptions of the method are given by Scime et al. [2002], Zaniewski et al. [2006], and Keesee et al. [2008], so only an overview of the methodology is provided here.

Consider ENA emission collected by a specific instrument pixel, that is, ENA emission collected along a particular line of sight. The high-energy portion of the energy spectrum, $F(E)$, is dominated by the hottest region along that line of sight [Scime and Hokin, 1992]. Assuming $F(E)$ is generated through charge exchange collisions between neutals and a Maxwellian ion population with temperature $T$, $F(E)$ is given by

$$F(E) dE \approx C \sigma(E) EdE \left( \frac{n_0(r) \Gamma(r) e^{-E/T(r)}}{\sqrt{2m_i \pi^3 T(r)^3}} \right) e^{-\int a(l) dl} \quad (1)$$

where $C$ is a constant geometric factor which accounts for the viewing perspective, $\sigma(E)$ is the energy-dependent charge exchange cross section, $T(r)$ is the ion temperature along the line of sight (the $r$ direction), $n_0$ is the neutral density, and $n_i$ is the ion density. Here $r = x$ corresponds to the location of the hottest region in the look direction. The factor $a(l)$ accounts for neutral flux losses due to collisions and ionization along the neutral’s path to the imaging pixel. These losses are insignificant in optically thin environments, and thus, equation (1) reduces to

$$\frac{F(E) dE}{\sigma(E) EdE} \approx C \left( \frac{n_0(x) \Gamma(x) e^{-E/T(x)}}{\sqrt{2m_i \pi^3 T(x)^3}} \right) \quad (2)$$

The peak ion temperature, $T(x)$ along the line of sight may be determined by fits against the “corrected” observed energy spectra given on the left-hand side of equation (2). Note that fluxes in the 1–32 keV energy range are used for these temperature fits. We have found empirically that the quality of the fits suffer when higher-energy bins are included. In addition, this energy range is consistent with the 0–40 keV energy range used for the TM model. Temperatures are calculated in this manner for each spatial bin in the magnetic equator by mapping to the time-dependent spacecraft locations and look directions, after collecting the ENA flux over the desired number of instrument actuator sweeps.
This method is applied to ENA data from both satellites, TWINS 1 and TWINS 2, resulting in temporally and spatially resolved 2-D ion temperature maps of the magnetosphere. Time cadence is typically 2–6 temperature maps per hour, per satellite, but may be limited by near-perigee viewing locations or low ENA counts. Time cadence is improved when both TWINS instruments are near apogee. In this study, ion temperatures are calculated with 20–40 min integration times throughout the region \( X_{\text{GSM}} \ Y_{\text{GSM}} = [-20, 20] \) \( R_E \) within a modeled magnetopause boundary [Shue et al., 1997], excluding the optically thick region inside of \( \approx 3 \) \( R_E \) where full ENA inversions would be required to obtain ion temperatures. Using full ENA inversions [Perez et al., 2000; Brandt et al., 2005] to calculate ion temperatures in the optically thick region would complement our results and provide a full picture of magnetospheric ion temperatures. In the optically thin region from 8 to 10 \( R_E \) that our study concerns, corresponding to the simulation outer boundary, temperatures are commonly calculated by fitting either a Maxwellian or Kappa distribution to the observed ENA fluxes; for the simulations discussed here, we assume the particle distributions are well described by a Maxwellian. This is a sound assumption, as evidenced in the fits shown in Keesee et al. [2012, Figure 3], which is to say that the errors associated with ENA-derived temperatures during this event are quite low. In addition, using full ENA inversions has been found to result in nearly identical ion temperatures in the optically thin region of the equatorial plane Zhang et al. [2005], increasing confidence that these low statistical uncertainties are accurate. The temperature calculation method is applied to the ENA data obtained from TWINS 1 and 2 for the 22 July 2009 geomagnetic storm.

An extensive description of the CRCM is given by Fok et al. [2001], so only a brief summary is provided here. The CRCM models the inner magnetosphere by combining the RCM [Harel et al., 1981] with the Fok kinetic model [Fok and Moore, 1997]. The CRCM solves the bounce-averaged Boltzmann equation for the average phase space density of a given species between mirror points on a field line. The CRCM also solves for the magnetospheric electric field self-consistently and uses an empirical model to specify the high-latitude electric potential boundary condition, which maps to the magnetic equator to specify the time-dependent cross-tail convection electric field at the outer boundary. The CRCM also includes loss cone, charge exchange, and magnetopause losses; charge exchange decay rates are determined using the Rairden et al. [1986] exospheric neutral Hydrogen model. The bounce averaging provides a 2-D magnetic equatorial projection of the particle distribution out to roughly 8–10 \( R_E \) on the nightside, which corresponds to the dynamic boundary of the model. For the simulations discussed in this manuscript, we use an ionospheric altitude of 120 km, zero dipole tilt angle, the Tsyganenko 1996 (T96) magnetic field model [Tsyganenko and Stern, 1996], and the Weimer model [Weimer, 2001] for electric potentials at the high-latitude boundary, which is just above 69° magnetic latitude. In addition, the simulation results we present consider only H\(^+\) ions; we intentionally exclude electrons and oxygen ions from these particular simulations so that we may more easily present the ion dynamics corresponding to the imposed boundary ion temperatures.

The CRCM simulations discussed here have a dynamic outer boundary that is typically located at 8–10 \( R_E \) during the simulations. The location of the outer boundary is spatially dynamic because magnetic field lines may change shape in the inner magnetosphere while they remain essentially fixed at ionospheric foot points. Ion temperatures at each boundary cell are sampled from the temperature data generated from each 2-D ENA map. The fundamental time step for advancing distribution functions and boundary conditions in CRCM is 10 s, and thus, temperature boundary conditions are linearly interpolated from one ENA-derived temperature map to the next. This interpolation is used to ensure smooth changes in boundary conditions and thereby prevent artificially steep phase space gradients, which drive the simulations unstable. To assign ion temperatures in bins where no temperature data are available (outside the instrument field of view), we first take available data and mirror about the \( Y_{\text{GSM}} = 0 \) axis, ensuring that existing data are not overwritten. Although dusk-dawn asymmetries are prolific in the inner magnetosphere, this mirroring method is consistent with the TM method, which is arguably the most comprehensive statistical plasma sheet model currently available. Any remaining pixels which have no ion temperature defined are assigned the mean temperature of the full map in the region \( X_{\text{GSM}} \ Y_{\text{GSM}} = [-20, 20] \) \( R_E \).

3. The 22 July 2009 Geomagnetic Storm

3.1. Overview

On 22 July 2009 a southward oriented IMF reached Earth's magnetosphere and was followed by a high-speed stream (HSS). At the time, this was the most intense storm observed during the minimum of solar cycle 23. Following 2000 UT on 21 July 2009, a gradual decrease in Sym-H was observed, during which
Figure 1. Geomagnetic indices and ACE data provided by OMNIWeb for the day of 22 July 2009. Red vertical bars indicate the times we selected for analysis.

Shock nose and geomagnetic indices for the relevant time interval of our simulations. The Sym-H index indicates the storm phase, and the AU and AL indices show moderate substorm activity. The solar wind density $n_{sw}$ and speed $V_{sw}$ show clear high-speed stream signatures starting late in the main phase, and the IMF $B_y$ and $B_z$ both show storm time reversals.

The 22 July 2009 storm has been studied in many prior publications, including Fok et al. [2010], Valek et al. [2010, 2013], and Ganushkina et al. [2012], and the reader is referred to these articles for informative discussions on the solar wind conditions and the magnetospheric response during this event. Fok et al. [2010] used CRCM to examine the impact of different magnetic field models (static and dynamic) on the inner magnetosphere during this event. Their simulations also used the TM boundary condition model; the authors emphasize the importance of a dynamic field model for reproducing TWINS ENA measurements and THEMIS-D fluxes. Our data-model comparison with THEMIS-D (section 3.3) is in direct agreement with their results. In addition, the ion temperatures discussed in this paper were used to study magnetospheric ion temperature evolution during this storm [Keesee et al., 2012]. New simulations of this storm are presented here to provide validation against these prior results. It should be noted that the TM plasma sheet model is statistically invalid for most of this storm, because one or more of the solar wind conditions fall outside of the statistical limits discussed in the Introduction (see Figure 1).

Figure 2 shows a comparison between the ENA-derived ion temperature boundary conditions $T_{ENA}$ and the TM ion temperature boundary conditions $T_{TM}$, in the bottom and top rows, respectively. Since the TM model is technically only valid beyond 10 $R_E$, we assign $r = 10 R_E$ ion temperatures when the CRCM outer boundary for that simulation is located inside of 10 $R_E$. Note the fine spatial and temporal structure visible in the $T_{ENA}$ row; these features are embedded in larger-scale, slowly varying temperature fluctuations. These larger-scale variations appear to have similar characteristic
Figure 3. Comparison of Sym-H* values for the 22 July 2009 event. The black line shows the OmniWeb Sym-H values corrected by contributions of the solar wind pressure, magnetopause currents, and currents induced within Earth. The red and blue solid (dashed) lines show the total energy contained within the simulation domain (within geosynchronous orbit). The dotted lines show simulated Sym-H* with losses due to the changing magnetic field removed.

Early in the initial southward $B_z$ phase, $T_{ENA}$ are considerably higher than $T_{TM}$, with a hot ($\approx 20$ keV) patch in the premidnight sector. The enhanced duskside ion temperatures are consistent with the superposed epoch analysis of HSS-driven storms performed by Denton and Borovsky [2008]. Note that the TM model produces temperatures that are highest at, and symmetric about, midnight. Starting near 0200 UT, $T_{TM}$ increase globally and $T_{ENA}$ decrease globally while maintaining a weak dawn-dusk asymmetry until 0330 UT. During the northward phase after the Sym-H minimum at 0530 UT, hotter $T_{ENA}$ are briefly found at the simulation boundary, while the TM model predicts rather rapid cooling down to roughly 3 keV. Following the subsequent southward turning at 0715 UT, the distribution at the $T_{ENA}$ boundary abruptly cools, while the $T_{TM}$ boundary gradually heats again. During the initial short northward phase beginning at 0930 UT, hotter populations are found at dawn and dusk in the ENA-derived temperatures. A global increase in $T_{ENA}$ follows, where they remain constant at 2 keV for nearly 2 h. The extended recovery phase follows, where $T_{ENA}$ show large-scale ion heating while still exhibiting small-scale structure. Another global increase in $T_{ENA}$ occurs at 1800 UT, which persists through the end of the simulation time frame.

In the following section, we present a comparison of the simulated H$^+$ pressure and the energy and time dependence of the H$^+$ flux within the simulation domain. Our comparison highlights differences observed between simulations using the different outer boundary condition models previously discussed.

### 3.2. Simulation Results of the 22 July 2009 Storm

All simulations discussed here begin at 2000 UT on 21 July 2009 with an empty magnetosphere and run for 28 h through 0000 UT on 23 July 2009. In this section, we focus on the 24 h period of 22 July. Figure 3 shows a comparison of Sym-H$^+$ values for this period. The Sym-H$^+$ calculated from 1 min OmniWeb data is in black and is the pressure-corrected Sym-H with contributions from magnetopause currents and currents induced within the Earth removed. The functional relation for converting observed Sym-H data (courtesy of OmniWeb) to Sym-H$^+$ is given by [Fok et al., 2010; Burton et al., 1975] as

$$\text{Sym-H}^+ = \frac{\text{Sym-H}}{1.5} - 15.8\sqrt{P_{sw}} + 20 \quad (3)$$
where $P_{sw}$ is the solar wind pressure in nPa. The solid red and blue lines correspond to Sym-H$^*$ values calculated by feeding the total simulation energy into the Dessler-Parker-Sckopke (DPS) relation [Dessler and Parker, 1959; Sckopke, 1966]; the dashed red and blue lines show the contribution to Sym-H$^*$ from the total energy inside of geosynchronous orbit, also calculated using the DPS relation. The dotted red and blue lines show the same as the solid lines, except with losses due to the changing magnetic field also subtracted off. During the main phase and early recovery phase, higher boundary ion temperatures result in an increase in the total simulation energy and thus a corresponding decrease in the predicted Sym-H$^*$. An example of this is found in the initial, brief recovery phase from 0600 to 0730 UT (see Figure 3). During this time, the $T_{ENA}$ boundary conditions are considerably hotter than those given by the TM model (see Figure 2), resulting in a pronounced Sym-H$^*$ minimum that better agrees with the observed Sym-H$^*$; note that such an obvious Sym-H$^*$ minimum is not present in the simulation utilizing $T_{TM}$ boundary conditions.

Figure 4 shows H$^+$ drift paths for a southward $B_z$ interval (0430 UT, left column) and a northward $B_z$ interval (0615 UT, right column) to provide context for the following discussion, where the spatial distribution of simulated fluxes is interpreted in terms of fundamental plasma drifts. Since a drifting particle changes its kinetic energy along its drift path (due to conservation of the first adiabatic invariant), one must specify the particle energy at a specific location to compute the drift paths. In the top row, drift paths are presented for 6 keV protons referenced at geosynchronous midnight. In the bottom row, the same location is chosen but for 28 keV protons. The important feature that distinguishes low-energy and high-energy particle drifts is that higher-energy particles experience a westward (duskward) gradient-curvature drift that dominates over the effect of the Earthward and dawnward $\vec{E} \times \vec{B}$ drift. The red dashed line superimposed on the plots indicate the dynamic outer boundary of the simulation at the chosen times.

Figure 5. (a–e) H$^+$ pressure (nPa) using ion temperature boundary conditions from the (top) TM model and (bottom) ENA-derived model at five time steps (columns). Spatial coordinates in GSM are shown at the bottom left row. In each row, the Sun is to the left and the white traces indicate geosynchronous orbit.
Figure 6. (a–e) Simulated 6–18 keV (12 keV) H\(^+\) flux (1/keV cm\(^2\) sr sec) using ion temperature boundary conditions from the (top) TM model and (bottom) ENA-derived model at five time steps (columns). Spatial coordinates in GSM are shown at the bottom left.

Figure 5 shows a comparison of simulated H\(^+\) pressure (nPa). The TM run is in the top row and the ENA run is in the bottom row, and the times shown for each column are the same as those indicated by vertical lines in Figures 1 and 2. The Sun is to the left, and the white traces indicate geosynchronous orbit at 6.6 RE. The two boundary condition models produce H\(^+\) pressures that are very similar in their spatial configuration and in time, although some differences can be observed. Specifically, the peak pressure from each boundary condition model occurs at nearly identical L shells for all times shown, but the MLT dependence at 0715 and 0900 varies between boundary condition models. At 0715 UT the peak pressure occurs near \(L = 4.8\), and the \(T_{\text{TM}} (T_{\text{ENA}})\) run shows its region of highest pressure skewed toward dusk (dawn). This comparative shift in MLT could be explained by a hotter (cooler) population convecting in from the inner plasma sheet edge in the \(T_{\text{TM}} (T_{\text{ENA}})\) run, which is opposite from the actual boundary conditions shown in Figure 1, but convection is weak during the interval 0530–0715 UT and thus the boundary conditions have only a minor impact on the ring current during this period. As will be shown in the discussion of Figures 6 and 7, the pressure in the \(T_{\text{TM}} (T_{\text{ENA}})\) run at 0715 UT is dominated by the contribution of higher (lower) energy flux, resulting in ion drifts that are consistent with the relative shifts in pressures shown in Figure 5c. At 0900 and 1210 UT the peak pressure occurs near \(L = 4.3\) \(R_E\); the difference at 0900 UT is more subtle, but the \(T_{\text{ENA}}\) run shows a slight duskward enhancement, while the \(T_{\text{TM}}\) shows a more dawn-dusk symmetric pressure. At 1100 UT the boundary condition models result in very similar pressures on the dawnside, but the \(T_{\text{TM}}\) run shows a slight enhancement in the noon-dusk quadrant, indicating more complete dayside ring current closure at that time.

Figure 7. (a–e) Simulated 18–39 (28 keV) keV H\(^+\) flux (1/keV cm\(^2\) sr sec) using ion temperature boundary conditions from the (top) TM model and (bottom) ENA-derived model at five time steps (columns). Spatial coordinates in GSM are shown at the bottom left.
Figure 6 shows a comparison of simulated proton fluxes (1/keV cm$^{-2}$ sr s) in the 6–18 keV energy range (hereafter referred to as 12 keV fluxes), and Figure 7 shows the fluxes for the 18–39 keV energy range (28 keV fluxes). During the initial southward $B_z$ interval from 0430 to 0530 UT, the midnight temperatures are $T_{\text{TM}} \approx 12$ keV and $T_{\text{ENA}} \approx 7$ keV. As plasma is convected in during this period, the colder, largely low-energy population in the $T_{\text{ENA}}$ run is expected to $\vec{E} \times \vec{B}$ drift primarily downward. This is found to be the case in Figure 6a; the $T_{\text{ENA}}$ run produces larger 12 keV fluxes than the $T_{\text{TM}}$ run, most noticeably in the midnight-dawn quadrant. In addition, the 12 keV flux from the $T_{\text{ENA}}$ run has a localized peak (around $L = 5$–6.6) while the flux provided by the $T_{\text{TM}}$ boundary conditions shows a much more diffuse distribution in $L$. The 28 keV fluxes however agree in magnitude and in spatial distribution during this time period, as shown in Figure 7a.

When the IMF turns northward near 0530 UT, inner magnetospheric drift paths change from open to closed, resulting in higher dayside fluxes until the subsequent southward turning at 0715 UT. At 0715 UT (see Figure 6c), the $T_{\text{ENA}}$ run produces 12 keV fluxes that are larger than those in the $T_{\text{TM}}$ run in both the post dawn sector and at dusk. In addition, the 12 keV H$^+$ flux at midnight is more diffuse in the $T_{\text{TM}}$ run, and the flux peaks much closer to geosynchronous orbit than in the $T_{\text{ENA}}$ run. This stronger nightside penetration found in the $T_{\text{ENA}}$ run, despite the hotter boundary conditions, is due in part to the negligible convection associated with northward IMF. Because convection is effectively turned off during the northward interval from 0530 to 0715 UT, there are negligible earthward fluxes from the plasma sheet during this time and thus the boundary conditions have a minimal impact on the energy dependence of inner magnetospheric fluxes. The colder plasma found at the $T_{\text{ENA}}$ simulation boundary during the earlier interval of southward IMF (ending at 0530 UT) penetrates to lower L shells than in the $T_{\text{TM}}$ run and subsequently moves along closed drift paths after the northward turning at 0530 UT. Thus, it is not simply the temperature boundary conditions that determine how fluxes are distributed in energy during the event but also the corresponding convection field strength. The $T_{\text{TM}}$ run shows slightly higher 28 keV fluxes near dusk compared to the $T_{\text{ENA}}$ run (Figure 7c), but the two boundary conditions produce otherwise spatially similar flux in the 28 keV energy range.

The IMF turns strongly southward at 0800 UT, resulting in enhanced convection until another northward turning at 0845 UT. During this southward period, the $T_{\text{ENA}}$ boundary conditions are cooler than those used in the $T_{\text{TM}}$ run. At 0900 UT the $T_{\text{TM}}$ run produces an enhancement of the 12 keV flux in the premidnight sector (Figure 6d), consistent with a higher-energy population experiencing westward gradient-curvature drift. The 28 keV fluxes are similar in spatial structure and in magnitude (Figure 7d), although the region of peak pressure in the $T_{\text{ENA}}$ run covers a slightly larger extent in L shell. At 0900 UT, the Sym-H reaches its second minimum, marking the beginning of the long recovery phase.

The IMF $B_z$ turns weakly southward for 1 h beginning at 1000 UT, by which time clear high-speed stream signatures were observed by ACE (see Figure 1). At 1100 UT, the IMF $B_z$ abruptly relaxes to zero and the solar wind conditions become effectively steady state. At this time, $T_{\text{ENA}} \approx 3$–4 keV and $T_{\text{TM}} \approx 6$–8 keV, and the ring current begins to close as transport to the dayside is increased. At 1210, there is an abrupt increase in nightside $T_{\text{ENA}}$ from 3 keV to 8 keV. The 12 keV ion fluxes in Figure 6e are consistent with these preceding boundary conditions; the $T_{\text{ENA}}$ run produces a strong gradient-curvature drift enhancement in the dusk-midnight sector out to $L = 7$ due to the larger relative fraction of high-energy protons, while the colder population convected in for the $T_{\text{TM}}$ run primarily experiences the $\vec{E} \times \vec{B}$ drift and convects to the dawnside. Higher 28 keV fluxes at dusk and midnight are also produced in the $T_{\text{ENA}}$ run at 1210 UT, again consistent with a hotter boundary population.

To provide context for the comparison with observations in the next section, we present simulated differential fluxes at geosynchronous orbit in Figure 8. Figures 8a–8e show how the fluxes at geosynchronous orbit are distributed in energy and magnetic local time for each boundary condition model. At 0430–0615 UT the peak $T_{\text{ENA}}$ fluxes are larger in magnitude than those from the $T_{\text{TM}}$ run, although the distributions in MLT are similar. The $T_{\text{ENA}}$ run produces a 3 keV enhancement near 20 MLT which is not found in the $T_{\text{TM}}$ run, indicating a localized low-energy population in the dusk-midnight quadrant. This feature is visible at both 0430 and 0615 UT (see Figures 8a and 8b). At 0715 UT (Figure 8c), multiple differences may be observed. First, the TM run produces much higher 12 keV fluxes at midnight than the ENA run; this is due to the more diffuse flux produced by the hotter TM boundary conditions prior to the northward turning near 0530 UT, which is consistent with the discussion of Figure 6c. In addition, the ENA run shows a significant depletion of low-energy, 3–4 keV flux at midnight as well. In the dawn-noon quadrant, the TM run produces a depletion
of low-energy flux. At 0900 UT (Figure 8d), both boundary condition models produce peak fluxes at 6 and 18 MLT (dawn and dusk), although the $T_M$ run shows slightly larger absolute magnitudes. The $T_M$ run also produces a low-energy (1 keV) enhancement at dawn and fluxes near midnight that are considerably lower than those found in the $T_{ENA}$ run. Later in the recovery phase at 1210 UT (Figure 8e), the fluxes calculated for each of the two boundary condition models are similar in magnitude ($\approx 1.3 \times 10^6$) but the energy dependence of flux at any given MLT is quite different; in particular, 1–10 keV fluxes in the premidnight sector are significantly higher in the $T_{ENA}$ run although both simulations produce a dropout centered at midnight.

3.3. Data-Model Comparisons During the 22 July 2009 Storm

In this section we take pitch angle averaged fluxes obtained from CRCM and perform comparisons with two distinct observational data sets. Figure 9 shows a data-model comparison of ion temperatures at geosynchronous orbit for all MLT at each of the 5 times previously discussed. Here the temperatures calculated from CRCM fluxes (red and blue curves) are actually the “kinetic temperatures” $k_B T$ which may be calculated for any arbitrary distribution function [see, e.g., Baumjohann and Treumann, 1997] with the familiar $k_B T = \bar{p}/n$, where $\bar{p}$ is the trace of the pitch angle averaged pressure tensor (which are presented in Figure 5) and $n$ is the local density. The temperature integrations are taken in the 0–25 keV energy range so as to be consistent with the THEMIS comparison in Figure 11. These simulated geosynchronous temperatures are compared with geosynchronous observations extracted from TWINS ENA maps, which are shown in black. Keesee et al. [2012] discussed convection of hot ions during the main phase of this event, but only Figure 9a overlaps with that study. Zhang et al. [2006] showed clear dusk-dawn temperature asymmetries at geosynchronous orbit during moderate storms at solar minimum. They use MPA data to conduct a superposed epoch analysis and find that near-zero epoch, the observed dusk (dawn) temperatures are 9–10 keV (4–5 keV). Here we illustrate how well the CRCM simulations and TWINS observations agree with their results.

For all times shown (Figures 9a–9e), both boundary condition models produce overall hotter (cooler) populations at dusk (dawn), which is consistent with our expectations from elementary drift theory [see, e.g.,}
Garner, 2003] and with the observations in Zhang et al. [2006] and Wing et al. [2005]. During the 0430–0530 UT period, recall that the IMF was southward and thus convection was near its strongest of the event, and also that $T_{\text{IM}} = 12$ keV, $T_{\text{ENA}} = 7$ keV, so it is natural to expect the temperatures at geosynchronous orbit, $T_{\text{IM,geo}}$ and $T_{\text{ENA,geo}}$, to reflect what is convecting in from the plasma sheet. At 0430 UT (Figure 9a), we find that the $T_{\text{IM}}$ run (blue) produces slightly higher nightside temperatures, $T_{\text{IM,geo}}$, than the $T_{\text{ENA}}$ run. The simulated temperatures are in good general agreement with the Zhang et al. [2006] results, as 0430 UT was near the zero epoch time used in their study. Both simulations also show localized, hot populations (peaks) in the dusk-midnight quadrant. This peak is not obvious in the TWINS observations in the dusk sector, but those observations do show a localized hot peak near 3 MLT. Here both simulations produce a dusk-dawn asymmetry that is oppositely directed than the TWINS observations. Keesee et al. [2012] demonstrated that this hot structure, which is found in the TWINS observations (Figure 9a), in fact convected across midnight from dusk and may be associated with a substorm expansion from 0000 to 0400 UT. Denton and Borovsky [2009] also identified this as a feature which is characteristic of HSS-driven events shortly after the time of convection onset. Overall, the $T_{\text{ENA}}$ run shows a slightly cooler $T_{\text{ENA,geo}}$ at 0615 UT than at 0430 UT, which is particularly evident near dusk. Unfortunately, the dawn sector was not within the TWINS field of view during this time, hence the absence of dawnside data (black) in Figure 9b. Note the observed hot patch from 0 to 2 MLT, which is also found, more subtly, in the simulated temperature using $T_{\text{ENA}}$ boundary conditions. At the end of the ensuing northward phase, Figure 9c shows that the $T_{\text{IM,geo}}$ and $T_{\text{ENA,geo}}$ are significantly cooler than those found during the preceding southward phase (Figure 9a). This is true for the $T_{\text{ENA,geo}}$ as well, with the exception of a weakly localized hot patch found in the midnight sector. This hot patch, also found at 0615 UT, agrees nicely with the TWINS observations as the $T_{\text{IM}}$ simulation produces the coolest temperatures in this region. In the premidnight sector, the $T_{\text{ENA}}$ simulation again agrees more closely with the TWINS observations in that the ion temperature curve is roughly constant from dusk to midnight. The magnitudes are not in perfect agreement, but the spatial distribution in this quadrant is reproduced well by the $T_{\text{ENA}}$ simulation. During the interval of southward IMF from 0715 to 0900 UT, both boundary condition models show nightside heating (Figure 9d) but where that heating occurs in MLT depends on the boundary condition model. The $T_{\text{ENA,geo}}$ near midnight remain roughly the same as at 0715 UT, but temperatures increase slightly near dusk which gives a temperature versus MLT picture that is similar to the earlier southward phase (Figure 9a). During this southward interval, the $T_{\text{IM}}$ run produces significant cooling in the dawn sector as well as significant heating around midnight. The observed temperature magnitudes near midnight are matched well by the $T_{\text{IM}}$ model and geosynchronous temperatures from $T_{\text{IM}}$ agree better in terms of how the temperature changes in MLT, although both simulations seem to correctly capture the cold $E \times B$ drifting populations found convecting to the dayside via dawn. Later in the recovery phase, at 1210 UT (Figure 9e), $T_{\text{ENA,geo}}$ are largely similar to $T_{\text{ENA,geo}}$ at 0900 UT, with a cooler population in the midnight-dawn sector. During the interval 0900–1200 UT, the temperature boundary conditions decrease significantly in both models, which is ultimately reflected in the calculated ion temperatures at geosynchronous orbit during that time. When the $T_{\text{ENA}}$ increase abruptly at 1210 UT, the impact at geosynchronous orbit is small because the convection field is very weak at that time. Both boundary condition models produce temperatures that approximately agree with the TWINS observations in that the dusk-dawn asymmetry is reproduced, although the premidnight $T_{\text{ENA}}$ model results better match the warm bump in the observed temperatures.

In addition to the comparison with remotely imaged observations with TWINS, we also present a comparison of our simulation results with in situ data. THEMIS-D (TH-D) sampled the inner magnetosphere during a subset of this 24 h period. TH-D entered the magnetosphere through the dusk magnetopause flank at 0400 UT, passing through the storm time ring current in the premidnight sector, reaching geosynchronous orbit (19 MLT) at 0810 UT, crossing the midnight meridian around 1055 UT at $L = 2$, and passing through the prenoon ring current during the recovery phase. Orbit plots for TH-D in the $x$-$y$, $x$-$z$, and $y$-$z$ planes (all in GSM coordinates) are shown in Figure 10.

The first row of Figure 11 shows the TH-D energy flux spectrogram generated by combining background-subtracted measurements from the ESA instrument with SST instrument measurements which have Sun contamination removed. The second and third rows of Figure 11 are simulated TH-D spectrograms generated from CRCM fluxes produced by the $T_{\text{ENA}}$ and $T_{\text{IM}}$ boundary conditions models, respectively. The fourth row of Figure 11 shows the data-model comparison of ion temperature moments computed over the energy range of the ESA instrument (0–25 keV for ions). Overall, both simulations reproduce the major features of the ring current observed by the THEMIS spacecraft during this time interval. The simulated TH-D
temperatures generally agree with the observed temperature, although the omission of a plasmasphere module in our simulations means that cold plasmaspheric populations (hundreds of eV) at low L shells are not captured in the CRCM simulations. This causes the ion temperature moments to diverge when TH-D is deep in the inner ring current (0900–1300 UT).

From 0415 to 0545 UT, the $T_{\text{TM}}$ produces ion temperatures roughly 20% higher than those from the $T_{\text{ENA}}$ model. Note that TH-D was located near the dusk meridian and that the $T_{\text{TM}}$ boundary conditions were hotter during this interval (see Figure 2). The southward orientation of the IMF enhanced convection from the plasma sheet and the hotter $T_{\text{TM}}$ boundary conditions result in higher fluxes in the high-energy range. This feature is evidenced in Figure 12a, which shows a comparison of observed and simulated energy spectra at 0430 UT. The simulated spectra agree with one another below 10 keV, but fluxes above 10 keV from the $T_{\text{ENA}}$ boundary condition model drop off at lower energies than fluxes from the $T_{\text{TM}}$ model. The simulated fluxes differ, roughly, by an order of magnitude in the 20–100 keV energy range. In addition, neither model represents the extent of the high-energy tail found in the TH-D data at this time. This is likely due to the limited energy ranges that are included in the temperature calculations for each model. As TH-D moves

Figure 10. THEMIS-D orbit plots (x-y, x-z, and y-z) in GSM coordinates for 0400–1600 UT during the 22 July 2009 event.

Figure 11. (first row) Observed and (second and third rows) simulated THEMIS-D spectrograms for 22 July 2009 covering the 0400–1600 UT interval. (fourth row) Observed ion temperatures are compared with simulated temperatures, where the black data are ESA moments and the red (blue) data are calculated from CRCM fluxes using the ENA (TM) boundary condition model.
through the ring current to lower L shells and toward the midnight meridian, a steady increase in observed and simulated temperatures is found (Figure 11, fourth row). By 0615 UT, the $T_{\text{ENA}}$ and $T_{\text{TM}}$ model yield similar temperatures (7 keV for $T_{\text{TM}}$, 6.5 keV for $T_{\text{ENA}}$), while the TH-D moment gives a local ion temperature of 4.8 keV. Figure 12b shows the energy spectra at 0615 UT; as before, both simulations give nearly identical spectra in the low-energy (<10 keV) range. However, the $T_{\text{ENA}}$ model agrees identically with the high-energy tail found in the TH-D SST data, while the $T_{\text{TM}}$ model fluxes are a factor of 10–100 higher than the observations. At 0715, the end of the northward interval, a dip in the simulated and observed temperatures occurs (Figure 11, fourth row), although the decrease in the observed temperature is more pronounced. TH-D was in the dusk-midnight quadrant at this time and the preceding $T_{\text{ENA}}$ boundary conditions were considerably hotter, and thus the simulated high-energy flux is expected to be higher in the dusk quadrant for the $T_{\text{ENA}}$ run. As shown in Figure 12c, the two simulations agree identically up to 30 keV at 0715. However the $T_{\text{ENA}}$ model produces a high-energy enhancement, which is consistent with our expectations. Note that during the time frame 0715–0900 UT, THEMIS was near-geosynchronous orbit (19 MLT) and observed constant temperatures (≈4 keV) during this interval. In this regard, the TWINS and THEMIS data are in good agreement (see Figures 9c and 9d) as TWINS also provides constant temperatures (5 keV) in this region.

The post midnight substorm injections at 0829 UT (1.7 MLT) and 0855 UT (2.1 MLT) and subsequent negative slope in the energy spectrogram from 0800 to 0900 UT are identifiable in the observations (Figure 11, first row), as emphasized and discussed by Fok et al. [2010]. The negative slope feature is reasonably reproduced by both boundary condition models, most visibly in the <3 keV range (Figure 11, second and third rows). At 0900 UT, the nightside boundary conditions are roughly equal and thus produce similar energy spectra across the entire energy range as shown in Figure 12d. Above 10 keV, the magnitudes of the simulated spectra do not agree well with observations. After 0900 UT, TH-D moves to lower L shells through the post midnight inner ring current edge and crosses the inner edge on its outbound pass beginning around 1200 UT. Both simulations reproduce the 10–20 keV drift hole encountered from 1200 to 1300 UT during this outbound pass in the dawn-noon quadrant. The observed and simulated energy spectra associated with this drift hole are shown in Figure 12e. The “bottom” of the drift hole (20 keV) agrees better with the $T_{\text{ENA}}$ run, but the $T_{\text{TM}}$ model does well in reproducing the 5–10 keV and 30–200 keV energy spectra. Around 1300 UT, TH-D is near noon at $L = 4$ sampling the core of the dayside ring current. Here the $T_{\text{ENA}}$ model produces higher peak fluxes than the $T_{\text{TM}}$ model (Figure 11), slightly higher than the color bar maximum. This is a consequence of the concurrent, abrupt increase of boundary ion temperatures in the $T_{\text{ENA}}$ model. Unfortunately, the magnitudes of the simulated temperatures are unphysical during this time (Figure 11, fourth row), and no direct comparison can be made with the TH-D data.

4. Conclusions

We have successfully incorporated ion temperature data derived from TWINS ENA images into CRCM. The ion temperatures provide outer boundary conditions for the simulations and are calculated using the techniques we have described. We have demonstrated that the temperature boundary conditions do have a significant impact on simulated fluxes and on ion energy spectra throughout the inner magnetosphere, although the simulated total pressure is found to be less sensitive to those boundary conditions during this event. We have also shown that the effects of varying boundary conditions on the inner magnetosphere and ring current are effectively throttled by the convection electric field strength; while this result is
not entirely unexpected, it illustrates the importance of the time history of both the boundary conditions and the convection field. We have also shown that temperatures at geosynchronous orbit, $T_{\text{geo}}$, can exhibit highly localized structure and change quickly in response to time-varying boundary conditions.

Through independent data-model comparisons with TWINS and THEMIS observations, we have illustrated the importance of boundary conditions in reproducing storm time ion temperature moments and ion energy spectra. The aforementioned hot, localized structures that are present in the prerecovery $T_{\text{ENA}}$ simulations agree well with TWINS observations, although using $T_{\text{TM}}$ boundary conditions also reproduces general features of those observations. Both boundary condition models are in general agreement with the dusk-dawn asymmetry that TWINS observed during this event, except for early in the main phase. Bursty transport due to substorm activity, which CRCM cannot fully capture, can help explain the disparity between the observations and simulations at that time.

Ion temperature boundary conditions determined with this method could easily be integrated into magnetospheric codes other than CRCM. Starting with the time-resolved, equatorially projected ion temperature maps derived from TWINS ENA data, users may interpolate the well-resolved temperatures at any given time onto the boundary of a simulation domain (regardless of the shape of the grid) and on timescales shorter than 1 h. Magnetospheric ion temperatures based on TWINS ENA data are available from June 2008 through the present day, and we anticipate continuing to calculate such temperatures throughout the lifetime of the TWINS mission. Even though this time frame may be relatively short, the timing is convenient in that TWINS provides a magnetospheric picture that includes the minimum of solar cycle 24, the subsequent period of increasing solar activity, the end of solar cycle 24 (solar maximum) and, presumably, the initial phase of decreasing activity of solar cycle 25. The fundamental aspect of being event specific yields opportunities that statistical models based on solar wind-plasma sheet correlations simply cannot. This important feature admits deeper study of transient processes, including how the ring current population(s) and their energy spectra respond to substorm activity or reconnection events in the tail. Finally, because TWINS data are available over the full range of recent solar activity, comprehensive studies windowed by solar activity levels can be readily performed based solely on the TWINS ENA data.

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