CIR versus CME drivers of the ring current during intense magnetic storms

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Ninety intense magnetic storms (minimum Dst value of less than $-100 \text{nT}$) from solar cycle 23 (1996–2005) were simulated using the hot electron and ion drift integrator (HEIDI) model. All 90 storm intervals were run with several electric fields and nightside plasma boundary conditions (five run sets). Storms were classified according to their solar wind driver, including corotating interaction regions (CIRs) and interplanetary coronal mass ejections (ICMEs). Data-model comparisons were made against the observed Dst index (specifically, Dst*) and dayside hot-ion measurements from geosynchronous orbiting spacecraft. It is found that the data-model goodness-of-fit values are different for CIR-driven storms relative to ICME-driven storms. The results are also different for the same storm category for different boundary conditions. None of the CIR-driven events was overpredicted by HEIDI, while the dayside comparisons were comparable for the different drivers. The results imply that the outer magnetosphere is responding differently to the two kinds of solar wind drivers, even though the resulting storm size might be similar. That is, for ICME-driven events, magnetospheric currents inside of geosynchronous orbit dominate the Dst perturbation, while for CIR-driven events, currents outside of this boundary have a systematically larger contribution.

Keywords: magnetosphere; magnetic storms; ring current; numerical modelling

1. Introduction

Liemohn & Jazowski (2008) showed the initial findings from a large-scale simulation effort involving numerical modelling of the inner magnetospheric plasma for every intense magnetic storm (Dst$_\text{min}$ less than $-100 \text{nT}$) of the last solar cycle. That study examined the results from the model for a complete run set of the storm intervals with a rather simplistic model configuration and boundary condition specification; the simulated total energy content of the ring current was then compared against the observed ground-based magnetic perturbation. The

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storm intervals were categorized according to their solar wind driver structure as compiled by Zhang et al. (2007a, b). A key finding was that storms driven by the sheath region ahead of an interplanetary coronal mass ejection (ICME) were quite reasonably matched by this model configuration, whereas storms driven by magnetic cloud structures of ICMEs or by corotating interaction regions/high-speed streams (CIRs/HSSs) solar wind structures were consistently underestimated by this model configuration.

Other studies have also noted differences between CIR/HSS-driven storm events and those driven by ICMEs (e.g. Tsurutani & Gonzalez 1997 and references therein). The solar wind structure of CIR/HSS intervals has been well classified as a repeatable and predictable sequence of plasma and field changes (e.g. Smith & Wolfe 1976; Hu 1993), and the resulting geospace activity has been the subject of several in-depth analyses (e.g. Tsurutani & Gonzalez 1987; Tsurutani et al. 1995; Richardson et al. 2006). ICME solar wind structures have also been studied extensively (e.g. Klein & Burlaga 1982), and their geoeffectiveness has been examined previously (e.g. Kamide et al. 1997; Gonzalez et al. 2004). In particular, a number of studies have used superposed epoch analysis of solar wind input parameters and geospace response values in order to discern the difference between CIR/HSS storms and ICME storms.

A common geospace dataset used in the analysis of the inner magnetospheric response to solar wind driving is the plasma and energetic particle observations from the geosynchronous orbiting satellites operated by the Los Alamos National Laboratory. For example, these data have been used to understand the superdense plasma sheet (e.g. Lavraud et al. 2005; Liemohn et al. 2008), the variation of the plasma parameters over a solar cycle (e.g. Denton et al. 2005, 2006), categorization by storm size and cycle phase (e.g. Zhang et al. 2006; Ilie et al. 2008) and classification by solar wind driver structure (e.g. Borovsky & Denton 2006). These studies by Denton and Borovsky have directly compared the input functions and responses within geospace owing to CIR/HSS storms and ICME storms, with Borovsky & Denton (2006) providing an excellent summary chart of the expected similarities and differences between these event classifications. Of special note from their findings is that the ring current is often stronger during ICME events than during CIR/HSS storms, while the radiation belts have just the opposite response.

A number of studies have investigated the partitioning of energy within the magnetosphere–ionosphere system during ICME-driven storms and CIR/HSS-driven storms. Huttunen & Koskinen (2004) found that sheath-driven storms (which include some ICME and all CIR/HSS storms) are different from storms driven by the ICME proper (especially magnetic cloud structures) because the solar wind inputs have high dynamic pressure and highly fluctuating parameters. This leads to enhanced high-latitude energy deposition into the ionosphere and preferential ring current trapping, i.e. a relative increase in the geoeffectiveness of the solar wind driver. Lu (2006) conducted a large-scale statistical study of energy partitioning in 53 storm events, and they concluded that CIR/HSS-driven storms are, on average, twice as geoeffective as ICME-driven storms. They found this to be true whether the sheath region, the ejecta region or both drove the ICME storm. The difference in the resulting ring current between these driver structures was noted by Turner et al. (2006, 2009), who found that CIR/HSS storms produce a systematically larger energy dissipation fraction into the ionosphere (in the
form of precipitating particle energy flux and Joule heating) and a significantly lower fraction into the ring current (compared with ICME-driven events). In light of the Huttunen & Koskinen (2004) results, this means that the ionospheric energy deposition is enhanced even more than ring current trapping during such events. This is consistent with studies of the auroral energy deposition during HSS passages, particularly during high-intensity, long-duration, continuous AE activity (HILDCAA) events (e.g. Tsurutani & Gonzalez 1987; Soraas et al. 2004; Guarnieri 2006).

Several studies have examined the ring current during CIR/HSS storms through simulations (e.g. Jordanova 2006,a,b; Liemohn & Jazowski 2008; Jordanova et al. 2009; Ilie et al. 2010). In modelling CIR/HSS-driven storms, Jordanova (2006a,b) and Jordanova et al. (2009) found that the recovery phase was not well reproduced by the electric field descriptions applied for the simulations, inferring that fluctuating fields or substorm-generated induced electric fields might be important for late phase ring current dynamics. Regarding this issue, Ganushkina et al. (2005, 2006) demonstrated the clear importance of the smaller-scale, substorm-associated electric fields in the ring current development during storms (but without separation between CIR and CME-driven events).

The conclusions from all of these previous studies lead to the understanding that the ring current is somehow different during CIR/HSS-driven storms than during ICME-driven storms. However, this does not explain why there is a difference in the resulting ring current between these two driver classifications. Specifically, does the inner magnetosphere behave differently during the driving conditions of CIR/HSS storms, or is it fundamentally the same as for other driver structures and the smaller ring currents are simply a result of smaller input conditions? This issue will be addressed in this study by extending the work of Liemohn & Jazowski (2008) with additional run sets and data-model comparisons. In particular, five complete run sets are now available, each with a different model configuration of the plasma source or the electric field description. In addition, comparisons against LANL plasma moments on the dayside will be used to further quantify the similarities and differences between the ring current resulting from CIR/HSS solar wind structures and ICMEs.

2. Methodology

Numerical simulations of the inner magnetosphere were conducted with the hot electron and ion drift integrator (HEIDI) model, drift physics code created in the early 1990s (e.g. Fok et al. 1993; Jordanova et al. 1996). There are now at least five versions of this model in use by the magnetospheric physics community (e.g. Fok et al. 2003; Khazanov et al. 2004; Jordanova et al. 2006; Liemohn et al. 2006; Zheng et al. 2006), with each branch undergoing its own development history over the last two decades. This code solves the gyration and bounce-averaged kinetic equation for the main hot particle species (H+, O+, He+ and electrons) in the keV energy range. The version used here (e.g. Liemohn et al. 2001, 2004) includes Coulomb collisional scattering and decay, precipitation loss to the upper atmosphere and charge exchange loss. It is run with the Rairden et al. (1986) neutral hydrogen geocoronal model for the charge exchange collisions.
and the Ober et al. (1997) dynamic global core plasma model for the thermal (plasmaspheric) population. For simplicity and computational tractability, a static dipole magnetic field was used in these simulations. Drift and collisional operators are solved with conservative, second-order accurate numerical schemes and the precipitation loss and charge exchange loss are applied through variable-dependent attenuation factors. For each species, the grid contains roughly 500 cells in physical space through the inner magnetosphere (inside of geosynchronous orbit) and about 3000 cells in velocity space at each of these spatial cell locations. Therefore, the particle distribution is found on an array of over a million cells throughout the phase space.

The two main parameters controlling the strength of the ring current during a storm interval is the plasma sheet density and the large-scale convection electric field (e.g. Kozyra & Liemohn 2003). For the simulations presented below, two different electric field calculations and three different outer boundary plasma inputs are used. The first electric field model is a shielded Volland–Stern potential pattern (Volland 1973; Stern 1975) with an activity dependence specified by the 3hKp index (Maynard & Chen 1975). The other electric field solution is a self-consistent formulation in which the field-aligned currents closing the partial ring current, as calculated from the hot particle solution within HEIDI, is used to modify the near-Earth electric potential pattern every time step. Details of this procedure are given by Liemohn et al. (2004, 2005, 2006). A primary difference in terms of input parameters is that the self-consistent formula uses upstream solar wind conditions to specify the high-latitude boundary on the electric potential calculation (using the Weimer (1996) empirical model values at 72° magnetic latitude in each hemisphere). The first of the three outer boundary condition specifications is the same as that used by Liemohn & Jazowski (2008), a time series of LANL satellite observations taking the maximum density observed by any satellite within 4 h of local midnight. The highest density of those observed is used as this best represents the unperturbed fresh plasma sheet material entering the inner magnetospheric simulation domain. These use both the magnetospheric plasma analyser (MPA) observations below 40 keV (Bame et al. 1993), applied to the H$^+$ and O$^+$ boundary conditions, and the synchronous orbiting particle analyser (SOPA) measurements above 50 keV (Belian et al. 1992), used only with the boundary condition for H$^+$. A compositional split is applied according to the formulas found by Young et al. (1982). The second outer boundary condition is the O’Brien & Lemon (2007) re-analysis of the LANL MPA plasma density moments. This dataset has hot ion and electron density and temperature values on an hourly cadence in both universal and local time for the entirety of solar cycle 23. Each bin is populated by an average of in situ measurements from the LANL satellites, if one or more is in that LT-UT bin, or by averaging values from other times at this location that have similar solar wind and geophysical conditions as that of the UT bin needing to be filled. This re-analysis dataset provides a continuous, local time-dependent outer boundary plasma condition for HEIDI. The final plasma boundary condition is a hybrid of the two other methods: a time series of inputs created by taking the re-analysis moments value with the maximum density within 4 h of local midnight. The latter two plasma boundary conditions do not use SOPA flux measurements, and instead assume a kappa distribution for the high-energy tail of the distribution (specifically, $\kappa = 5$).
Table 1. Run number designations for the combinations of plasma and electric field boundary conditions.

<table>
<thead>
<tr>
<th>Condition</th>
<th>LANL sat. data</th>
<th>LANL re-analysis</th>
<th>re-analysis averages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volland–Stern E-field</td>
<td>#1</td>
<td>#3</td>
<td></td>
</tr>
<tr>
<td>self-consistent E-field</td>
<td>#2</td>
<td>#4</td>
<td>#5</td>
</tr>
</tbody>
</table>

Table 2. Event totals with respect to driver classification.

<table>
<thead>
<tr>
<th>Run set</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>#5</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘usable’ events</td>
<td>79</td>
<td>69</td>
<td>76</td>
<td>67</td>
<td>66</td>
</tr>
<tr>
<td>CIR events</td>
<td>11</td>
<td>10</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>ICME events</td>
<td>69</td>
<td>59</td>
<td>67</td>
<td>58</td>
<td>57</td>
</tr>
</tbody>
</table>

Table 1 summarizes the application of these electric field and plasma boundary conditions for the five run sets to be discussed in this study. The run sets will be referred to by their number for the rest of this report.

Of the 90 intense storms from 1996 to 2005, not all of them were usable in this study. There are various reasons for omitting a storm from consideration, and these reasons vary depending on the run set. The biggest cause for removal from run sets #1 and #2 is that a large (greater than 4 h) gap exists in nightside LANL satellite coverage during the main phase of the storm. Run sets #2, #4 and #5 also need solar wind data, and a large (greater than 4 h) gap during the main phase was the reason for exclusion. Yet another reason for these three run sets to lose a storm from consideration is instability in the numerical result, often caused by intense localized electric fields that yield negative phase space densities. The tallies of usable storm events for each run set is given in Table 2, along with the breakdown of how many of these remaining storms were driven by a CIR/HSS solar wind structure or an ICME (as defined by Zhang et al. (2007a,b)).

The inputs for all 90 storms were examined visually to determine the goodness of the MPA data during each storm’s main phase and those storms missing more than 4 h of data in this interval were excluded from the analysis. The final tally of usable storm intervals is given in Table 1. It is seen that 11 of the 90 storms were dropped from consideration, most of these (7 of the 11) from magnetic cloud-driven events (the other four classifications each lost one event from their original total).

3. Results

The HEIDI model was used to simulate the ring current intensity and morphology throughout a 4-day window including the pre-storm phase, main phase, and recovery phase for each of the intense storms. Data-model comparisons were
conducted against the Dst* index and the geosynchronous plasma moment values near local noon. Each of these comparisons is objectively presented below, followed by a discussion and interpretation of the results in the following section.

(a) DPS–Dst* comparison

The Dst index is a global, low-latitude magnetic perturbation quantifying the distortion of Earth’s magnetic field away from a dipole (Sugiura & Kamei 1991). This index, however, includes perturbations from current systems beyond those in near-Earth space, and so this study will use the Dst* index instead. The Dst* is more relevant because it removes the influence of the magnetopause currents and induced currents within the Earth, as well as adds in a quiet-time offset value. The form to be used here is

$$\text{Dst}^* = \frac{\text{Dst} - D_{MP}D_Q}{C_{IC}},$$

where $D_{MP}$ is an estimate of the contribution from the magnetopause currents (based on the upstream solar wind dynamic pressure), $D_Q$ the quiet-time offset value (11 nT) and $C_{IC}$ the correction factor for the contribution from induced currents within the Earth (here, 1.3). A simulation equivalent to the Dst* index comes from the Dessler–Parker–Sckopke relationship (Dessler & Parker 1959; Sckopke 1966)

$$\text{Dst}^*_{DPS} \text{ (nT)} = -3.98 \cdot 10^{-30} E_{RC} \text{ (keV)}$$

(hereinafter referred to as DPS), which relates the total energy content of the plasma within the inner magnetosphere to a magnetic perturbation at the centre of the Earth. Carovillano & Siscoe (1973) showed that this is identical to the perturbation averaged around the Equator of the Earth, and therefore, it is used as a rough equivalent modelled value to the Dst* index. Even though there are many caveats to using this equivalence (e.g. Liemohn 2003), it is a useful comparison for the overall accuracy of the simulation result.

Liemohn & Jazowski (2008) showed a number of example cases of run set #1 results, particularly for the more numerous ICME-driven events. Here, a CIR-driven storm is highlighted to demonstrate a typical Dst*–DPS comparison. Figure 1 presents input and output time series for the storm on 4 September 2002 for run sets #2 and #4 (figure 1a,b, respectively). The rows show plots for the solar wind velocity ($x$ component), the interplanetary magnetic field ($z$ component), the density of the MPA values in the nightside boundary condition time series (re-analysis average and maximum for run set #4 in figure 2c) and the observed and modeled Dst*/DPS magnetic perturbations. It is seen that run set #2 model configuration accurately reproduces the Dst* time series, while run set #4 configuration matches the timing and trends of the time series but not the overall magnitude of the storm. This is actually a ‘best-case’ simulation result for a CIR–HSS-driven event, in which the model results are quite close to the observed values.

Various forms of quantitative data-model comparison can be extracted from these time series. Figure 2 is one such comparison, showing scatter plots of the peak (i.e. minimum) Dst* and DPS values for each storm. Each column shows a different run set. Scatter plots with the results for all of the usable events are

shown in the top panel for each run set. The lower panels categorize the events according to their solar wind drivers. It is seen that run sets #1 and #3 (V–S E-field) have more variability about the unity line than run sets #2, #4, and #5 (S–C E-field), with some storm events significantly over- or underestimated by the model. In addition, the S–C E-field run sets are tightly aligned and better correlated with the Dst* minimum values, but the linear fit is often below unity.

Figure 3 shows a similar set of scatter plots, except that the y-axis value is an approximate ring current input function (again, plotted against the simulated DPS minimum value). The input function is a multiplication of the outer boundary plasma density and a measure of the electric field at the nightside outer boundary

\[ \text{Input function} = I = A \cdot n_{\text{corr}}. \]

Figure 2. Scatter plots of the simulated minimum Dst* value (given by the DPS relation) against the observed minimum Dst* value for each storm for (a) run set #1, (b) run set #2, (c) run set #3, (d) run set #4 and (e) run set #5. The panels show the results for (i) all usable events, (ii) CIR-driven storms only and (iii) ICME-driven storms only. The dashed line in each panel shows a perfect prediction of the minimum value, and the $R$-value in each panel is the linear correlation coefficient of the points. (a)(i) $R = 0.74$. (a)(ii) and (e)(ii) $R = 0.65$. (a)(iii) $R = 0.73$. (b)(i) $R = 0.84$. (b)(ii) $R = 0.30$. (b)(iii) $R = 0.83$. (c)(i) $R = 0.76$. (c)(ii) $R = 0.63$. (c)(iii) $R = 0.74$. (d)(i),(iii) and (e)(i) $R = 0.86$. (d)(ii) $R = 0.48$. (e)(iii) $R = 0.85$.

The $A$ parameter is different for the run sets, depending on the electric field description. For the Volland–Stern electric field simulations, the $A$ parameter is the Kp-dependent activity coefficient from Maynard & Chen (1975). For the self-consistent electric field simulations, the $A$ parameter is the largest radially inward electric field value on the outer boundary of the simulation. The $n_{corr}$ value is a
modified version of the nightside plasma density to account for the slight increase in density owing to the assumed compositional split with the Young et al. (1982) formula (see Liemohn & Jazowski 2008). The input values plotted in figure 3 are not instantaneous values at some time during the event, but rather an average over the 12h prior to the storm peak. This duration was chosen because Thomsen et al. (1998) also used 12h for their input function analysis, and Ilie et al. (2008) found that the main phase of intense storms at solar maximum is, on average, 12h long.

Figure 3. Same as figure 2 except comparing the 12h integrated input function against the modelled DPS minimum value for each storm. Note that the scales are different between the V-S and S-C electric field run sets ((a) #1 and (c) #3 are on the same scale, while (b) #2, (d) #4 and (e) #5 are on a different scale). (a): (i) $R = 0.79$, (ii) $R = -0.77$, $R = -0.78$. (b) (i) $R = 0.67$, (ii) $R = 0.68$, (iii) $R = 0.66$. (c) (i) $R = -0.74$, (ii) $R = -0.46$, (iii) $R = -0.73$. (d) (i) $R = 0.72$, (ii) $R = 0.42$, (iii) $R = 0.70$. (e) (i) $R = 0.68$, (ii) $R = 0.39$, (iii) $R = 0.67$. (i) All events; (ii) CIR events; (iii) ICME events.

Table 3. Ground magnetic perturbation data-model comparisons.

<table>
<thead>
<tr>
<th></th>
<th>set #1</th>
<th>set #2</th>
<th>set #3</th>
<th>set #4</th>
<th>set #5</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPS/Dst*: CIRs</td>
<td>0.62</td>
<td>0.62</td>
<td>0.45</td>
<td>0.48</td>
<td>0.42</td>
</tr>
<tr>
<td>DPS/Dst*: ICMEs</td>
<td>0.84</td>
<td>0.76</td>
<td>0.64</td>
<td>0.66</td>
<td>0.59</td>
</tr>
<tr>
<td>DPS ratio: CIR/ICME</td>
<td>0.75</td>
<td>0.81</td>
<td>0.70</td>
<td>0.73</td>
<td>0.72</td>
</tr>
<tr>
<td>input integral: CIRs</td>
<td>1.22</td>
<td>2.09</td>
<td>1.02</td>
<td>1.81</td>
<td>1.84</td>
</tr>
<tr>
<td>input integral: ICMEs</td>
<td>2.15</td>
<td>3.19</td>
<td>1.98</td>
<td>2.64</td>
<td>2.61</td>
</tr>
<tr>
<td>input ratio: CIR/ICME</td>
<td>0.57</td>
<td>0.65</td>
<td>0.52</td>
<td>0.69</td>
<td>0.70</td>
</tr>
</tbody>
</table>

**Figure 3** shows high correlations between the input functions and the resulting DPS minimum. This, of course, is expected, because the resulting DPS minimum is a product of the input function. The variability between these two quantities, however, differs for the five run sets and for the different solar wind drivers. In particular, scatter plots for run set #1 show far more spread in the \(\langle I \rangle\)-to-DPS relationship than those of the other runs sets, with run sets #4 and #5 exhibiting the tightest linear correlation in this input–response relationship. In addition, the variability within each plot is greater for larger storm intensity, especially for run sets #1, #2 and #3. There are many individual storms in which the simulated DPS values are well above or below what is expected for the integrated input function for that event owing to differences between the modelled and true input conditions or convection patterns. All of the CIR/HSS storms have small input functions and small resulting DPS minimum values.

**Table 3** shows a further quantification of these scatter plots. Listed are the ratios of the modelled and observed DPS/Dst* minima, categorized by solar wind driver, as well as the model–model ratio for these two driver classes. On average, this numerical configuration of the HEIDI model underestimates the observed Dst*. This is true not only for the minimum values of the storms but also for the average Dst* values throughout the event (not shown). HEIDI is less accurate with the re-analysis moments (run sets #3 and #4), even though this input includes spatial dependence and should yield a better solution. HEIDI is also more accurate for ICME storms than for CIR/HSS storms regardless of the model configuration, with the model–model ratio between 0.7 and 0.8 for all five run sets.

**Table 3** also lists the average input function values for CIR/HSS and ICME storms and model–model ratios for the input function values from these solar wind drivers. The model–model ratio of the input functions ranges from 0.5 to 0.7 across the run sets, with no particular correlation to the model–model ratios of the DPS minima (third row).

(b) **LANL MPA moments comparison**

The Dst*–DPS comparisons are interesting and useful for an assessment of the overall intensity of the ring current, but they cannot assess morphology and other ring current properties. One method of investigating this is to compare the HEIDI results with dayside particle observations. To do this, LANL MPA moments of
the hot ions (in the energy range of 100 eV to 45 keV) will be compared against HEIDI density and temperature integrals whenever one of the satellites is near local noon. Because the flow trajectories are from the nightside to the dayside, this data-model comparison involves a mutually exclusive set of observations from those used to provide the outer boundary condition to the simulations.

Figures 4 and 5 present hot-ion moments from satellite LANL-97A and LANL-01A (figures 4 and 5, respectively), along with HEIDI simulation results from run sets #2 and #4 (figures 4a,b and 5a,b, respectively). The x-axis time interval is the 24h of 4 September 2002, which is the day of the storm peak (Dst$_{\text{min}}$ of $-109$ nT at 06 UT). The two vertical dashed lines in each plot show the times when each of the LANL satellites passed by local noon (yellow) and local midnight (black). In addition to the MPA moments, three values from the HEIDI simulation are shown in each plot: that for H$^+$ only, O$^+$ only and a combined H$^+$ and O$^+$ result.

For the density time series, the LANL values should be compared against the combined H$^+$ and O$^+$ values. Note that this is not a simple summation but rather only includes a quarter of the O$^+$ density from the model. This takes into the account how the O$^+$ ions are included in the MPA moment calculations (a calculation that assumes everything is H$^+$). For the two temperature time series, the MPA values should be compared against the O$^+$-only numbers from HEIDI. This is because the H$^+$ values include SOPA measurements at high energies in the outer boundary condition, whereas the O$^+$ boundary condition does not.

The time interval of interest for this study is that near local noon (the yellow vertical dashed line in each panel). This is because the LANL values are used as the nightside boundary condition, and noon represents the local time farthest away from this possible double usage of the data. Therefore, the data-model comparisons are made by taking an average of the appropriate moments within an hour of local noon, removing any times when the satellite or simulation crossed into the magnetosheath. For LANL-97A (figure 4), this occurs during the late main phase of the storm. For LANL-01A (figure 5), the satellite passes local noon during the recovery phase, over 6h past the storm peak. In general, the simulation results agree quite well against the data within an hour or so of local noon. Except for a few mistimed density spikes, combined (H$^+$ and O$^+$) density curves from HEIDI match the observed MPA density in all of the comparisons. Similarly, the O$^+$-only temperature results from HEIDI are very close to the observed MPA temperatures, except for run set #4 compared with LANL-01A (where the model results are quite low).

There are some very interesting similarities and differences between the four sets of plots (for the two satellites and two run set results). One of the similarities is a characteristic pattern in the prenoon sector of a very low density and rather hot temperature, both in the measurements and in the simulations. Because low-energy ions convect/corotate around the dawn side of the Earth and high-energy ions magnetically drift around the dusk side, the LANL hot-ion moments in the morning sector during storms often reveal an abrupt change from a high-density, low-temperature population near dawn to a low-density, high-temperature population near noon. The exact location of this shift is directly related to the spatial morphology and time history of the convection electric field. Given a straight dawn-to-dusk electric field (like in the Volland–Stern description), stronger field intensity will move this transition away from dawn
Figure 4. Data-model comparisons of geosynchronous orbit hot-ion moments for (a) run set #2 and (b) run set #4 against MPA moments from LANL satellite LANL-97A during the magnetic storm on 4 September 2002. Shown are the comparisons for (i) density, (ii) perpendicular temperature and (iii) parallel temperature. The yellow dashed vertical line indicates local noon (during the main phase of the storm) and the vertical black dashed line is local midnight. For the density, the MPA values should be compared with the summed HEIDI values, while the MPA temperature time series should be compared with the HEIDI O+-only values.
Figure 5. Same as figure 4 except showing the HEIDI-MPA comparison with LANL satellite LANL-01A. This satellite crosses local noon during the recovery phase of this storm. Black line, MPA value; red line, HEIDI (H\(^+\) and O\(^+\)); blue line, HEIDI (H\(^+\)); green line, HEIDI (O\(^+\)).
and towards noon. In figure 4, run set #4 results actually show a double peak just prior to local noon (just to the ‘left’ of the yellow line), with a short interval of the dense, cold population in the middle of the tenuous and hot population. This is due to time history effects and a complicated spatial pattern for the electric field, rapidly moving the boundary relative to the spacecraft position as it moves around the dayside. Run set #2 shows a small double peak, but it is far less pronounced.

Another similar feature in the plots is a density peak and temperature minimum near dusk. This is because of the open drift paths at this location and the ability of plasma sheet ions to skim the simulation domain.

It is interesting to note that the nightside HEIDI moments do not exactly follow the MPA values, even though the MPA values are being used in the creation of the outer boundary condition. There are several explanations for this discrepancy, but the two main reasons are as follows: several LANL satellites are combined to make the outer boundary condition; and moments instead of actual fluxes are used in the outer boundary condition.

Figure 6 shows scatter plots of the model/data density ratio for each satellite for each storm simulation. The ratio values represent an average value over a 2 h window straddling local noon on the second day of the simulations (which is the day of the storm peak). There is no separation for the timing of the storm peak relative to the satellite’s passage by local noon, so comparisons during the main phase and recovery phase are mixed in each of these plots. In addition, because there are anywhere from one to five LANL satellites with data available for each storm, there are many more points on these plots than those that are in figures 2 and 3, which had only one point per storm event.

There are several important features to note in these plots. The first is that the model, on average, matches the observed density and the median ratio value is very close to unity for all five run sets for all three storm classification options shown. The overall median for all points in figure 6 is 1.1 and 70 per cent of the ratios are between 0.67 and 1.5 (i.e. within 50% of unity). A second feature is that the correlation coefficients are nearly zero, indicating no significant correlation between storm intensity and this density ratio for any of the run sets or classifications. A third feature is that the CIR/HSS-driven storms have about the same ratios as the ICME-driven events.

Figure 7 is similar to figure 6, except for the perpendicular temperature comparisons (between MPA and the O\(^+\)–only HEIDI results, within ±1 h of local noon on the day of the storm peak, for each satellite). Some of the features are the same as in the density ratio comparisons of figure 6. All of the correlations are near zero, indicating that the dayside temperature data-model comparison is independent of storm intensity. In addition, the CIR/HSS-driven storm ratios (plot (iii) for each run set) look very much like the ratios for the ICME-driven storms (plot (ii) for each run set), implying that there is no difference between storm drivers in this data-model comparison. There is one significant difference between figures 6 and 7, however. While the median values for run sets #1 and #2 are near unity, the ratios for run sets #3, #4 and #5 are systematically lower. This means that the model result has lower temperatures than the observed values on the dayside. This is a direct result of the nightside boundary condition having too low of a temperature (which, for these three run sets, came from the O’Brien & Lemon (2007) re-analysis study).

Figure 6. Same as figure 2 except showing the ratio between the HEIDI and LANL MPA near-noon density moments as a function of the simulated DPS minimum for LANL satellite for each storm for (a) run set #1, (b) run set #2, (c) run set #3, (d) run set #4 and (e) run set #5, as categorized by their solar wind drivers. (a) (i) $R = 0.03$, (ii, iii) $R = 0.02$. (b) (i) $R = -0.12$, (ii) $R = -0.14$, (iii) $R = -0.18$. (c) (i) $R = -0.23$, (ii) $R = -0.11$, (iii) $R = -0.22$. (d) (i) $R = -0.30$, (ii) $R = -0.15$, (iii) $R = -0.31$. (e) (i) $R = -0.39$, (ii) $R = -0.12$, (iii) $R = -0.40$. (i), all events; (ii), CIR events; (iii) ICME events.

Table 4 distills these ratio scatter plots further by averaging the density and perpendicular temperature ratios as a function of run set and storm classification. Note that these are averages instead of medians, and so the high-value tail of the distribution skews the numbers upward.
There is a difference between CIR/HSS-driven storms and ICME-driven storms in the density ratios. For run sets #1 and #2 (time series of the event-specific LANL data for the plasma outer boundary condition), the CIR events have a higher average ratio, while for run sets #3, #4 and #5 (the LANL reanalysis values), the ICME events have a higher ratio. This is clearly seen in row 3 of table 4, which lists the ratio of CIR/HSS densities to the density values for the ICME events. The change appears to be with the CIR/HSS-driven events, because the density values for the ICME events (row 2) do not change much in their
CIR and CME drivers of the ring current

Table 4. Hot-ion moments data-model comparisons.

<table>
<thead>
<tr>
<th></th>
<th>set #1</th>
<th>set #2</th>
<th>set #3</th>
<th>set #4</th>
<th>set #5</th>
</tr>
</thead>
<tbody>
<tr>
<td>density ratio: CIRs</td>
<td>1.57</td>
<td>1.67</td>
<td>1.34</td>
<td>1.22</td>
<td>1.22</td>
</tr>
<tr>
<td>density ratio: ICMEs</td>
<td>1.42</td>
<td>1.35</td>
<td>1.53</td>
<td>1.33</td>
<td>1.44</td>
</tr>
<tr>
<td>density ratio: CIR/ICME</td>
<td>1.10</td>
<td>1.24</td>
<td>0.87</td>
<td>0.92</td>
<td>0.85</td>
</tr>
<tr>
<td>Tperp ratio: CIRs</td>
<td>1.30</td>
<td>1.33</td>
<td>0.38</td>
<td>0.40</td>
<td>0.11</td>
</tr>
<tr>
<td>Tperp ratio: ICMEs</td>
<td>1.03</td>
<td>1.17</td>
<td>0.39</td>
<td>0.40</td>
<td>0.20</td>
</tr>
<tr>
<td>Tperp ratio: CIR/ICME</td>
<td>1.25</td>
<td>1.14</td>
<td>0.98</td>
<td>1.00</td>
<td>0.57</td>
</tr>
</tbody>
</table>

average ratio across the run set, while the CIR/HSS event ratios (row 1) drop by several tenths between the two broad classes of outer boundary condition. All of the ratio values in the first two rows of table 4 are above unity, however, indicating that the HEIDI code is reproducing (or overestimating) the density of the ring current ions for both ICME and CIR/HSS storms.

The temperature ratios do not show such a difference between the CIR/HSS storms and the ICME storms, but they do have very different values between the two boundary condition sources. The average temperature ratios for run sets #1 and #2 are above unity for both CIR/HSS and ICME storm classes, while the average ratios for run sets #3, #4 and #5 are well below 0.5 for both storm classes. The final row in table 4 lists the division of the CIR/HSS ratio over the ICME ratio. These model–model ratios are near unity for all of the run sets except #5, for which the CIR/HSS storms are significantly lower than the ICME storms.

4. Discussion

The question was posed at the beginning of this article about whether the fundamental physics of the ring current is different between ICME-driven intense storms and CIR/HSS-driven intense storms. This was explored with a number of numerical simulations for all of the intense magnetic storms over the last solar cycle (for years 1996–2005). Two main data-model comparisons were conducted, one between the Dst* time series and a simulated analogue using the DPS relation and the other between observed and modeled hot-ion moments near local noon.

There are a few key differences between the ICME-driven events and the CIR/HSS-driven events. While the Dst* minimum value is, on average, underestimated by HEIDI, the amount of underestimation is larger for the CIR/HSS storms than for the ICME storms by 20–30%. The input function integrals are also lower for the CIR/HSS storms; in fact, they are lower by an even larger amount (up to a factor of two in run set #3). Another difference is that the CIR/HSS storms show a boundary condition dependence in their dayside data-model comparisons that is not seen in the ICME event comparisons.

A detailed examination of figure 2 reveals an interesting fact. The HEIDI model underestimated the Dst* minimum value for all of the CIR/HSS events, regardless of storm intensity and regardless of runs set (i.e. model configuration options). This is not the case for the ICME events, which include at least one over-estimated Dst* minimum for each run set. This underestimation is consistent

with the systematic lower value in input function integral for the CIR/HSS events relative to the ICME events. From this, it can be inferred that, while HEIDI is underestimating Dst* for all events on average, it is more accurate at simulating ICME-driven intense storms than CIR/HSS-driven intense storms.

However, a counterargument can be made from the dayside data-model comparisons with \textit{in situ} observations. The goodness of fit in the comparisons is about the same between CIR/HSS storms and ICME storms (averaging across the five run sets), and HEIDI on average, overestimates the density regardless of the input/boundary conditions. In fact, for run sets #1 and #2, the dayside density comparisons reveal a larger overestimation in the CIR/HSS events than in the ICME events. From this, it can be inferred that HEIDI is not underestimating the ring current intensity and, in fact, is preferentially overestimating the ring current density for CIR/HSS storms.

How can these two findings be consistent? A possible resolution to this dilemma is that the Dst*–DPS equivalence is not entirely justified. That is, for the CIR/HSS-driven events, it is possible that Dst* has other contributors beyond the inner magnetosphere (or, more precisely, these other contributors are systematically larger for this class of storm). There are several candidate current systems that can also contribute to the Dst index.

One is the tail current (or, more generally, any cross-field current beyond the simulation domain of HEIDI). Turner \textit{et al.} (2000, 2001) estimated that roughly 25 per cent of the storm-time Dst index is from the tail current, and Liemohn (2003) showed that this is roughly accounted for by a systematic overestimation inherent in the DPS relation (because of the assumption that all of the plasma is within the integration volume, the DPS relation implicitly includes a truncation current). As has been noted previously (e.g. Soraas \textit{et al.} 2004), charged particles in the plasma sheet are not driven as intensely or towards the Earth during HSSs (relative to ICME-storm injections) and therefore are not penetrating as far into the dipolar region of the inner magnetosphere. If, for CIR/HSS storms, the cross-tail current is intensified without a similarly sized increase in convection, then the tail current will preferentially contribute more to the Dst index than during other storm intervals. This is, in our view, the most likely cause of the discrepancy.

In support of this view, Ganushkina \textit{et al.} (2004, 2010) showed that the tail current intensifies first and tracks the drop in the Dst index. The ring current develops more slowly and then stays at an increased level longer than the tail current. Ganushkina \textit{et al.} (2004) classified storms according to the Dst minimum, concluding that the currents dominantly contributing to the Dst index are different during small and large storms. They found a Dst transition of roughly $-150\,\text{nT}$, where storms smaller than this level have a Dst index dominated by the tail current and more intense magnetic storms have Dst dominated by the ring current. Because all of the CIR/HSS driven storms in this study have a Dst minimum value higher (i.e. closer to zero) than $-150\,\text{nT}$, a particularly large contribution from the tail current can explain the Dst–DPS discrepancy for these events.

Another possibility is an unusually large contribution from ionospheric currents. It has been shown that ionospheric currents might contribute tens of nanotesla (positive) to the Dst index during substorm expansion phases if a Dst magnetometer station is directly equatorward of the substorm current wedge and a similar offset negative if all stations are far from the current wedge (e.g. Friedrich \textit{et al.} 1999; Munsami 2000). Therefore, if CIR/HSS storms have a relatively large...
number of substorms during the main and early recovery phases of the storm, and the timing of these is such that the Dst* index is preferentially lower (made more negative), then the Dst* index might be systematically off from that in other storm classifications.

Another way in which the storm responses could be different is that the injection rates into the inner magnetosphere are systematically different between ICME and CIR/HSS storms. That is, ICME-driven storms often have a prolonged period of strong and relatively steady southward IMF, which drives strong convection within the magnetosphere and the formation of a strong ring current (e.g. Kamide et al. 1997; Daglis et al. 2003). CIR/HSS events, however, often have a fluctuating IMF that results in ring current injections that are numerous but weak (e.g. Soraas et al. 2004; Tsurutani et al. 2004). Our self-consistent model results should account for this difference, because the upstream solar wind conditions are included in the simulation to define the high-latitude boundary condition on the electric potential solution.

A final possibility that could be influencing the Dst index is a particularly weak magnetopause current contribution. The Dst* conversion removes magnetopause currents with an empirical relationship depending on the solar wind dynamic pressure. However, other factors in the formation of the magnetopause current include the IMF magnitude (an additional pressure balance term), the southward intensity of the $z$ component of the IMF (erosion of the dayside magnetosphere by reconnection) and the shape of the magnetopause (changing the way the current contributes to a low-latitude magnetic field distortion). If CIR/HSS storms have a systematically low IMF magnitude, weak IMF $B_z$ south or high radius of curvature for the magnetopause topology, then the standard correction in the Dst* formula might over-represent this current’s contribution and Dst* would be more negative than it should be.

A final comment should be made about this study in relation to those of Jordanova (2006a,b) and Jordanova et al. (2009). These other studies also examined data-model comparisons of CIR/HSS and ICME storms using a very similar numerical model. They also found the model is better at simulating ICME storms that CIR/HSS storms, in particular during the recovery phase, which was severely underestimated by the model for the CIR/HSS storms. A primary contribution that the present study offers in addition to the conclusion of these earlier works is statistical significance. Both Jordanova (2006a,b) and Jordanova et al. (2009) each examined two storms, one each from the ICME and CIR/HSS categories, in their analysis. The present study has considered all of the intense storms from the last solar cycle, including the four in these two previous studies, and included a number of different model configurations to explore the similarities and differences. It is reassuring that our findings are consistent with those of these two other studies, but that does not negate the findings of this work.

5. Conclusions

The 90 intense magnetic storms ($\text{Dst}_{\text{min}}$ less than $-100\text{nT}$) of solar cycle 23 (from 1996 to 2005, inclusive) were simulated with the HEIDI model. Five different simulation run sets were conducted using two different electric
field descriptions and three different plasma outer boundary conditions. The storms were classified according to their solar wind driver structure, in particular separating CIR/HSS-driven events from ICME-driven events. Data-model comparisons were conducted to explore the similarities and differences between these two storm categories, in particular to determine if the physical processes of the ring current are different during these two classes of storm drivers.

The synthesis of the findings from this study is that the fundamental physics of the inner magnetosphere are most likely not different between CIR/HSS-driven intense storms and ICME-driven intense storms. A few minor differences exist, but the overall response of the ring current to the storm driving is roughly the same. The differences in the data-model comparisons were just as large when comparing results for the same category but with different boundary conditions (plasma and electric field) as the differences between the storm categories for the same boundary conditions.

However, something else is different between these event categories, and this is revealed in the inconsistency of the Dst*–DPS comparisons and the dayside in situ data-model comparisons. The discrepancy shows that the HEIDI model tends to underestimate Dst* for CIR/HSS storms (relative to ICME events) but systematically overestimates the dayside hot-ion density for CIR/HSS storms (again, relative to ICME events). This leads to the conclusion that either the dayside comparisons are flawed or that other contributors to the Dst* index are different between these two storm classes. While the former is possible, the latter is more likely and physically justifiable. Several possibilities were discussed above, but the leading candidate is an unusually large contribution from the tail current.

It is worth noting that Liemohn et al. (2007) also found that HEIDI reproduced the ring current intensity but underestimated the Dst* time series. That study, however, considered a sawtooth oscillation interval during an intense storm driven by a magnetic cloud passage. That event (18 April 2002) is included in the ICME-driven events of this study. Therefore, not all ICME-driven events are alike, and some might have similar outer magnetospheric processes governing geospace as that in the CIR/HSS storm class.

Finally, it should be stated that this is not a definitive study on statistical data-model comparisons between CIR/HSS storms and ICME storms. One obvious extension of this study is to include more events, especially for the CIR/HSS storm class. Another is to consider comparisons of only similarly sized storms (i.e. comparing those storms within a particular Dst_min range). A third possible extension is to compare storms with similarly sized input condition intensities (either solar wind values or the integral input function). A final point to mention is that only two datasets were considered in the data-model comparisons, Dst* and dayside LANL plasma observations. Many more datasets exist that could be included in this analysis. Therefore, future work in this field is encouraged.

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