GEOPHYSICAL RESEARCH LETTERS, VOL. 38, L20106, doi:10.1029/2011GL049611, 2011

Deciphering magnetospheric cross-field currents

Michael W. Liemohn,[1] Darren L. De Zeeuw,[1] Raluca Ilie,[2] and Natalia Y. Ganushkina[1,3]

Received 7 September 2011; accepted 23 September 2011; published 27 October 2011.

[1] A single near-tail magnetic field line can be part of a variety of cross-field current systems, making the interpretation of such currents difficult. It is shown that global, coupled-model simulation results from the 22 October 1999 storm include a field line crossing downtail at L = 8 during the main phase that contains partial ring current, symmetric ring current, and tail current simultaneously. Such field lines with multiple currents are common in the near-Earth tail. Another time from the same event showed two closely-spaced field lines (L = 6.0 and 6.5) with completely different current systems on them (one entirely symmetric ring current and the other entirely tail current). It is shown that, for this storm from this simulation, the tail current inner edge systematically shifts inward then outward during the storm main phase and that most of the Dst perturbation is from the ring current (both partial and symmetric). Caution is advised when analyzing observational or numerical cross-field currents and when making conclusions about which type of current system dominates the distortion of the near-Earth magnetosphere.

Citation: Liemohn, M. W., D. L. De Zeeuw, R. Ilie, and N. Y. Ganushkina (2011), Deciphering magnetospheric cross-field currents, *Geophys. Res. Lett.*, *38*, L20106, doi:10.1029/2011GL049611.

1. Introduction

[2] The interpretation of currents in the near-Earth magnetotail and inner magnetosphere is difficult. Yet, this is important for understanding the physics governing particle flow because these currents distort the magnetosphere from its typical quiet-time configuration [e.g., *Parker and Stewart*, 1967; *Chun and Russell*, 1997; *Tsyganenko et al.*, 2003; *Ganushkina et al.*, 2004; *Antonova*, 2004; *Daglis*, 2006]. As the hot ion energy content increases, a diamagnetic cavity forms, altering the flow of plasma through the region, as seen in self-consistent magnetic field modeling studies [e.g., *De Zeeuw et al.*, 2004; *Chen et al.*, 2006; *Zaharia et al.*, 2006]. The distortion is not uniform, however, and is a strong function of the intensity and location of the magnetospheric current systems. Furthermore, ionospheric closure of the partial ring current distorts the near-Earth electric field, resulting in additional feedback on the drift paths of particles through geospace [e.g., *Jaggi and Wolf*, 1973; *Fok et al.*, 2001, 2003; *Ridley and Liemohn*, 2002; *Sazykin et al.*, 2002; *Ebihara et al.*, 2005]. In addition, the dayside magnetopause is often compressed during times of strong driving, leading to multiple magnetic field minima along the dayside closed field lines just inside the magnetopause [e.g., *Tsyganenko*, 1995; *Antonova and Ganushkina*, 2000] and the creation of unusual drift paths for energetic particles [e.g., *Shabansky and Antonova*, 1968; *Sheldon et al.*, 1998; *Chen et al.*, 1998; *Dandouras et al.*, 2009] and a bifurcated "cut ring current" in this region [e.g., *Antonova*, 2004].

[3] Furthermore, each current system contributes differently to the nonlinear feedback processes within geospace. Only the partial ring and tail currents lead to asymmetric magnetic field distortions, and only the partial ring current leads to electric field perturbations. The response of geospace to a particular driving condition is therefore dependent on the changing nature of the current closure within geospace because a redistribution of current flow from one closure path to another could radically change the electric and magnetic distortions. Deciphering the relative locations, intensities, and variability of near-Earth currents is integral to understanding the geospace dynamics, especially at the system level.

[4] It is problematic to obtain near-Earth currents from observations. While it is possible to determine local current intensities from observed plasma pressure time series [e.g., *Lui et al.*, 1987], it is impossible to decipher the closure of these currents. Because all non-zero-energy charged particles gradient-curvature drift, they all contribute to the local current density. Indeed, all overlapping particle populations at a given spatial location must contribute to the same current system because current streamlines cannot cross or coexist. Furthermore, it is impossible to tell to which current system a particle contributes simply from the plasma characteristics (e.g., temperature or spatial location).

[5] Currents (or their related magnetic perturbations) can be compiled statistically from all available data, and then binned according to some relevant parameter [e.g., *Zanetti et al.*, 1984; *Tsyganenko*, 1989, 1995; *Lui et al.*, 1994; *Alexeev et al.*, 1996; *Le et al.*, 2004], or the currents can be deciphered from the available observations for a particular storm [e.g., *Lui et al.*, 1987; *Iyemori*, 1990; *Chun and Russell*, 1997], or a hybrid of the two [e.g., *Ganushkina et al.*, 2002; *Tsyganenko and Sitnov*, 2007]. Magnetospheric currents have even been extracted from inversions of energetic neutral atom images [*Roelof et al.*, 2004]. *Ohtani et al.* [2007] found that, for a given value of Sym-H (Dst), the ENA emission from the ring current is more intense and the geosynchronous magnetic field is more stretched during the main phase than during the recovery phase and suggested that the relative contribution of the ring current (tail current) is more significant during the main phase (recovery phase). The relative contribution also changes during the course of storm-time substorms [*Ohtani et al.*, 2001; *Pulkkinen et al.*, 2006; *Kubyshkina et al.*, 2008]. The problem is that it is difficult to create a physically realistic description of the current systems and simultaneously ensure the uniqueness of the resulting current system.

---

[1] Atmospheric, Oceanic, and Space Sciences Department, University of Michigan, Ann Arbor, Michigan, USA.

[2] Los Alamos National Laboratory, Los Alamos, New Mexico, USA.

[3] Also at Finnish Meteorological Institute, Helsinki, Finland.

0094-8276/11/2011GL049611

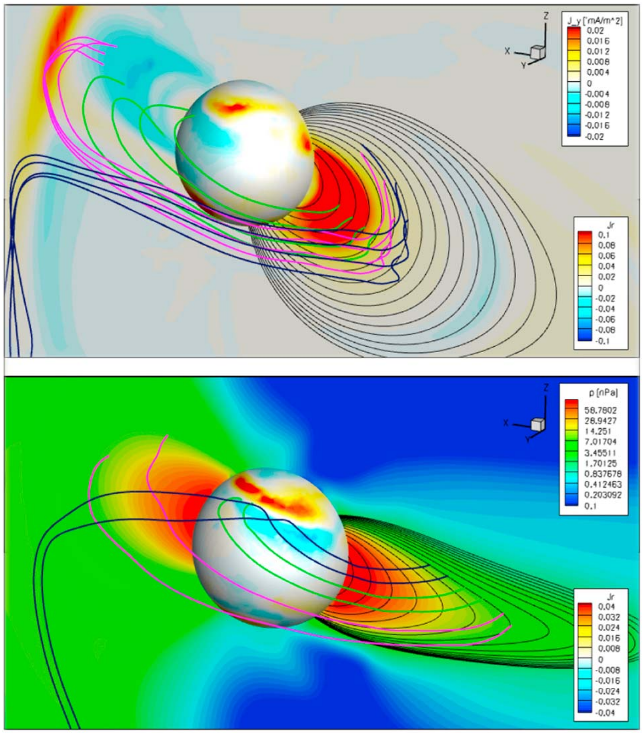

Figure 1. SWMF simulation results for the 22 October 1999 magnetic storm showing current streamtraces (thick colored lines) over a y = 0 planar slice and an R = 2.5 R_E spherical surface, with black lines showing magnetic field line traces, started every 0.5 R_E along the negative x axis out to 10 R_E. The current traces are colored by their type: symmetric ring (magenta), partial ring (green), and tail (blue). (top) Results at 0200 UT, during a convective lull in the main phase of the storm, with Jy current density on the plane and radial current density on the sphere. All of the symmetric ring current traces are at L = 6.0 and the tail current traces are at L = 6.5. (bottom) Results at 0930 UT, just prior to the simulated storm peak. The current streamtraces started at various latitudes along the L = 8.0 magnetic field line.

[6] Particle-transport-based modeling approaches offer some hope to determining the three-dimensional current systems. For example, *Liemohn et al.* [2001] examined the currents from a near-Earth hot ion drift physics model, concluding that most (at times nearly all) of the main phase Dst perturbation was from the partial ring current. This, however, is in conflict with studies like *Alexeev et al.* [1996], *Turner et al.* [2000], and *Kalegaev et al.* [2005], who found that the magnetotail current is a major contributor to the storm-time Dst perturbation. The study of *Ganushkina et al.* [2010] systematically analyzed the near-tail currents from two different modeling techniques, finding a disconnection between results that are observationally consistent (that is, yielding good data-model comparisons) and physically accurate (that is, satisfying particle drifts through geospace).

[7] Thus, the problem has remained unresolved because it is complicated to unravel the flow of current through the near-Earth tail region. There is disagreement about which magnetospheric current dominates at what times during storms. This study shows that there is reason for the confusion: a single field line can contain perpendicular current belonging to several different current systems. It is very hard to interpret local current observations as belonging to one system or another, and caution must be used when deciphering near-Earth currents from either data or modeling results.

2. Numerical Approach

[8] This study uses the Space Weather Modeling Framework (SWMF) for its numerical simulations. The SWMF is a suite of space physics models that are fully coupled to each other through a robust coupling scheme [*Toth et al.*, 2005]. In particular, three numerical models are included as part of the geospace domains: the BATS-R-US magnetohydrodynamic (MHD) model [*Powell et al.*, 1999; *Gombosi et al.*, 2002; *Toth et al.*, 2006], the Rice Convection Model (RCM) [*Harel et al.*, 1981; *De Zeeuw et al.*, 2004]; and the Ridley Ionosphere Model (RIM) [*Ridley and Liemohn*, 2002; *Ridley et al.*, 2004].

[9] The focus of the presentation below is on the storm event of October 21–23, 1999. This was an intense magnetic storm driven by the sheath of an interplanetary coronal mass ejection, with the Dst index reaching a minimum value of −230 nT early on the 22nd. *Ganushkina et al.* [2010] studied this interval, conducting an initial analysis of the magnetospheric currents from this SWMF simulation. More details on the code set up, this magnetic storm interval, and the time history of the currents calculated by the SWMF is given by *Ganushkina et al.* [2010].

3. Results

[10] Examples of the complexity of the current within the near-Earth tail region is shown in Figure 1. Figure 1 (top) taken at 0200 UT on October 22, which is during a lull in the convection within the main phase. Prior to this, partial ring current and tail current dominated the inner magnetospheric current density. During the convective lull, however, the hot ions began to fill the drift paths around the Earth, converting some of the partial ring current into symmetric ring current. A very sharp boundary exists between the symmetric ring current and tail current at this time, with closely-spaced field lines in the near-Earth tail (L = 6 and 6.5) containing completely different current systems. Inward of the symmetric ring current, the partial ring current dominates, including at the equatorial plane. This partial ring current region includes banana currents (not shown), current loops that encircle a localized pressure peak with an outside westward current and an inside eastward current. The cross-field current through the midnight plane (color background in Figure 1, top) smoothly varies through these abrupt transitions in closure topology. This illustrates the difficulty is predefining currents to certain morphologies and regions.

[11] A second example is shown in Figure 1 (bottom), taken at 0930 UT, just prior to the simulated storm peak. Figure 1 (bottom) highlights an L = 8 field line with three different current systems flowing perpendicularly across it. Near the equator, the cross-field current closes around the Earth as symmetric ring current. Farther up the field line, partial ring loops are found that close through field-aligned currents into the ionosphere. Still farther up the field line, the cross-field current flows all the way to the magnetopause (thus, it is tail current). The pressure distribution in the

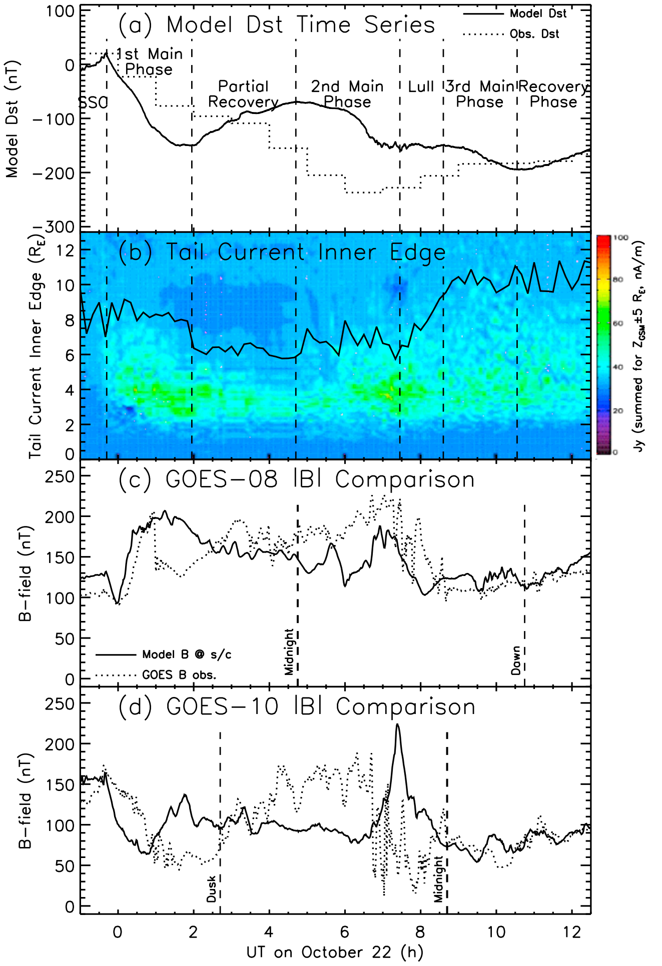

Figure 2. Time series of various results from the SWMF simulation of the 22 October 1999 storm. (a) Simulated (solid) and observed (dotted) Dst, with storm phases from the simulation indicated by dashed vertical lines. (b) Azimuthal current Jy through the y = 0 plane, integrated from −5 to +5 R_E in the z direction, from 0 to 13 R_E downtail. The black line is the innermost edge of the tail current streamtraces in the magnetic equatorial plane. As in 2a, the vertical dashed lines indicate the simulated Dst storm phase changes. (c) Magnetic field magnitude from the GOES-08 spacecraft (dotted), along with the MHD |B| value (solid) at the satellite location. The vertical lines mark local times, as indicated. (d) Same as Figure 2c except for the GOES-10 spacecraft.

midnight meridional plane (background color) shows no indication of distinct identifiers that coincide with the current system changes. The hot ions on this field line, therefore, contribute to all three of these cross-field current systems as they move along their bounce trajectory. This illustrates the difficulty in defining current systems from in situ particle pressure or flux observations.

[12] Figure 2 presents a detailed analysis of the near-Earth nightside current for this storm interval. Figure 2a presents the observed Dst time series, along with a simulated Dst value from a Biot-Savart integral of the entire MHD simulation domain. The overall intensity is very close between the two curves, but the timing and features in the simulated Dst do not exactly follow the measurement-based Dst progression. Storm phases for the simulated Dst time series are indicated on the plot.

[13] The color background in Figure 2b shows the current density Jy through the y = 0 plane, integrated from −5 to +5 R_E in the z direction, for a range of negative x distances in the near-Earth nightside. The overplotted black line is the innermost edge of the tail current in the magnetic equatorial plane, found manually through numerous current streamtrace extractions. Inward of this line, the magnetic equatorial plane contains banana current, partial ring current, and/or symmetric ring current. Of course, tail current exists inward of this line in some places at higher latitudes along the field lines, but it is a useful diagnostic for analyzing the systematic changes of the near-Earth current closure during this storm. Hereinafter, this line is referred to as the tail-ring breakpoint.

[14] In Figure 2b, it is seen that the tail-ring breakpoint often shifts abruptly when the simulated Dst undergoes a slope change. This is expected as the hot ions carrying the current respond to changes in the convective forces controlling their drift. During the initial segment of the main phase, the tail-ring breakpoint is near L = 8. It then suddenly shifts inward by 2 R_E at the start of the convective lull. It shifts outward slightly as strong convection resumes, oscillating around L = 7 during the second segment of the main phase. During the second convective lull, the tail current rapidly retreats beyond L = 10 and remains in the L = 10–12 range as the storm simulation reaches its peak. When the breakpoint is beyond L = 10, tail current still exists on lower field lines, as shown in Figure 1 (bottom) (at L = 8, for example), at higher latitudes along the field line. However, the current in the magnetic equatorial plane is symmetric ring current from inside of L = 6 to beyond L = 10 throughout this time interval.

[15] Another interesting point to make about Figure 2b is that the vast majority of the current intensity is located Earthward of the tail-ring breakpoint. This is true throughout the interval, regardless of storm phase. In fact, the tail-ring breakpoint closely tracks the 35 nA/m color contour. This implies that, for this storm from this numerical simulation, the ring current (partial and symmetric together) overwhelmingly dominate the Dst perturbation throughout the entire storm interval, with only a minor contribution from the tail current. *Ganushkina et al.* [2010], however, in their analysis of this same storm and model result, concluded that the SWMF results most likely underestimated the true intensity of the tail current. This could very well be true, given that the BATS-R-US MHD model often has plasma sheet temperatures that are too low (but densities are high, giving a realistic pressure [e.g., *De Zeeuw et al.*, 2004; *Zhang et al.*, 2007]. These MHD moments are then used as the boundary condition for the RCM, and the low temperatures might cause too much inward penetration of the Earthward edge of the hot ion pressure, therefore overpredicting the ring current intensity.

[16] As a validity check on these results, Figures 2c and 2d show GOES-08 and GOES-10 magnetic field data-model comparisons. The magnitudes are often reasonably close, especially in the late main phase and early recovery (when the tail-ring breakpoint is beyond L = 10). There are times when |B| is over or underestimated, and the GOES-10 model results show a premidnight dipolarization around 0730 UT, but in general the agreement is good. It appears that |B| is overestimated during the first main phase segment. This implies that the cross-field current is either too large inside

of geosynchronous orbit or too small beyond this altitude, supporting the finding of *Ganushkina et al.* [2010]. However, the opposite is seen for the second main phase segment, implying that either the near-Earth currents are too weak or the currents beyond geosynchronous orbit are too strong. During the third main phase segment, the data-model comparison is excellent, implying that the magnitudes of modeled currents are accurate.

4. Conclusions

[17] This study has shown that the current systems within the near-Earth nightside region exhibit spatially and temporally dynamic and complex morphologies that can quickly change depending on the flow of particles through geospace. Cross-field currents along a single field line can close in a number of ways: (a) entirely within the magnetosphere (either a banana current loop confined to one side of Earth, in which case it is part of the partial ring current, or as a symmetric ring current loop circumferencing the Earth); (b) through the ionosphere via field-aligned currents, in which case it is called partial ring current; or (c) via the magnetopause, in which case it is called tail current. For the 22 October 1999 storm, it was found in the SWMF results that the inner edge of the tail current changes systematically with storm phase, retreating to beyond L = 10 at the peak of the storm. The model shows that a majority of the Dst perturbation is caused by ring (partial and symmetric) current rather than tail current for this storm.

[18] The obvious caveat to this study is that it is based on simulation results from a single model suite, the SWMF. The result could be specious, looking nice but being physically unrealistic. However, the SWMF has been used to accurately simulate storm intervals [e.g., *Zhang et al.*, 2007; *Ilie et al.*, 2010a, 2010b] and has been validated against numerous data sets [e.g., *Wang et al.*, 2008; *Yu and Ridley*, 2008; *Welling and Ridley*, 2010]. The point of this study is not to show that the current systems are necessarily correct, but that they are complicated. A natural extension of this work, which is already underway, is a systematic analysis of cross-field current systems with the global magnetospheric results from modeling suites such as the SWMF and a quantification of current system locations relative to geospace driving conditions.

[19] That the cross-tail current systems are difficult to interpret is not a new concept. As mentioned in the introduction, many studies have considered the location and configuration of cross-field currents in the near-Earth tail, including overlapping regions for the tail and ring current [e.g., *Tsyganenko*, 1989; *Alexeev et al.*, 1996]. This study, however, presents an exact mapping of these currents through a global, three-dimensional, self-consistent numerical solution, showing that the currents are regularly abutted next to each other in very close proximity and change location throughout a storm event. Individual particles can contribute to a variety of current systems during a single bounce along the magnetic field, and certainly as they drift through the near-Earth tail and inner magnetosphere. It is impossible to tell, certainly from a local particle measurement but even from a radial slice through the near-Earth tail, which currents are located where with respect to the particle flux intensities.

[20] One implication of this finding is that predefining the locations of current loops within the nightside magnetosphere may not be a particularly accurate method of modeling the magnetospheric current systems. The issue is one of uniqueness. While it is very useful and physically insightful to determine a best-fit solution to a particular set of free parameters for the geospace current systems, it could be that there are other current configurations that match that set of observations equally well. That is, care must be taken in clearly understanding the fixed parameters in the current system definitions and the limitations that these constraints place on the results and subsequent findings.

[21] Another implication of these results is that magnetospheric current systems do not map well to characteristic features of the particle populations. This was qualitatively seen in Figure 1, with the changes in the current closure unconnected to any features in the plasma pressure or current intensity. Populations at particular locations and energies are not necessarily indicative of a certain cross-field current flowing through that region. Indeed, the same particle population can contribution to multiple cross-field current systems as they travel along their bounce path. For example from this study, low-energy plasma sheet particles at 10 R_E downtail contribute to the ring current at the peak of the storm and, conversely, high-energy inner magnetospheric particles (at $L < 6$) contribute to the tail current early in the main phase. Furthermore, current streamlines do not follow particle drift paths, and many different particles can carry the current at various places along the current loop. This is the case for the magnetospheric and ionospheric segments of the partial ring current loop, and this study illustrates that it is also true within the magnetosphere. Currents are not synonymous with plasma features and a clear distinction should be made between the terminology for current systems and that for particle populations.

[22] **Acknowledgments.** The authors would like to thank the US government for sponsoring this research, in particular NASA and NSF through various research grants. Support for NYG was provided by both Finnish and US sponsors, including the Academy of Finland.

[23] The Editor thanks George Siscoe for his assistance in evaluating this paper.

References

Alexeev, I. I., E. S. Belenkaya, V. V. Kalegaev, Y. I. Feldstein, and A. Grafe (1996), Magnetic storms and magnetotail currents, *J. Geophys. Res.*, *101*, 7737–7747, doi:10.1029/95JA03509.

Antonova, E. E. (2004), Magnetostatic equilibrium and current systems in the Earth's magnetosphere, *Adv. Space Res.*, *33*, 752–760, doi:10.1016/S0273-1177(03)00636-7.

Antonova, E. E., and N. Y. Ganushkina (2000), Inner magnetospheric currents and their role in the magnetosphere dynamics, *Phys. Chem. Earth, Part C*, *25*(1–2), 23–26, doi:10.1016/S1464-1917(99)00028-8.

Chen, J., T. Fritz, R. Sheldon, H. Spence, W. Spjeldvik, J. Fennell, S. Livi, C. Russell, and D. Gurnett (1998), Cusp energetic particle events: Implications for a major acceleration region of the magnetosphere, *J. Geophys. Res.*, *103*, 69–78, doi:10.1029/97JA02246.

Chen, M. W., S. Liu, M. Schulz, J. L. Roeder, and L. R. Lyons (2006), Magnetically self-consistent ring current simulations during the 19 October 1998 storm, *J. Geophys. Res.*, *111*, A11S15, doi:10.1029/2006JA011620.

Chun, F. K., and C. T. Russell (1997), Field-aligned currents in the inner magnetosphere: Control by geomagnetic activity, *J. Geophys. Res.*, *102*, 2261–2270, doi:10.1029/96JA01819.

Daglis, I. A. (2006), Ring current dynamics, *Space Sci. Rev.*, *124*(1–4), 183–202, doi:10.1007/s11214-006-9104-z.

Dandouras, I., H. Rème, J. Cao, and P. Escoubet (2009), Magnetosphere response to the 2005 and 2006 extreme solar events as observed by the Cluster and Double Star spacecraft, *Adv. Space Res.*, *43*, 618–623, doi:10.1016/j.asr.2008.10.015.

De Zeeuw, D. L., S. Sazykin, R. A. Wolf, T. I. Gombosi, A. J. Ridley, and G. Tóth (2004), Coupling of a global MHD code and an inner magnetospheric model: Initial results, *J. Geophys. Res.*, *109*, A12219, doi:10.1029/2003JA010366.

Ebihara, Y., M.-C. Fok, R. A. Wolf, M. F. Thomsen, and T. E. Moore (2005), Nonlinear impact of the plasma sheet density on the ring current, *J. Geophys. Res.*, *110*, A02208, doi:10.1029/2004JA010435.

Fok, M.-C., R. A. Wolf, R. W. Spiro, and T. E. Moore (2001), Comprehensive computational model of the Earth's ring current, *J. Geophys. Res.*, *106*, 8417, doi:10.1029/2000JA000235.

Fok, M.-C., et al. (2003), Global ENA image simulations, *Space Sci. Rev.*, *109*, 77–103, doi:10.1023/B:SPAC.0000007514.56380.fd.

Ganushkina, N. Y., T. I. Pulkkinen, M. V. Kubyshkina, H. J. Singer, and C. T. Russell (2002), Modeling the ring current magnetic field during storms, *J. Geophys. Res.*, *107*(A7), 1092, doi:10.1029/2001JA900101.

Ganushkina, N. Y., T. I. Pulkkinen, M. V. Kubyshkina, H. J. Singer, and C. T. Russell (2004), Long-term evolution of magnetospheric current systems during storms, *Ann. Geophys.*, *22*, 1317–1334, doi:10.5194/angeo-22-1317-2004.

Ganushkina, N., M. Liemohn, M. Kubyshkina, R. Ilie, and H. Singer (2010), Distortions of the magnetic field by storm-time current systems in Earth's magnetosphere, *Ann. Geophys.*, *28*, 123–140, doi:10.5194/angeo-28-123-2010.

Gombosi, T. I., G. Tóth, D. L. De Zeeuw, K. C. Hansen, K. Kabin, and K. G. Powell (2002), Semirelativistic magnetohydrodynamics and physics based convergence acceleration, *J. Comput. Phys.*, *177*, 176–205, doi:10.1006/jcph.2002.7009.

Harel, M., R. A. Wolf, P. H. Reiff, R. W. Spiro, W. J. Burke, F. J. Rich, and M. Smiddy (1981), Quantitative simulation of a magnetospheric substorm: 1. Model logic and overview, *J. Geophys. Res.*, *86*, 2217–2241, doi:10.1029/JA086iA04p02217.

Ilie, R., M. W. Liemohn, and A. Ridley (2010a), The effect of smoothed solar wind inputs on global modeling results, *J. Geophys. Res.*, *115*, A01213, doi:10.1029/2009JA014443.

Ilie, R., M. W. Liemohn, J. U. Kozyra, and J. E. Borovsky (2010b), An investigation of the magnetosphere-ionosphere response to real and idealized co-rotating interaction region events through global magnetohydrodynamic simulations, *Proc. R. Soc. A*, *466*, 3279–3303, doi:10.1098/rspa.2010.0074.

Iyemori, T. (1990), Storm-time magnetospheric currents inferred from mid-latitude geomagnetic field variations, *J. Geomagn. Geoelectr.*, *42*, 1249–1265, doi:10.5636/jgg.42.1249.

Jaggi, R. K., and R. A. Wolf (1973), Self-consistent calculation of the motion of a sheet of ions in the magnetosphere, *J. Geophys. Res.*, *78*, 2852–2866, doi:10.1029/JA078i016p02852.

Kalegaev, V. V., N. Y. Ganushkina, T. I. Pulkkinen, M. V. Kubyshkina, H. J. Singer, and C. T. Russell (2005), Relation between the ring current and the tail current during magnetic storms, *Ann. Geophys.*, *23*, 523–533, doi:10.5194/angeo-23-523-2005.

Kubyshkina, M., T. I. Pulkkinen, N. Y. Ganushkina, and N. Partamies (2008), Magnetospheric currents during sawtooth events: Event-oriented magnetic field model analysis, *J. Geophys. Res.*, *113*, A08211, doi:10.1029/2007JA012983.

Le, G., C. T. Russell, and K. Takahashi (2004), Morphology of the ring current derived from magnetic field observations, *Ann. Geophys.*, *22*, 1267–1295, doi:10.5194/angeo-22-1267-2004.

Liemohn, M. W., J. U. Kozyra, C. R. Clauer, and A. J. Ridley (2001), Computational analysis of the near-Earth magnetospheric current system, *J. Geophys. Res.*, *106*, 29,531–29,542, doi:10.1029/2001JA000045.

Lui, A. T. Y., R. W. McEntire, and S. M. Krimigis (1987), Evolution of the ring current during two geomagnetic storms, *J. Geophys. Res.*, *92*, 7459–7470, doi:10.1029/JA092iA07p07459.

Lui, A. T. Y., H. E. Spence, and D. P. Stern (1994), Empirical modeling of the quiet time nightside magnetosphere, *J. Geophys. Res.*, *99*, 151–157, doi:10.1029/93JA02647.

Ohtani, S., M. Nose, G. Rostoker, H. Singer, A. T. Y. Lui, and M. Nakamura (2001), Storm-substorm relationship: Contribution of the tail current to *Dst*, *J. Geophys. Res.*, *106*, 21,199–21,209, doi:10.1029/2000JA000400.

Ohtani, S., Y. Ebihara, and H. J. Singer (2007), Storm-time magnetic configurations at geosynchronous orbit: Comparison between the main and recovery phases, *J. Geophys. Res.*, *112*, A05202, doi:10.1029/2006JA011959.

Parker, E. N., and H. A. Stewart (1967), Nonlinear inflation of a magnetic dipole, *J. Geophys. Res.*, *72*, 5287–5293, doi:10.1029/JZ072i021p05287.

Powell, K. G., P. L. Roe, T. J. Linde, T. I. Gombosi, and D. L. De Zeeuw (1999), A solution-adaptive upwind scheme for ideal magnetohydrodynamics, *J. Comput. Phys.*, *154*, 284–309, doi:10.1006/jcph.1999.6299.

Pulkkinen, T. I., N. Y. Ganushkina, E. I. Tanskanen, M. Kubyshkina, G. D. Reeves, M. F. Thomsen, C. T. Russell, H. J. Singer, J. A. Slavin, and J. Gjerloev (2006), Magnetospheric current systems during stormtime sawtooth events, *J. Geophys. Res.*, *111*, A11S17, doi:10.1029/2006JA011627.

Ridley, A. J., and M. W. Liemohn (2002), A model-derived description of the penetration electric field, *J. Geophys. Res.*, *107*(A8), 1151, doi:10.1029/2001JA000051.

Ridley, A. J., T. I. Gombosi, and D. L. De Zeeuw (2004), Ionospheric control of the magnetosphere: Conductance, *Ann. Geophys.*, *22*, 567–584, doi:10.5194/angeo-22-567-2004.

Roelof, E. C., P. C. Brandt, and D. G. Mitchell (2004), Derivation of currents and diamagnetic effects from global plasma pressure distributions obtained by IMAGE/HENA, *Adv. Space Res.*, *33*, 747–751, doi:10.1016/S0273-1177(03)00638-0.

Sazykin, S., R. A. Wolf, R. W. Spiro, T. I. Gombosi, D. L. De Zeeuw, and M. F. Thomsen (2002), Interchange instability in the inner magnetosphere associated with geosynchronous particle flux decreases, *Geophys. Res. Lett.*, *29*(10), 1448, doi:10.1029/2001GL014416.

Shabansky, V. P., and A. E. Antonova (1968), Topology of particle drift shells in the Earth's magnetosphere [in Russian], *Geomagn. Aeron., Engl. Transl.*, *8*, 993–997.

Sheldon, R., H. Spence, J. Sullivan, T. Fritz, and J. Chen (1998), The discovery of trapped energetic electrons in the outer cusp, *Geophys. Res. Lett.*, *25*, 1825–1828, doi:10.1029/98GL01399.

Toth, G., et al. (2005), Space Weather Modeling Framework: A new tool for the space science community, *J. Geophys. Res.*, *110*, A12226, doi:10.1029/2005JA011126.

Toth, G., D. L. D. Zeeuw, T. I. Gombosi, and K. G. Powell (2006), Parallel explicit/implicit time stepping scheme on block-adaptive grid, *J. Comput. Phys.*, *217*, 722–758, doi:10.1016/j.jcp.2006.01.029.

Tsyganenko, N. A. (1989), A magnetospheric magnetic field model with a warped tail current sheet, *Planet. Space Sci.*, *37*, 5–20, doi:10.1016/0032-0633(89)90066-4.

Tsyganenko, N. A. (1995), Modeling the Earth's magnetospheric magnetic field confined within a realistic magnetopause, *J. Geophys. Res.*, *100*, 5599–5612, doi:10.1029/94JA03193.

Tsyganenko, N. A., and M. I. Sitnov (2007), Magnetospheric configurations from a high-resolution data-based magnetic field model, *J. Geophys. Res.*, *112*, A06225, doi:10.1029/2007JA012260.

Tsyganenko, N. A., H. J. Singer, and J. C. Kasper (2003), Storm-time distortion of the inner magnetosphere: How severe can it get?, *J. Geophys. Res.*, *108*(A5), 1209, doi:10.1029/2002JA009808.

Turner, N. E., D. N. Baker, T. I. Pulkkinen, and R. L. McPherron (2000), Evaluation of the tail current contribution to Dst, *J. Geophys. Res.*, *105*, 5431–5439, doi:10.1029/1999JA000248.

Wang, H., A. J. Ridley, and H. Lühr (2008), Validation of the Space Weather Modeling Framework using observations from CHAMP and DMSP, *Space Weather*, *6*, S03001, doi:10.1029/2007SW000355.

Welling, D. T., and A. J. Ridley (2010), Validation of SWMF magnetic field and plasma, *Space Weather*, *8*, S03002, doi:10.1029/2009SW000494.

Yu, Y., and A. J. Ridley (2008), Validation of the Space Weather Modeling Framework using ground-based magnetometers, *Space Weather*, *6*, S05002, doi:10.1029/2007SW000345.

Zaharia, S., V. K. Jordanova, M. F. Thomsen, and G. D. Reeves (2006), Self-consistent modeling of magnetic fields and plasmas in the inner magnetosphere: Application to a geomagnetic storm, *J. Geophys. Res.*, *111*, A11S14, doi:10.1029/2006JA011619.

Zanetti, L. J., W. Baumjohann, T. A. Potemra, and P. F. Bythrow (1984), Three-dimensional Birkeland-ionospheric current system, determined from Magsat, in *Magnetospheric Currents*, *Geophys. Monogr. Ser.*, vol. 28, edited by T. A. Potemra, 123 pp., AGU, Washington, D. C., doi:10.1029/GM028p0123.

Zhang, J.-C., M. W. Liemohn, D. L. De Zeeuw, J. E. Borovsky, A. J. Ridley, S. Sazykin, M. F. Thomsen, J. U. Kozyra, T. I. Gombosi, and R. A. Wolf (2007), Understanding storm-time ring current sources through data-model comparisons of a moderate storm, *J. Geophys. Res.*, *112*, A04208, doi:10.1029/2006JA011846.

D. L. De Zeeuw, N. Y. Ganushkina, and M. W. Liemohn, Atmospheric, Oceanic, and Space Sciences Department, University of Michigan, 2455 Hayward St., Ann Arbor, MI 48109-2143, USA. (liemohn@umich.edu)

R. Ilie, Los Alamos National Laboratory, MS D466, Los Alamos, NM 87544, USA.