Large Geomagnetic Storms: Introduction to Special Section

N. Gopalswamy
NASA Goddard Space Flight Center,
Greenbelt, Maryland, USA

Abstract: Solar cycle 23 witnessed the accumulation of rich data sets that reveal various aspects of geomagnetic storms in unprecedented detail both at the Sun where the storm causing disturbances originate and in geospace where the effects of the storms are directly felt. During two recent coordinated data analysis workshops (CDAWs) the large geomagnetic storms (Dst ≤ -100 nT) of solar cycle 23 were studied in order to understand their solar, interplanetary, and geospace connections. This special section grew out of these CDAWs with additional contributions relevant to these storms. Here I provide a brief summary of the results presented in the special section.

1. Introduction

The coordinated data analysis workshops (CDAWs) have been serving as a forum to analyze large and disparate data sets by members of the science community. Two such CDAWs were conducted in March 2005 (George Mason University) and 2007 (Florida State University) focusing on the set of all large geomagnetic storms (Dst ≤ -100 nT) of solar cycle 23 until the end of 2005. There were 88 large storms in all [*Zhang et al.*, 2007]. The solar cycle 23 started in May 1996 and continued into 2008, although occasional observations active regions belonging to cycle 24 have been made since

December 14, 2007. After 2005, there have been only two additional large magnetic storms in cycle 23: one on April 14, 2006 with Dst ~-111 nT and the other on December 15, 2006 with Dst ~-146 nT. Thus the CDAW storms represent an almost complete set for the whole solar cycle. It was possible to assemble atmospheric, ionospheric, magnetospheric, interplanetary, and solar data on the 88 storms. The uniform and extended data on coronal mass ejections (CMEs) and the inner corona (including coronal holes) available from the Solar and Heliospheric Observatory (SOHO) mission has facilitated the study of solar connection of geomagnetic storms with unprecedented clarity. It must be noted that solar cycle 23 is the first cycle in which CME data are available over the whole cycle since the first detection of CMEs in the early 1970s. The availability of simultaneous space and ground based data covering the Sun-Earth space has made the solar cycle 23 storms as one of the best set of events that could serve as bench mark to compare storms of future and past cycles.

Papers constituting this special section fall into three groups addressing solar – interplanetary phenomena, magnetospheric phenomena, and ionospheric phenomena related to cycle 23 storms with a single exception dealing with an important storm from cycle 22 (Cliver et al., 2008). The superstorms of the Halloween 2003 and November 2004 periods are the subject of investigation in several papers.

2. Solar and Interplanetary phenomena

Asai et al. (2008) present a detailed examination of a peculiar active region (AR NOAA 10798) that emerged in the middle of a small coronal hole, and formed a sea anemone like configuration. Two successive CMEs from this active region caused a large geomagnetic storm (Dst = -216 nT) on 24 August 2005. The CMEs were very fast (1200 km/s for the first one and 2400 km/s for the second) as observed by SOHO. Based on the height – time plots of the two CMEs, it was estimated that the CMEs interacted on the way to Earth resulting in an interplanetary CME (ICME) with intense southward magnetic field that was responsible for the large storm. It is suggested that the coronal hole surrounding the active region might have channeled the CMEs with relatively reduced friction between the solar wind and the CMEs.

Cliver et al. (2008) report on the solar source of the great geomagnetic storm (Dst = -354 nT) on 8-10 November 1991. The solar source is identified as the large-scale eruption of a long (~25°) solar filament followed by a soft X-ray arcade that spanned ~90° of solar longitude, distinguishing the geomagnetic storm as the largest yet associated with a quiescent filament eruption. The storm was found to rank 15th on a list of Dst storms from 1905 to 2004. The November 1991 event also underscores the difficulties in predicting such storms.

Gopalswamy et al. (2008) report that many CMEs originating from close to the disk center (within ±15° in longitude) do not arrive at Earth, while the shocks driven by them do. Such "driverless" shock events occurred only during the declining phase of solar cycle 23. In each case there was at least one large coronal hole near the eruption suggesting that the coronal holes might have deflected the CMEs away from the Sun-Earth line. The presence of abundant low-latitude coronal holes during the declining phase further explains why these events were found in the declining phase. As a control study, they also examined CMEs that originated close to the disk center and arrived at Earth as shocks with drivers. For these, the coronal holes were located such that they either had no influence on the CME trajectories, or they deflected the CMEs towards the

Sun-Earth line. Disk-center CMEs interacting with coronal holes were not geoeffective, while those minimally influenced by coronal holes were all geoeffective. This work demonstrates that in addition to source and kinematic properties of CMEs, one also has to consider the source environment in order to understand the geoeffectiveness of CMEs.

Jackson et al. (2008) present a low-resolution three-dimensional (3D) reconstruction of the 27-28 May 2003 halo CME sequence observed by Solar Mass Ejection Imager (SMEI) and the Solar and Heliospheric Observatory (SOHO) mission. These events are known to have caused a major geomagnetic storm on 2003 May 28 (see http://cdaw.gsfc.nasa.gov/CME_list/daily_plots/dsthtx/2003_05/dsthtx.20030528.html). From the reconstruction they were able to infer the shape, extent, and mass of this CME sequence as it reached the vicinity of Earth. The 3D reconstructed density, derived from the remote-sensed Thomson scattered brightness agrees well with the in situ measurements from the Advanced Composition Explorer (ACE) and Wind spacecraft. Bisi et al. (2008) apply the same reconstruction technique to the early November 2004 events and compare the reconstructed structures with in situ measurements from the ACE and Wind spacecraft, thus validating the reconstruction results. The early November 2004 events have caused two super intense (Dst ~ -373 nT and -289 nT) storms (Gopalswamy et al., 2006). Information derived from the reconstruction technique serve as input to the ENLIL 3D magnetohydrodynamic (MHD) numerical model of the solar wind.

Zhang et al. (2008) report on the multiple dips in the Dst index profile during the storm interval. They studied the properties of the interplanetary drivers of 90 intense geomagnetic storms during 1996 to 2006 to trace the cause of the dips. Since the decrease in Dst index is caused by an interval of southward component of the interplanetary magnetic field, multiple dips mean multiple intervals of southward magnetic field within the overall storm interval. The majority of the 90 storms (66%) showed two or more dips. One frequent cause of two-dip storms is the occurrence of the southward field in the sheath and in the ICME such that the first dip is caused by the sheath field while the second dip by the ICME. Double or multiple dips are also caused by the presence of multiple sub-regions of southward magnetic field within a complex solar wind flow, resulting from two successive, closely spaced ICMEs.

3. Magnetospheric Phenomena

Liemohn et al. (2008) report on the simulation of the intense magnetic storms from solar cycle 23 using the hot electron and ion drift integrator (HEIDI) model. The simulations were run using a Kp-driven shielded Volland-Stern electric field, static dipole magnetic field, and nightside plasma data from instruments on the Los Alamos geosynchronous satellites. The storms were analyzed by grouping them according to their solar wind driver: ICMEs and corotating interaction regions (CIRs). They find that the HEIDI model was able to best reproduce the Dst time series for storms driven by ICME sheaths. Storms driven by CIRs were the least reproducible class of storms, with simulated minimum Dst* values typically only half to two-thirds of the observed minimum value. In general, there was a strong correlation between the observed and modeled minimums of Dst*, and essentially no correlation between the observed minimum Dst* and the modeled-to-observed Dst* ratio. One of the implications of this study is that a Kp-driven HEIDI simulation is consistently on the low side of predicting storm intensity, except for sheath-driven events.

Jordanova et al. (2008) study the effect of electromagnetic ion cyclotron (EMIC) wave scattering on radiation belt electrons during the large geomagnetic storm of 21 October 2001 (Dst=-187 nT) using their global physics-based model. They calculate the excitation of EMIC waves (field-aligned and oblique) and evaluate particle interactions with these waves according to the quasi-linear theory. They find that pitch angle scattering by EMIC waves causes significant loss of radiation belt electrons at energies >1 MeV due to precipitation into the atmosphere. On the other hand, the relativistic electron flux dropout during the main phase of the storm at large L values (>5) is due mostly to outward radial diffusion. Global simulations indicate significant relativistic electron precipitation within regions of enhanced EMIC instability, whose location varies with time but is predominantly in the afternoon-dusk sector. The minimum resonant energy is found to increase at low L and relativistic electrons (<1 MeV) do not precipitate at L<3 during the October 2001 storm.

Ilie et al. (2008) examine how the reference time selection affects the superposed epoch analysis (SEA) for intense storms at solar maximum. Analyzing solar wind data from ACE along with near-Earth data from the LANL MPA instruments, they find that for different choices of the time stamp, different storm characteristics are reproduced in the averaged data. In the ACE data they find that when using the storm sudden commencement (SSC) as a time reference, the SSC-related jump in solar wind parameters is very well reproduced, but near the storm peak, the vertical component of the magnetic field (Bz) does not follow the criteria for intense storms (Bz<-10nT for more than 3 hours). On the other hand, the Bz criterion is readily met when the zero epoch time is chosen near the storm peak, but the jump in solar wind pressure is not as sharp.

Keesee et al. (2008) present time resolved, remote ion temperature measurements of the magnetosphere from 10 R_E to -60 R_E for the 2000 October 4-7 storm. They calculate the ion temperatures from Maxwellian fits to IMAGE/MENA data. They find that the calculated ion temperatures in the magnetotail are consistent with in situ measurements from multiple geosynchronous spacecraft and GEOTAIL at $x = -9$ R_E. During the October 2000 storm, two separate instances of an Earthward propagating increase in ion temperature are found. When the solar wind-magnetospheric coupling is strong, the measured ion temperatures are consistent with predictions of a solar wind velocity correlation equation; at other times, the measured ion temperature is 2-3 times larger than the predicted value.

Manninen et al. (2008) investigate the steady magnetospheric convection period between the two episodes of the November 2004 superstorm. During the interval in question (18-04 UT on 8-9 November), the Dst index was stable but considerably low (-125 nT) and the Bz was steady and slightly negative (~ -5 nT). The strongest magnetic disturbances were observed in the midnight sector of the Earth, rather than in the expected morning side geomagnetic activity and Pc5 geomagnetic pulsations. The results were obtained using the Scandinavian multi-point observations of geomagnetic variations and pulsations, visible auroras, and energetic particle precipitation.

4. Ionospheric Phenomena

Ding et al. (2008) report on the large-scale traveling ionospheric disturbances associated with the major geomagnetic storms during 2002-2005. They use total electron content (TEC) perturbation maps obtained from more than 600 GPS receivers in North America (geographical latitudes of 25°N–55°N) and find 135 cases of such disturbances with amplitudes of up to 3.5 TECU and a maximum front width of ~4000 km. The mean velocity (300 m/s) is slower than that observed at lower latitudes. The occurrence of the disturbances peaks at 1200 LT and at 1900 LT. They also find that the UT dependence of the occurrence of auroral geomagnetic disturbances plays a major role in the forming of UT and LT dependence of the occurrence of the traveling ionospheric disturbances at midlatitudes. Perevalova et al. (2008) report on the large-scale traveling ionospheric disturbance registered in the auroral zone following the sudden storm commencement (SSC) related to the 29 October 2003 event. The disturbance represented a large-scale solitary type wave with an annular front shape whose center was located near the geomagnetic pole. They also detected a "swirling" effect in the disturbance movement in a direction opposite to the Earth's rotation.

Balan et al. (2008) report the occurrence of the F3 layer in the equatorial ionosphere at American, Indian, and Australian longitudes during the November 2004 superstorms (November 8 and 10). The observations show the occurrence, reoccurrence, and quick ascent to the topside ionosphere of unusually strong F3 layer accompanied by large reductions in peak electron density and total electron content. Observations and modeling indicate that the unusual F3 layers arise mainly from unusually strong fluctuations in the daytime vertical $E \times B$ drift.

Eriksson et al. (2008) report on an analysis of the great magnetic storm of 15 May 2005 associated with a well-known magnetic cloud (Yurchyshyn et al., 2006) using DMSP, TIMED/GUVI, and IMAGE/WIC observations. In particular, they analyze the high-latitude response of sunward E × B flow and Birkeland field-aligned currents. Using DMSP observations, they were able to confirm a dawnward migration of a Northern Hemisphere sunward E × B flow channel between a downward and upward field aligned current pair. Using TIMED/GUVI observations, they also show that the dawnward migration of the upward field aligned current coincides with a drifting transpolar auroral arc.

Su. Basu et al. (2008) report on the impact of large ionospheric velocities on GPS-based navigation systems within the midlatitude region in the North American sector during the 2004 November superstorm. The 2004 November storm was marked by the absence of appreciable storm-enhanced density gradients compared to the 2003 Halloween storms. This study demonstrates that it is possible to disable GPS-based navigation systems for many hours even in the absence of appreciable TEC gradients, provided an intense flow channel, generally known as the sub-auroral polarization stream (SAPS), is present in the ionosphere during nighttime hours.

Mannuci et al. (2008) report the prompt daytime ionospheric responses for four intense geomagnetic storms (during the 2003 Halloween period and 2004 November period). They perform a superposed epoch analysis of the storms and use measurements from the GPS receivers onboard the CHAMP satellite (400 km altitude) and from ground. The TEC data indicate significant low- to middle-latitude daytime TEC increases for three of the storms (~1400 local solar time) except for the 2003 November 20 storm, for which the largest TEC increases appear several hours (~5–7) following the Bz event onset. Estimates of vertical plasma uplift near the equator at Jicamarca longitudes (~281 E) suggest that variability of the timing of the TEC response is associated with variability in the prompt penetration of electric fields to low latitudes. They also found that for the November 2003 magnetic storm the cross-correlation function between the SYM-H index and the interplanetary electric field reached maximum correlation with a lag time of 4 h. Such long delays of both the ionosphere and magnetosphere responses need to be better understood.

Pokhotelov et al. (2008) apply a novel technique of extracting the storm time E × B convection boundary from in situ measurements of plasma bulk motion obtained by LEO DMSP satellites to the 20 November 2003 storm. They compare the results with the global distributions of the ionospheric plasma deduced from characteristics of GPS signals. The tomographic inversion of GPS data reveals that the convective flow expanded low enough in latitude to encompass, in part, the formation of the midlatitude TEC anomaly. Some features of the TEC dynamics observed during the 20 November 2003 storm, however, suggest that mechanisms other than the expanded ionospheric convection (such as thermospheric neutral winds) are also involved in the formation of the midlatitude anomaly.

Sahai et al. (2008a,b) report the effects of the November 2004 storms on the F-region in the Latin American and East Asian sectors. Virtually no spread F (phase fluctuations) on the nights of 09-10 and 10-11 November were observed in the Latin American sector. The East Asian sector showed very pronounced effects during the second superstorm which was preceded by two intense storms. There was no spread-F in the Vietnamese sector, but a strong spread-F in the Japanese sector suggesting the behavior of the nighttime F-region during intense geomagnetic disturbance could be very different in close-by longitudinal sectors.

Zhao et al. (2008) investigate the ionospheric disturbances in the Southeast Asian region during the super magnetic storm of 20–22 November 2003 using an ionosonde chain and a GPS network assisted by space-borne instruments. They report that the equatorial ionosphere was elevated to a very high level during the storm. The penetration efficiency of the interplanetary electric field to the equatorial ionosphere was larger at night than in the daytime. During the recovery phase, the interplanetary electric field was severely inhibited owing to a wind convergence and possibly because of the westward disturbance dynamo electric field.

Villante and Regi (2008) report on the remarkable solar flare effect (SFE) due to the 28 October 2003 solar flare that caused increased photoionization effects in the dayside ionosphere. The aspects of the SFE onset and initial phase reveal a close correspondence with those of the EUV flux. At equatorial/electrojet latitudes, the SFE manifestation can be mostly interpreted in terms of a significant enhancement of the pre-flare current system during normal electrojet conditions, with some evidence for a highly confined counter electrojet in the dawn sector. Additional elements, at higher latitudes, might suggest in these regions a more significant role of the X-ray flux and the onset of additional currents below the normal dynamo current region.

5. Conclusion

Results presented in this special section represent the complexity arising from interactions between the solar, interplanetary, magnetospheric and ionospheric/thermospheric regions during large storms. The dynamic range provided by these storms continues to yield better insight into their physics and stand testimony to the multi-disciplinary effort required to gain a complete understanding of the storms. Such efforts are expected to continue with the complete data base accumulated on the large geomagnetic storms available to the scientific community for further analysis.

Acknowledgments: The author thanks J. Zhang and R. Lopez for hosting the CDAW workshops in 2005 and 2007, respectively. The CDAWs were supported by NASA/LWS program.

References

Asai, A., K. Shibata, T. Ishii, M. Oka, R. Kataoka, K. Fujiki, and N. Gopalswamy (2008), Evolution of Anemone AR NOAA 10798 and the Related Geo-Effective Flares and CMEs, J. Geophys. Res., doi:10.1029/2008JA013291, in press.

Balan, N., S. V. Thampi, K. Lynn, Y. Otsuka, H. Alleyne, S. Watanabe, M. A. Abdu, and B. G. Fejer (2008), F_3 layer during penetration electric field, J. Geophys. Res., 113, A00A07, doi:10.1029/2008JA013206

Basu, Su., S. Basu, J. J. Makela, E. MacKenzie, P. Doherty, J. W. Wright, F. Rich, M. J. Keskinen, R. E. Sheehan, and A. J. Coster (2008), Large magnetic storm-induced nighttime ionospheric flows at midlatitudes and their impacts on GPS-based navigation systems, J. Geophys. Res., 113, A00A06, doi:10.1029/2008JA013076

Bisi, M. M., B. V. Jackson, P. P. Hick, A. Buffington, D. Odstrcil, and J. M. Clover (2008), Three-dimensional reconstructions of the early November 2004 Coordinated Data

Analysis Workshop geomagnetic storms: Analyses of STELab IPS speed and SMEI density data, J. Geophys. Res., 113, A00A11, doi:10.1029/2008JA013222

Cliver, E. W., K. Balasubramaniam, N. V. Nitta, and X. Li (2008), Great geomagnetic storm of 9 November 1991: Association with a disappearing solar filament, J. Geophys. Res., doi:10.1029/2008JA013232, in press.

Ding, F., W. Wan, L. Liu, E.L. Afraimovich, S.V. Voeykov, and N.P. Perevalova (2008), A statistical study of large-scale traveling ionospheric disturbances observed by GPS TEC during major magnetic storms over the years 2003–2005, J. Geophys. Res., 113, A00A01, doi:10.1029/2008JA013037

Eriksson, S., M. R. Hairston, F. J. Rich, H. Korth, Y. Zhang, and B. J. Anderson (2008), High-latitude ionosphere convection and Birkeland current response for the 15 May 2005 magnetic storm recovery phase, J. Geophys. Res., 113, A00A08, doi:10.1029/2008JA013139

Gopalswamy, N., S. Yashiro, and S. Akiyama (2006), Coronal mass ejections and space weather due to extreme events, Proceedings of the ILWS Workshop, Editors: N. Gopalswamy and A. Bhattacharyya. Quest Publications, Mumbai, p.79.

Gopalswamy, N., P. Makela, H. Xie, S. Akiyama, and S. Yashiro (2008), CME Interaction with Coronal Holes and their Interplanetary Consequences, J. Geophys. Res., doi:10.1029/2008JA013686, in press.

Ilie, R., M. W. Liemohn, M. F. Thomsen, J. E. Borovsky, and J. Zhang (2008), Influence of epoch time selection on the results of superposed epoch analysis using ACE and MPA data, J. Geophys. Res., 113, A00A14, doi:10.1029/2008JA013241

Jackson, B. V., M. M. Bisi, P. P. Hick, A. Buffington, J. M. Clover, and W. Sun (2008), Solar Mass Ejection Imager 3-D reconstruction of the 27–28 May 2003 coronal mass ejection sequence, J. Geophys. Res., 113, A00A15, doi:10.1029/2008JA013224

Jordanova, V. K., J. Albert, and Y. Miyoshi (2008), Relativistic electron precipitation by EMIC waves from self-consistent global simulations, J. Geophys. Res., 113, A00A10, doi:10.1029/2008JA013239

Keesee, A. M., E. Scime, and M. B. Moldwin (2008), Remote measurements of ion temperatures in the terrestrial magnetotail, J. Geophys. Res., 113, A00A03, doi:10.1029/2008JA013130

Liemohn, M.W., and M. Jazowski (2008), Ring current simulations of the 90 intense storms during solar cycle 23, J. Geophys. Res., doi:10.1029/2008JA013466, in press.

Manninen, J., N. G. Kleimenova, O. V. Kozyreva, A. Ranta, K. Kauristie, S. Mäkinen, and T. A. Kornilova (2008), Ground-based observations during the period between two strong November 2004 storms attributed to steady magnetospheric convection, J. Geophys. Res., 113, A00A09, doi:10.1029/2007JA012984

Mannucci, A. J., B. T. Tsurutani, M. A. Abdu, W. D. Gonzalez, A. Komjathy, E. Echer, B. A. Iijima, G. Crowley, and D. Anderson (2008), Superposed epoch analysis of the dayside ionospheric response to four intense geomagnetic storms, J. Geophys. Res., 113, A00A02, doi:10.1029/2007JA012732

Perevalova, N. P., E. L. Afraimovich, S. V. Voeykov, and I. V. Zhivetiev (2008), Parameters of large-scale TEC disturbances during the strong magnetic storm on 29 October 2003, J. Geophys. Res., 113, A00A13, doi:10.1029/2008JA013137

Pokhotelov, D., C. N. Mitchell, P. S. J. Spencer, M. R. Hairston, and R. A. Heelis (2008),Ionospheric storm time dynamics as seen by GPS tomography and in situ spacecraft observations, J. Geophys. Res., 113, A00A16, doi:10.1029/2008JA013109

Sahai, Y., F. Becker-Guedes, P.R. Fagundes, R. de Jesus, et al. (2008a), Effects observed in the Latin American sector ionospheric F-region during the intense geomagnetic disturbances in the early part of November 2004, J. Geophys. Res., doi:10.1029/2007JA013007, in press.

Sahai, Y., F. Becker-Guedes, P.R. Fagundes, R. de Jesus, et al. (2008b), Effects observed in the ionospheric F region in the east Asian sector during the intense geomagnetic disturbances in the early part of November 2004, J. Geophys. Res., doi:10.1029/2008JA013053, in press.

Villante, U., and M. Regi (2008), Solar flare effect preceding Halloween storm (28 October 2003): Results of a worldwide analysis, J. Geophys. Res., 113, A00A05, doi:10.1029/2008JA013132

Yurchyshyn, V., C. Liu, V. Abramenko, J. Krall (2006), The May 13, 2005 Eruption: Observations, Data Analysis and Interpretation, Solar phys., 239, 317-335.

Zhang, J. et al. (2007), Solar and interplanetary sources of major geomagnetic storms (Dst <= -100 nT) during 1996-2005, *J. Geophys. Res.*, 112, A10102, doi: 10.1029/2007JA012321

Zhang, J., I. G. Richardson, and D. F. Webb (2008), Interplanetary origin of multiple-dip geomagnetic storms, J. Geophys. Res., 113, A00A12, doi:10.1029/2008JA013228

Zhao, B., W. Wan, K. Tschu, K. Igarashi, T. Kikuchi, K. Nozaki, S. Watari, G. Li, L. J. Paxton, L. Liu, B. Ning, J.-Y. Liu, S.-Y. Su, and H. P. Bulanon (2008), Ionosphere disturbances observed throughout Southeast Asia of the superstorm of 20–22 November 2003, J. Geophys. Res., 113, A00A04, doi:10.1029/2008JA013054