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A new parameter of geomagnetic storms for the severity of space weather

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Abstract

Using the continuous Dst data available since 1957 and *H* component data for the Carrington space weather event of 1859, the paper shows that the mean value of Dst during the main phase of geomagnetic storms, called mean Dst_{MP}, is a unique parameter that can indicate the severity of space weather. All storms having high mean Dst_{MP} (≤ -250 nT), which corresponds to high amount of energy input in the magnetosphere–ionosphere system in short duration, are found associated with severe space weather events that caused all known electric power outages and telegraph system failures.

Background

Geomagnetic storms are disturbances in earth's magnetic field produced by enhanced solar wind–magnetosphere coupling and ionosphere–magnetosphere plasma coupling (e.g., Svalgaard 1977; Gonzalez et al. 1994). Scientific analysis of geomagnetic storms lead to improved fundamental understanding of the earth's surrounding space weather environment (e.g., Prölss 2004; Kamide and Balan 2015). Applied analysis of the storms enables the assessment and mitigation of space weather-related hazards, for example, on satellite systems and orbits, satellite communication and navigation, over-the-horizon radio communication, geophysical surveys, electric power grids, and oil and gas metal pipe lines (e.g., Daglis 2004). Of particular concern are the effects associated with rare but extremely intense geomagnetic storms (e.g., Hapgood 2011; Cannon et al. 2013; Cliver and Dietrich 2013). A Carrington type event of 1859 (e.g., Carrington 1859) at present times, for example, can cause very serious social and economic impacts in the High-Tech society (e.g., Baker et al. 2008). It is therefore important for scientific and technological reasons to search for some parameter(s) of space weather events that can indicate their severity.

The disturbance storm time (Dst) index (Sugiura 1964) represents geomagnetic storms. The intensity of the storms, which is the maximum negative value of Dst (or DstMin) during the storms, has conventionally been considered to represent the severity of space weather. However, recently by analyzing the Dst data since 1998, we (Balan et al. 2014) showed that DstMin is an insufficient indicator, and the mean value of Dst during the main phase (MP) of the storms (mean Dst_{MP}) can indicate the severity of space weather in causing damages to technological systems such as electric power grids and telegraph systems. In this paper, using all the Dst data available since 1957 and *H* component data during the Carrington event of 1859, we confirm that the mean Dst_{MP} is a unique parameter that can indicate the serenity of space weather.

Dst data and analysis

We use the hourly Dst data of 1 nT resolution for 58 years available at Kyoto WDC since 1957, with no data gaps and no erroneous values (http://swclob-kugi.kyoto-u.ac.jp). The Dst index is obtained from the horizontal *H* component measured at four low-latitude stations (3 in north and 1 in south) outside the equatorial electrojet belt (Sugiura 1964; Sugiura and Kamei 1991). A disturbance time series is estimated for each station by subtracting a non-storm quiet time baseline; and the Dst time series is obtained as an average of the individual disturbance time series from the four stations. For the

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Carrington storm of September 1859, we use the *H* range data measured at Mumbai and reported by Tsurutani et al. (2003). H range is similar to Dst but positive. For consistency, we take *H* range also as negative like Dst.

The Dst storms are identified by developing a computer program which minimizes non-storm like fluctuations and avoids human errors. Figure 1, for example, illustrates the procedure. The program first detects the negative slopes in the Dst variation (green dots, Fig. 1a) and identifies the preliminary main phase onsets (MPOs) when Dst starts decreasing (red starts) and DstMin when Dst reaches maximum negative values (black stars, Fig. 1b). The program then applies the selection criterion (1) DstMin ≤ -50 nT and MP duration >2 h, and criterion (2) absolute value of MP range, that is, IDst$_{MPO}$ − Dst-MinI ≥ 50 nT. By applying criteria (1) and (2), many short-period, non-storm like negative fluctuations of Dst are eliminated (Fig. 1c). With a view to further avoid the short-period positive deflections during MP and identify clearly separated storms, the criterion (3), that is, separation between DstMin and next MPO >6 h, is applied. Further to avoid very slowly varying, non-storm like long duration decreases in Dst, the criterion (4), that is, rate of change of Dst during MP or (dDst/dt)$_{MP}$ <−5 nT/h, is applied, which results in the detection of the clear storm in Fig. 1d. By applying the procedure to the whole Dst data, the computer program identified 810 storms which include 365 intense storms (DstMin ≤ -100 nT) and 39 super storms (DstMin ≤ -250 nT).
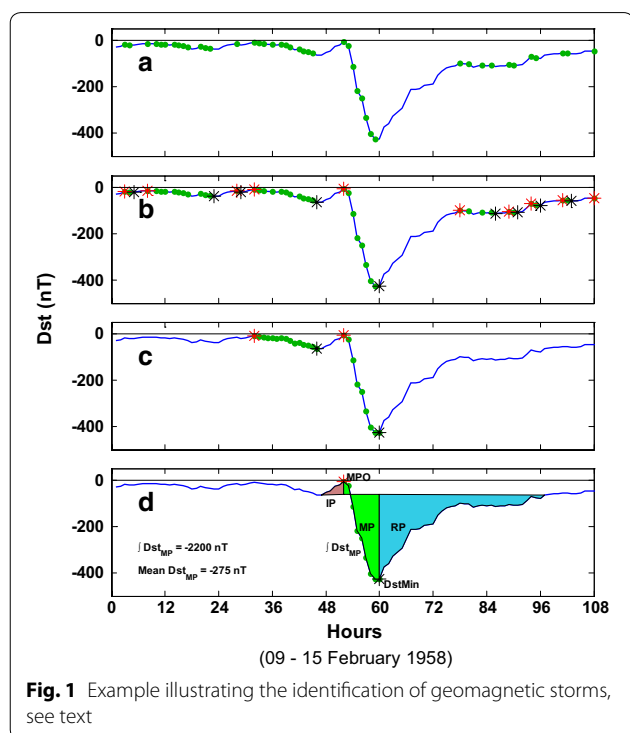
The estimation of the storm parameters are illustrated using Fig. 1d which also shows the storm phases. The impact at the Earth of a coronal mass ejection (CME) compresses the dayside magnetopause, intensifies its eastward directed current, and generates a positive perturbation in Dst, known as initial phase (IP) which usually lasts from tens of minutes to a few hours. It may be noted that IP is not well identifiable in all storms. This is followed by the main phase (MP) when the field decreases due to the enhancement of the westward ring current, which begins with the southward turning of IMF (interplanetary magnetic field) Bz and consequent solar wind–magnetosphere coupling and loading of solar wind energy into the ring current; it lasts for several hours to over ten hours when IMF Bz remains southward. When IMF Bz returns to zero or turns northward, the solar wind forcing diminishes, ring current intensity eventually dissipates, and Dst recovers back to its near-zero pre-storm level recovery phase (RP) usually taking tens of hours to several days.

The storms are analyzed for their important parameters. Main phase duration T$_{MP}$ is the time interval between MPO and DstMin which are defined above and identified in Fig. 1d; UT hours of MPO and DstMin are noted. ∫Dst$_{MP}$ is the integral (or sum) of Dst during MP. For storms with positive initial phase, it is the negative of the sum of the magnitudes of Dst from MPO to DstMin. Mean Dst$_{MP}$ = ∫Dst$_{MP}$/T$_{MP}$ is the new parameter which indicates the strength of geomagnetic storms while Dst-Min represents their intensity, discussed in "Results and discussion" section. (dDst$_{MP}$/d*t*)$_{max}$ is the maximum rate of change of Dst during MP, which is the maximum successive difference of Dst during MP.

Results and discussion

Although over 800 storms are identified, we consider the 39 super storms (DstMin ≤ -250 nT) and the Carrington storm because storms weaker than super storms are unlikely to be associated with system damages (e.g., Baker et al. 2008; Balan et al. 2014). The characteristics of the storms such as date of DstMin, value of DstMin, time of MPO, time of DstMin, MP duration, mean Dst$_{MP}$, and (dDst$_{MP}$/d*t*)$_{max}$ are listed in Table 1. The solar activity index (F10.7) is also listed.

Figure 2 displays the characteristics of all 40 super storms arranged in the order of decreasing mean Dst$_{MP}$. For clarity, the scales of mean Dst$_{MP}$, (dDst$_{MP}$/d*t*)$_{max}$, and DstMin are limited. Purple color represents the storms associated with severe space weather (SvSW) events that caused electric power outages and/or telegraph system


Fig. 1 Example illustrating the identification of geomagnetic storms, see text

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Table 1 Characteristics of geomagnetic storms (DstMin ≤ -250 nT)

No	Date	DstMin (nT)	T1–T2 (UT h)	MPD (hr)	Mean Dst$_{MP}$ (nT)	dDst$_{MP}$/dt (nT/h)	Daily 10.7
1	1859-09-01	−1710	05-07	2	−700	1390	–
2	1989-03-13	−589	14-02	12	−357	111	253
3	1958-02-11	−426	04-12	8	−275	103	224
4	2001-11-06	−292	02-07	5	−259	168	233
5	2003-10-30	−383	18-23	5	−258	98	268
6	1957-09-05	−324	14-04	14	−239	90	241
7	2001-03-31	−387	04-09	5	−238	148	245
8	1981-04-13	−311	00-07	7	−235	75	255
9	1967-05-26	−387	17-05	12	−230	106	219
10	2004-11-10	−263	02-11	9	−229	43	103
11	1989-10-21	−268	06-17	11	−220	61	206
12	1960-04-01	−327	10-19	9	−217	56	201
13	1957-09-13	−427	02-11	9	−216	122	272
14	2004-11-08	−374	20-07	11	−209	96	122
15	2003-11-20	−422	09-21	12	−204	100	171
16	1959-07-15	−429	09-20	11	−204	92	253
17	1958-09-04	−302	14-23	9	−201	55	261
18	1991-10-29	−254	23-08	9	−188	29	269
19	1991-11-09	−354	14-02	12	−187	63	194
20	1960-04-30	−325	13-19	6	−184	151	164
21	2000-04-06	−288	17-01	8	−183	74	178
22	2003-10-29	−353	07-01	18	−179	95	275
23	1989-11-17	−266	10-23	13	−179	52	215
24	1982-09-06	−289	00-12	12	−175	44	172
25	2000-07-15	−301	16-01	9	−172	137	220
26	1958-07-08	−330	10-23	13	−170	92	240
27	1982-07-14	−325	17-02	9	−163	110	269
28	1991-03-25	−298	15-01	10	−157	63	235
29	1970-03-08	−284	15-23	8	−156	90	173
30	1961-10-28	−272	10-19	9	−154	62	86
31	2001-04-11	−271	16-24	8	−145	58	160
32	1960-11-13	−339	17-10	17	−142	81	178
33	1957-09-23	−303	11-07	45	−138	65	297
34	1990-04-10	−281	23-19	20	−133	45	149
35	1960-10-07	−287	21-01	28	−120	45	145
36	1957-01-21	−250	14-23	9	−116	80	219
37	1992-05-10	−288	21-15	18	−111	62	127
38	1989-09-19	−255	15-05	14	−106	40	197
39	1986-02-08	−307	04-01	45	−105	72	94
40	1957-03-02	−255	21-08	11	−83	100	180

Date is of DstMin. T1 and T2 are times of MPO and DstMin. MPD is MP duration. F10.7 is on the day of DstMin

failures; and blue color corresponds to normal space weather (NSW) events that did not cause such damages, discussed below. The unique parameter that distinguishes SvSW and NSW events is the mean Dst$_{MP}$ (panel a). All five storms associated with SvSW events (purple color) have mean Dst$_{MP} \leq -258$ nT and all remaining 35 storms associated with NSW events have mean Dst$_{MP} \geq -238$ nT. Also, 20 of the storms associated with NSW events have lower DstMin (as low as −429 nT) than the highest DstMin corresponding to SvSW events (panel c). Although (dDst$_{MP}$/dt)$_{max}$ (panel b) is high (>95 nT/h) for SvSW events, it does not distinguish SvSW and NSW events because 8 NSW events have higher value for the parameter than the lowest value associates with SvSW

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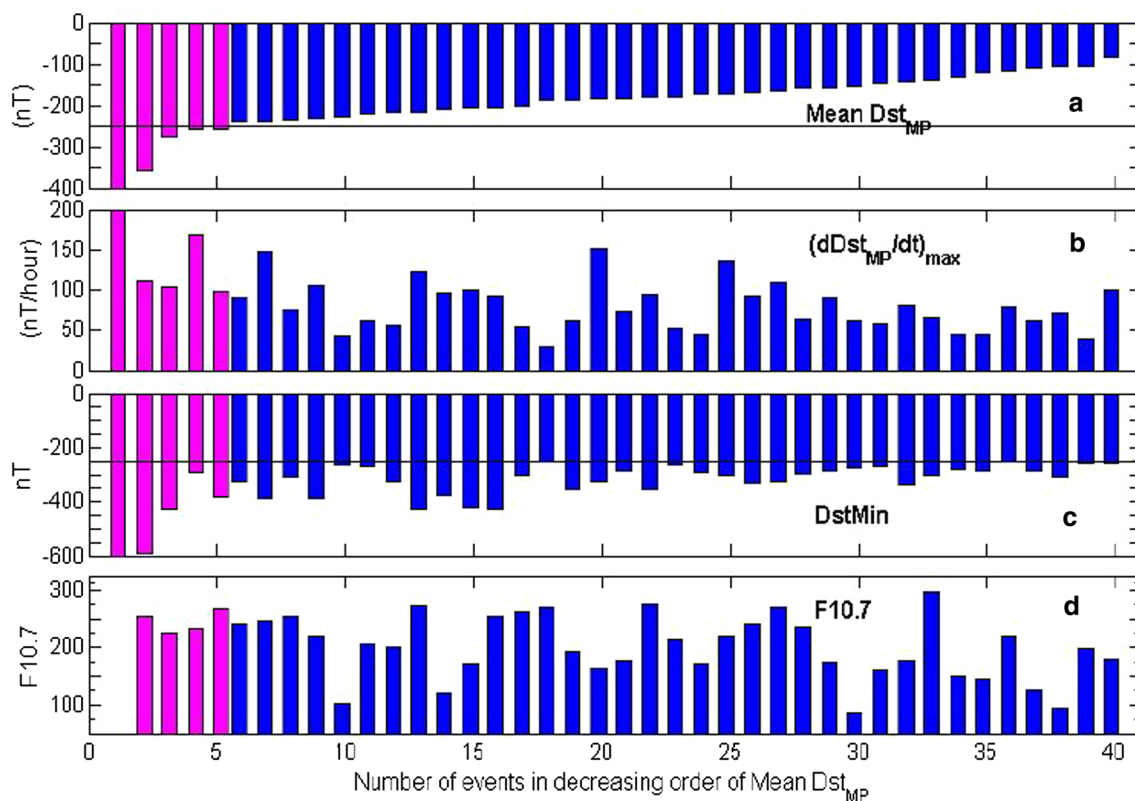
Fig. 2 Parameters of super storms (mean Dst_{MP}, $(dDst_{MP}/dt)_{max}$, and DstMin) and solar activity index F10.7 arranged in the order of decreasing mean Dst_{MP}

events. While all 5 super storms associated with SvSW events occurred under high solar activity (F10.7 >225), the storms in general are independent of solar activity (panel d). Mean Dst_{MP} (≤-250 nT) therefore is a unique parameter of geomagnetic storms that can indicate the severity of space weather while the conventional parameter DstMin is insufficient.

The most famous severe space weather event (Carrington 1859) caused telegraph system failures (event 1, Fig. 2) and produced the most extreme geomagnetic storm in known history (Tsurutani et al. 2003) with highest values of mean Dst_{MP} (-700 nT) and DstMin (-1710 nT) though Akasofu and Kamide (2005) commented that such extremely high value of Dst is unrealistic. The famous electric power outage in Quebec on March 13, 1989 (e.g., Medford et al. 1989) is associated with an extreme storm (event 2) of mean Dst_{MP} <-350 nT. The SvSW event on February 11, 1958 (event 3), which caused fire and severe damages in the telegraph systems in Sweden (e.g., Wik et al. 2009), also produced an extreme storm (mean Dst_{MP} = -275 nT). The SvSW events on Nov 06, 2001 and Oct 30, 2003 (events 4 and 5) caused power outages in New Zealand (Marshall et al. 2012)

and Sweden (e.g., Wik et al. 2009) and produced extreme storms (mean Dst_{MP} < -255 nT).

High value of the unique parameter mean Dst_{MP} corresponds to high $\int$Dst occurring in short duration MP. For example, the most famous SvSW event has the highest $\int$Dst (or $\int H$) occurring in the shortest MP of duration only about 2 h. Such storms are produced by CMEs having high front velocity ΔV (sudden increase over the background) and sufficiently large IMF Bz southward at the front (Balan et al. 2014). The physics of high mean Dst_{MP} therefore seems high amount of energy input into the magnetosphere–ionosphere system in short duration probably through continuous and rapid magnetic reconnection (e.g., Borovsky et al. 2008), so that the system responds impulsively. The impulsive response causes strong electric currents in the ionosphere especially at high latitudes, which, in turn, leads to technological system damages through secondary electrical induction on ground systems.

Conclusions

High value of mean Dst during the main phase of geomagnetic storms (Dst_{MP} ≤-250 nT), which represents

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high amount of energy input in the magnetosphere–ionosphere system in short duration, corresponds to the severe space weather events that caused all known electric power outages and telegraph system damages. The information can help identify the characteristic parameter of SvSW in other geophysical data and in the design of technological systems.

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Competing interests
The authors declare that they have no competing interests.

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