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- The estimation of interplanetary E field conditions for intense magnetic storms
- The historical geomagnetic storms recorded at Colaba Observatory, India
- Variation of ring current injection rate during intense storms

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Estimation of interplanetary electric field conditions for historical geomagnetic storms

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Abstract Ground magnetic measurements provide a unique database in understanding space weather. The continuous geomagnetic records from Colaba-Alibag observatories in India contain historically longest and continuous observations from 1847 to present date. Some of the super intense geomagnetic storms that occurred prior to 1900 have been revisited and investigated in order to understand the probable interplanetary conditions associated with intense storms. Following Burton et al. (1975), an empirical relationship is derived for estimation of interplanetary electric field (IEFy) from the variations of *Dst* index and ΔH at Colaba-Alibag observatories. The estimated IEFy values using *Dst* and ΔH_{ABG} variations agree well with the observed IEFy, calculated using Advanced Composition Explorer (ACE) satellite observations for intense geomagnetic storms in solar cycle 23. This study will provide the uniqueness of each event and provide important insights into possible interplanetary conditions for intense geomagnetic storms and probable frequency of their occurrence.

1. Introduction

Geomagnetic storms are the disturbances in Earth's magnetic field that are usually defined by the geomagnetic field horizontal (*H*) component variations at low latitudes observed from ground-based magnetometers. The primary interplanetary cause of geomagnetic storms is the presence of southward interplanetary magnetic field (IMF) in the solar wind [*Gonzalez and Tsurutani*, 1987; *Tsurutani et al.*, 1988; *Gonzalez et al.*, 1994; *Echer et al.*, 2005]. The southward IMF allows magnetic reconnection and energy transfer from the solar wind to the Earth's magnetosphere. This energy is distributed in different regions of the magnetosphere. The energetic protons and ions having the energy between ~20 and 200 keV experience a westward drift because of gradient and curvature of the geomagnetic field. This westward motion of energetic ions generates a toroidal current in the region from ~2 to 7 R_E and is known as ring current [*Singer*, 1957; *Baumjohann and Treumann*, 1996]. The *Dst* (disturbance storm time) index is a standard measure of ring current, which is derived from hourly averages of the horizontal component of the geomagnetic field usually recorded at four to five low latitude stations and subtracting mean solar quiet (*Sq*) and main geomagnetic field variations, thus representing the westward ring current variations [*Sugiura*, 1964]. The decrease in *Dst* index is directly related to the total energy of the ring current particles and thus is a good measure of the energetics of the magnetic storm [*Dessler and Parker*, 1959; *Sckopke*, 1966]. The main phase (MP) of the magnetic storms is characterized by enhancement of ring current (decrease in *Dst*) and recovery phase by decay of ring current (recovery of *Dst*) due to a combination of several different energetic particle loss mechanisms [*Gonzalez et al.*, 1994, 1999; *Fok et al.*, 1996; *Kozyra et al.*, 1997]. The energetic solar wind events from Sun such as coronal mass ejections (CMEs) and corotating interaction regions (CIRs) travel through interplanetary space and can cause geomagnetic storms under suitable reconnection conditions (southward IMF B_z). *Burton et al.* [1975] derived an empirical relationship between *Dst* index and the causative interplanetary parameters. Magnetic clouds (MCs), which are the interplanetary manifestations of the CMEs, are found to be responsible for the occurrence of intense magnetic storms [*Burlaga et al.*, 1981; *Klein and Burlaga*, 1982; *Tsurutani et al.*, 1992]. The MC structure in solar wind is generally characterized by enhanced magnetic field, low proton temperature with a large and smooth rotation of magnetic field vector. The MCs with high velocity can cause compression of plasma and can form collisionless shock ahead of it. The region behind the shock that contains compressed magnetic fields and heated plasma is generally known as sheath region. The sheath regions can also produce magnetic storms during the southward IMF. Solar energetic particle (SEP) events are the energetic outbursts as a result of acceleration of heliospheric particles by solar flares and

CMEs and are characterized by the abrupt enhancement in proton flux in the energy range of keV to MeV. There are some intense SEP events that occurred in association with severe geomagnetic storms during solar cycle 23.

In recent times, great attention has been paid in understanding Sun-Earth interactions and space weather events, solar flares, CMEs, and geomagnetic storms, due to ever increasing reliability on space-based technological systems. Geomagnetic storms are the most dramatic and perhaps the most important phenomenon of space weather effect on Earth. Super intense magnetic storms ($Dst < -400$ nT) are very rare, but they could have a great impact on society and technological systems such as severe power outages, satellite damage, communication failures, and navigational problems. The records of super intense magnetic storms are very rare. For example, during the space age since 1958, only one storm on 13 March 1989 has been recorded with minimum value of *Dst* as low as −589 nT. Although there was a huge CME in October 2003, it could not produce super intense magnetic storm, instead produced an intense double storm with *Dst* value of −383 nT, whereas a much weaker CME in November 2003 produced a super intense storm with *Dst* −422 nT, which clearly shows that the strength of geomagnetic storms not only depends upon the speed of CME but the solar wind magnetic field plays an important role. Recently, NASA Solar Terrestrial Relations Observatory spacecraft observed the largest solar eruption ever recorded on 23 July 2012, but it was not Earth directed. *Baker et al*. [2013] suggested that if the eruption had occurred just a week before, the Earth could have experienced an extreme geomagnetic storm like the famous Carrington event of 1859. It was also suggested that impact on the surface of the Earth could have been similar to the March 1989 storm that collapsed the Hydro-Québec power grid in Canada [*Ngwira et al*., 2013]. Hence, it is very important to understand what would be the possible interplanetary conditions that can cause such super intense geomagnetic storms.

Tsurutani et al. [2003] investigated the unique magnetic records from Colaba observatory in Bombay, India, for Carrington magnetic storm on 1–2 September 1859 and estimated the probable interplanetary electric field conditions that could produce such a super intense magnetic storm of -1600 ± 10 nT at Colaba ($Dst \approx -1760$ nT). A huge interest is instigated on the Carrington event of 1–2 September 1859 and raised lot of discussions and debates over the extreme characteristics of the event. *Cliver and Dietrich* [2013] discussed the 1859 space weather event in detail and compared it with the magnetic records available during that era (references therein). The large negative excursion of −1600 nT at Colaba magnetogram is debated by many researchers, and they concluded that the decrease could be due to the combined magnetopsheric and ionospheric effects in addition to the ring current [*Green and Boardsen*, 2006]. A few reports also discussed this event through model simulations, the largest imaginable magnetic storm with typical characteristics and the estimation of *Dst* based on models [*Siscoe et al*., 2006; *Vasyliunas*, 2011; *Li et al*., 2006]. *Tsurutani et al*. [2003] provided a list of old historic intense magnetic storms observed at Indian magnetic observatories, Colaba, Alibag, and world observatories of stations Kew, Greenwich, and Potsdam.

The Colaba-Alibag observatories, being one of the oldest and longest operated magnetic observatories in the world, have recorded a rich set of historic geomagnetic storms since 1841. In addition to famous Carrington event, there were many unique historic records of intense geomagnetic storms at Colaba-Alibag observatories that have occurred prior to space age and have not been widely reported in literature. For example, Figure 1 shows some of the intense geomagnetic storms observed at Colaba observatory which are used for present analysis. Figure 1a shows super intense magnetic storm of Carrington event of 1–2 September 1859 which was well investigated [*Tsurutani et al*., 2003]. Figure1b shows another super intense storm event which occurred during 11–12 October 1859 when the *H* component decreased to a minimum of ~−980 nT from its quiet time midnight value ($\Delta H < -980$ nT) at Colaba.

A detailed revisit and analysis of intense geomagnetic storms from longest database available from Colaba-Alibag observatories can provide important insights on probable frequency of occurrence of intense geomagnetic storms. Although there are only one or two super intense geomagnetic storms recorded and reported during the space age, there are many such super intense storms that have occurred prior to 1957. Having the continuous and long history of geomagnetic field observations from one of the oldest observatories, Colaba, Bombay, the study of historical geomagnetic storms can help to create a good database for intense and super intense geomagnetic storms. Further, an approximation of plausible interplanetary conditions that lead to such intense geomagnetic storms may give important clues on the probability of occurrence of intense geomagnetic storms and their impact on modern hi-tech society. With this motivation, a comprehensive investigation is made on the relationship between interplanetary electric field (IEFy)

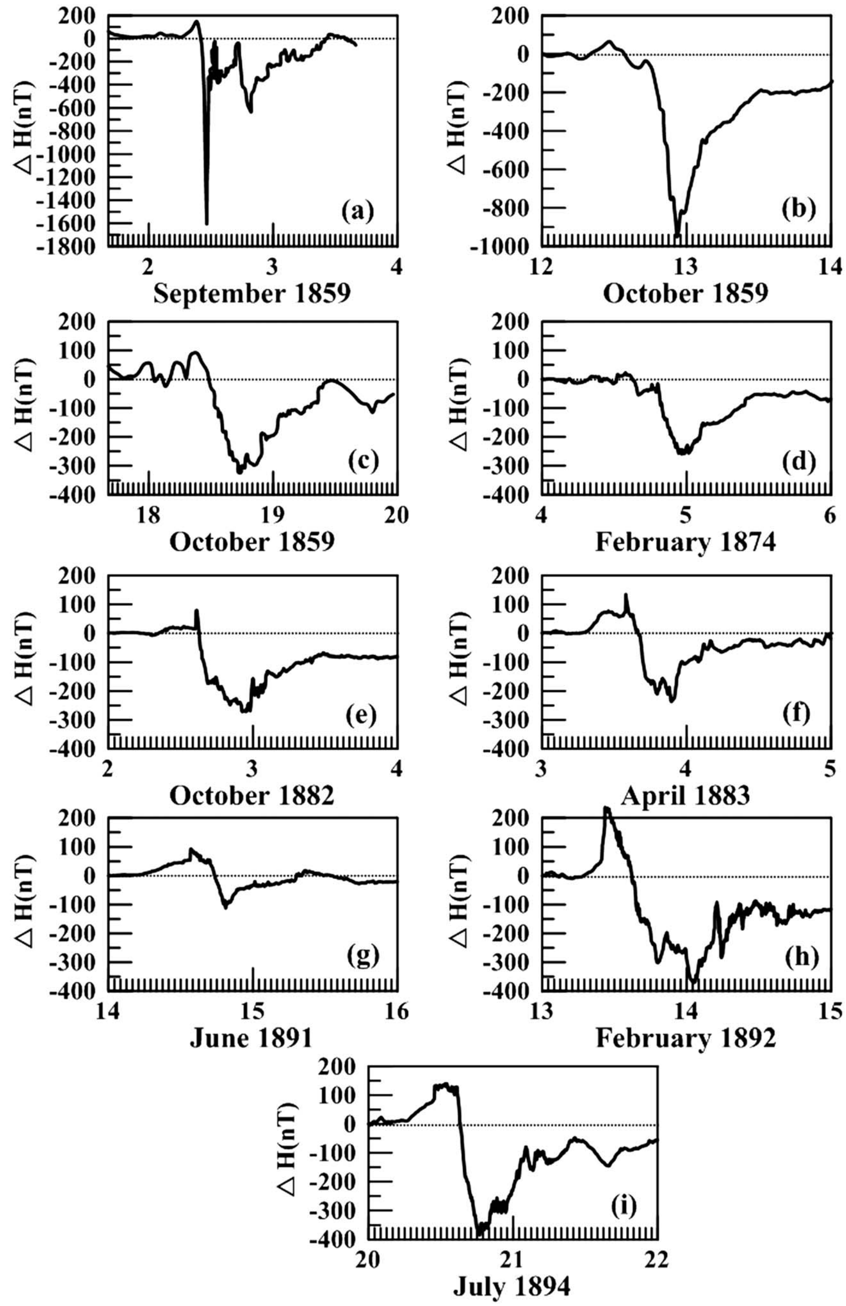

Figure 1. Some of the intense magnetic storms recorded at Colaba magnetic observatory, India, used in the present analysis. The *X* axis shows the duration of storm period in local time. The magnetic data (*X* axis) are 1 h time resolution, but during main phase time resolution is 15 min.

and the ring current injection rate (*Q*) derived from *H* component of geomagnetic field during the moderately intense geomagnetic storms that occurred in solar cycle 23. Using this derived empirical relationship between IEFy and *Q*, an attempt is made to estimate the IEFy conditions that were responsible for intense geomagnetic storms recorded at Colaba-Alibag observatories prior to the space era.

2. Historical Observations and Data Analysis

The Colaba (geographic latitude 18.5°N, geographic longitude 72.9°E) observatory started in 1823 for astronomical observations and timekeeping by the East India company in order to support British and other shipping

Table 1. List of Intense Historic Magnetic Storms Recorded at Colaba With Main Phase Onset, Range, and Estimated Time-Integrated Interplanetary Electric Fields Using ΔH_{COL}

Date	MP Onset (LT)	MP Range[a] (nT)	Σ IEFy Estimated (mV m^{-1} h)
02/09/1859	11:00	1600	273
12/10/1859	17:00	915	355
18/10/1859	09:00	415	260
04/02/1874	19:00	220	67
02/10/1882	14:00	350	102
03/04/1883	14:00	371	86
14/06/1891	10:00	173	41
13/02/1892	10:00	607	95
20/07/1894	14:00	513	102
13/03/1989[b]	02:00 (UT)	572	275

[a]The main phase range is the difference between maximum and minimum of *H*.
[b]For 13 March 1989 storm *Dst* index is used and time is in UT.

companies as Bombay was a major port. Arthur Bedford Orlebar, Professor of Astronomy at the Elphinstone College, Bombay, installed the instruments at Colaba to set up the first indian magnetic observatory in 1840. Magnetic measurements during the period of 1841 to mid-1845 were intermittent; following 1845 the observations were taken bihourly, later became hourly. A self-recording photographic magnetometer with a light source, a mirror for amplifying the magnet's movement, and a drum of photographic paper gradually replaced the older manual method of taking eye observations. Observatories all over the world started using the method of continuous recording of geomagnetic elements by the new photographic drum, and in 1846 regular observations were started at Colaba magnetic observatory. Ground magnetic measurements contribute and provide a unique and inexpensive database in space weather studies. About 200 years ago the changes in the geomagnetic field components were observed, and in the early eighteenth century India joined the Göttingen Magnetic Union.

Using Grubb's magnetometer, systematic recordings of the hourly eye observations on all days except holidays were carried out at Colaba from 1846 to 1867 as reported in the *Royal Society* [1842] and *Taylor* [1840]. On days of geomagnetic disturbances observed in the movement of magnets, eye observations were made at every 15 min, and the frequency of observations were increased to 5 min intervals during severe disturbances. Due to urbanization, the ordinary tram lines in Bombay were replaced by electric traction in 1900, and the electric power drawn from overhead wires caused disturbances in magnetic field observations at Colaba. Hence, the observatory was relocated to a quiet coastal town Alibag (geographic latitude 18.5°N, geographic longitude 72.9°E) (28 km southeast of Colaba) in 1904. Thereafter, until 1905 continuous photographic recordings of geomagnetic elements were undertaken using Kew magnetometer as described in *Moos Volume 1 and 2* [1910]. The continuity and compatibility of the recordings were maintained by parallel observations made for 2 years (1904–1906) at both Colaba and Alibag. The Colaba and Alibag observations together constitute one of the longest series of geomagnetic data in the world (from 1846 until today). The old magnetic instruments like LaCour variometer; Watson quartz fiber variometer; and IZMIRAN II variometer were used to measure the variation in the intensity of the horizontal, declination, and vertical components of the Earth's magnetic field. Finally, the state-of-the-art digital fluxgate magnetometers were installed for digital recording of the magnetic field variations at Alibag observatory. Only a few observatories in the world such as Kew and Greenwich were operating along with Colaba-Alibag observatories during the eighteenth century.

The description of magnetometers and methodology used for data calibration is described by *Tsurutani et al*. [2003]. The meticulous method of data reduction and analysis facilitated the study of some of the interesting storm events prior to 1900. For example, the most intense magnetic storm recorded in the history of the Earth, in nearly 13 solar cycles, occurred on 1–2 September 1859 driven by a huge solar flare on 31 August 1859 [*Carrington*, 1859; *Hodgson*, 1859], and the depression in *H* component recorded at Colaba was estimated to be ≈ -1600 nT (estimated $Dst \approx -1760$ nT) [*Tsurutani et al*., 2003]. On similar lines, some selected historic storm events (Table 1) were also calibrated and analyzed to estimate the main phase decrease in *H* component. Also, there are several intense magnetic storms recorded at Colaba within the *H* range of -350 to -500 nT. A few intense magnetic storms considered in this study are shown in Figures 1a–1i, and their main phase characteristics are listed in Table 1.

Further in this study, the geomagnetic activity index *Dst* is taken from World Data Center, Kyoto University (http://wdc.kugi.kyoto-u.ac.jp/index.html). The hourly averaged interplanetary and solar wind magnetic field parameters measured by Advanced Composition Explorer (ACE) satellite at L1 point have been taken from http://cdaweb.gsfc.nasa.gov/cgi-bin/eval1.cgi. In the present analysis, 69 magnetic storms in solar cycle 23 with

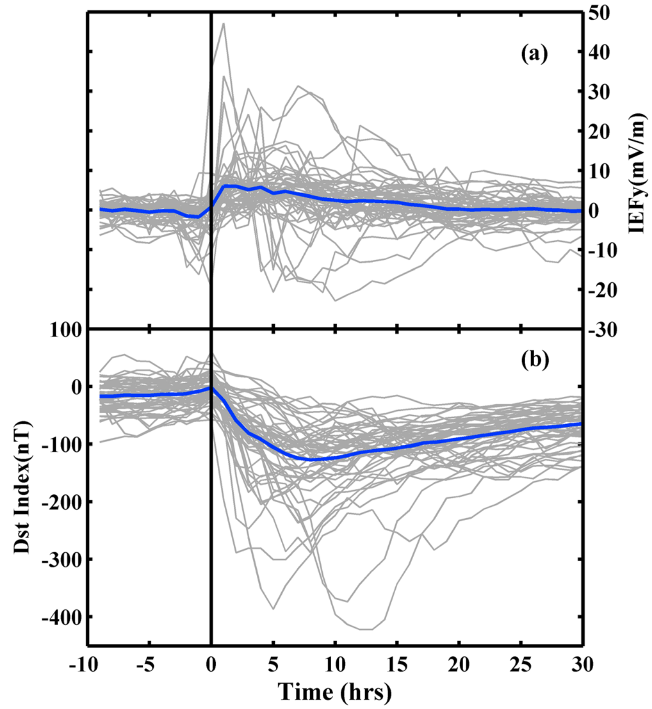

Figure 2. Superposed epoch plot of magnetic storms of solar cycle 23 used for the analysis. (a) The associated interplanetary electric fields and (b) the *Dst* index. The solid black line shows the main phase onset.

clear main phase signatures and without much fluctuations are considered for the analysis with $Dst < -100$ nT. The cases in which either solar wind velocity or southward IMF B_z (B_s) data were not available were ignored. Figure 2 shows the superposed epoch plot of *Dst* index and associated IEFy centered on time of main phase onset for all the geomagnetic storms considered in this study during solar cycle 23. The digital ground magnetic data with 1 h resolution have been taken from the Indian low-latitude station, Alibag, for the magnetic storms during solar cycle 23, and for historic magnetic storms hourly data of Colaba observatory, Bombay, have been used. The interplanetary coronal mass ejection (ICME) classification of MC, ejecta, and sheath of all magnetic storms are taken from *Gopalswamy et al.* [2010].

3. Analysis and Results

The basic mechanism of energy transfer from solar wind to the Earth's magnetosphere is magnetic reconnection [*Dungey*, 1961], and the primary cause of intense magnetic storm is a long duration of southward interplanetary magnetic field which interacts with Earth's magnetic field and allows the solar wind energy transport into the Earth's magnetosphere [*Gonzalez et al.*, 1994]. *Burton et al.* [1975] have established an empirical relationship for the rate of change of *Dst* in terms of the dawn-to-dusk interplanetary electric field for intense magnetic storms,

$$\frac{\mathrm{d}Dst}{\mathrm{d}t} = Q - \frac{Dst}{\tau} \tag{1}$$

where Q is an important parameter that represents the ring current injection rate which is a function of interplanetary electric field and τ is the decay constant in hours $\frac{1}{\tau} = 0.13$.

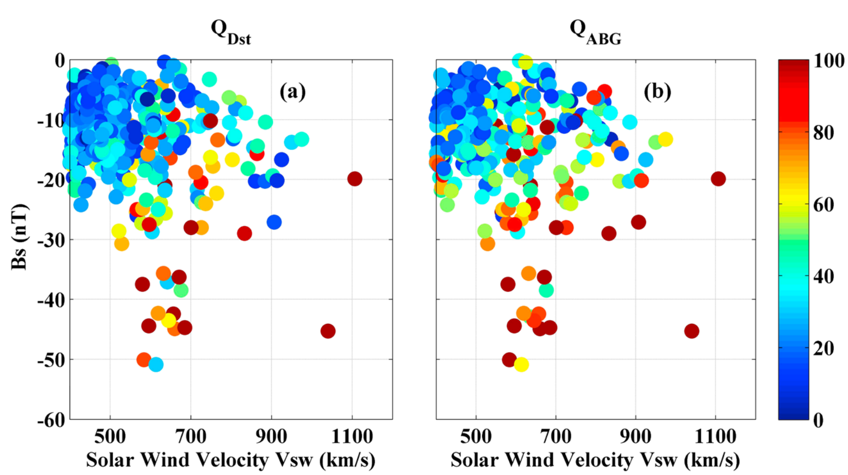

Figure 3. The variation of ring current energy (Q) with IMF B_s and solar wind velocity (V_{sw}). The variations of (a) Q_{Dst} and (b) Q_{ABG}. The color bar shows the strength of Q.

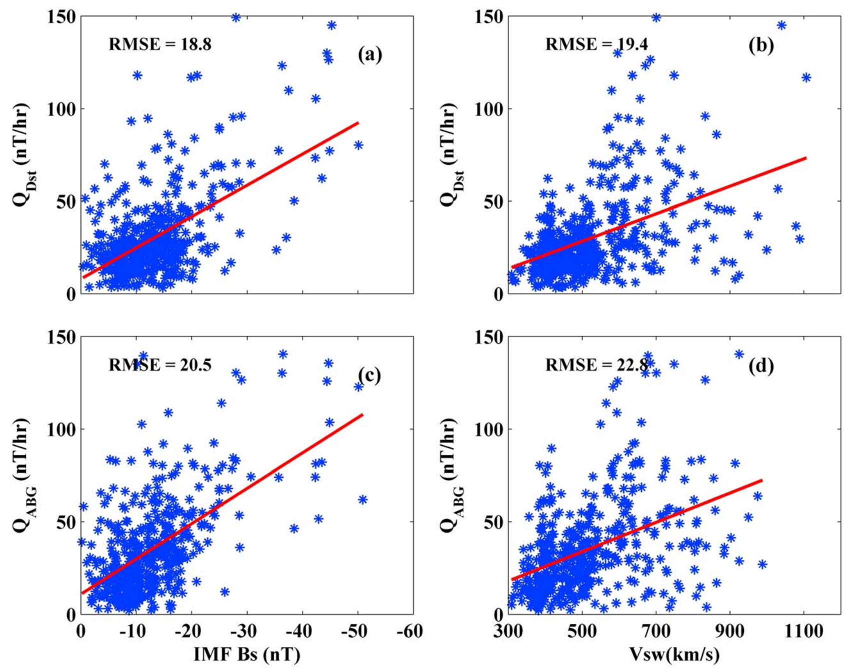

Figure 4. The scatterplots of (a, c) Q_{Dst}/Q_{ABG} and B_s for all the values of V_{sw} and (b, d) Q_{Dst}/Q_{ABG} and V_{sw} for all the values of B_s. The red line represents the linear fitting with RMSE values.

From equation (1), one can estimate the ring current injection rate Q from the variation of Dst as below:

$$Q_{Dst} = \frac{\mathrm{d}Dst}{\mathrm{d}t} + \frac{Dst}{\tau} \tag{2}$$

A total of 69 intense geomagnetic storms ($Dst < -100$ nT) with clear (without fluctuations) main phase during the solar cycle 23 (shown in Figure 2) were considered to examine the dependency of Q_{Dst} on solar wind velocity (V_{sw}) and southward component of IMF B_z (hereinafter referred as B_s). Figure 3a shows the variation of Q_{Dst} with V_{sw} and B_s during the entire main phase period of 69 geomagnetic storms. It can be clearly observed that the Q_{Dst} increases significantly for large negative B_s values and also increases with V_{sw}.

The Colaba-Alibag observatories being at low-latitude locations are well outside the equatorial electrojet region and also sufficiently far from the high-latitude geomagnetic disturbances. Hence, the variations in H component at Colaba-Alibag observatory due to ring current are expected to be similar to the variations in Dst. With a view to examine this, the ΔH values (after subtracting the quiet time midnight base value) from Alibag for the selected 69 geomagnetic storms were considered to compute the ring current injection rate as below:

$$Q_{\mathrm{ABG}} = \frac{\mathrm{d}\Delta H_{\mathrm{ABG}}}{\mathrm{d}t} + \frac{\Delta H_{\mathrm{ABG}}}{\tau} \tag{3}$$

Figure 3b shows the variation of Q_{ABG} as a function of V_{sw} and B_s. It can be observed from Figures 3a and 3b that the dependency of ring current injection rate on V_{sw} and B_s is similar for both Q_{Dst} and Q_{ABG}.

In order to examine the independent contributions of V_{sw} and B_s for ring current injection rate, the hourly values of Q_{Dst} and Q_{ABG} (computed from equations (2) and (3), respectively) have been plotted as a function of B_s and V_{sw} in Figures 4a–4d. Figures 4a and 4b show the variation of Q_{Dst} with B_s and V_{sw}, whereas Figures 4c and 4d show the variation of Q_{ABG} with B_s and V_{sw}. It can be observed from these figures that the ring current injection rates Q_{Dst} and Q_{ABG} derived from Dst index and ΔH_{ABG} exhibit similar variations with B_s and V_{sw}. Further, both the Q_{Dst} and Q_{ABG} increase with increases in B_s and V_{sw}. With a view to examine the dependency of ring current injection rate on solar wind parameters, the linear least squares fit is applied between the Q_{Dst}/Q_{ABG} and V_{sw}/B_s for each plot in Figure 4. It can be observed from these figures that the

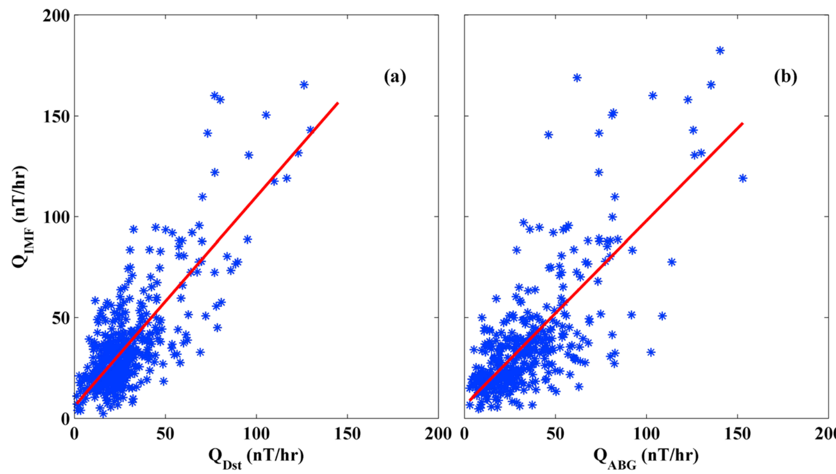

Figure 5. The linear relationship (a) between Q_{Dst} and Q_{IMF} and (b) between Q_{ABG} and Q_{IMF}.

ring current injection rate (Q_{Dst}/Q_{ABG}) varies almost linearly with B_s and V_{sw}; however, the large scatter of points indicates the complex variability of Q. The root-mean-square error (RMSE) values vary from 18 to 22.6 and nearly similar for both between Q_{Dst}/Q_{ABG} versus B_s and V_{sw}. However, the slopes of linearly fitted curves between Q_{Dst}/Q_{ABG} and B_s in Figures 4a and 4c are larger (−1.68/−1.90) than the slopes between Q_{Dst}/Q_{ABG} and V_{sw} (0.074/0.079) in Figures 4b and 4d. This indicates that the ring current injection rate, Q, increases more rapidly with the increase in B_s than with V_{sw}.

Burton et al. [1975] have also derived an empirical relationship between Q and the interplanetary electric field (the product of V_{sw} and B_s) as

$$Q_{\text{IMF}} = \alpha \cdot V_{\text{sw}} \cdot B_s \tag{4}$$

where α is empirically $-1.5 \times 10^{-3}\,\text{nT s}^{-1}\,(\text{mV/m})^{-1}$ and $V_{\text{sw}} \cdot B_s$ is in mV/m (constant value of −0.5 mV/m given by *Burton et al.* [1975] is negligible for intense storms). Now the integrated Q_{IMF} during the main phases of 69 geomagnetic storms in solar cycle 23 are computed using equation (4) and compared with Q_{Dst} and Q_{ABG}, as shown in Figures 5a and 5b, respectively. It can be observed from Figures 5a and 5b that the Q_{IMF} exhibits good linear relationship with both Q_{Dst} and Q_{ABG} with correlation coefficients 0.79 and 0.74, respectively. The linear relationship between Q_{Dst} and Q_{IMF} (Figure 5a) is given by

$$Q_{\text{IMF}} = 1.04 \cdot Q_{Dst} + 5.87 \tag{5}$$

Similarly, the relationship between the Q_{ABG} and Q_{IMF} (Figure 5b) is given by

$$Q_{\text{IMF}} = 0.92 \cdot Q_{\text{ABG}} + 6.12 \tag{6}$$

From equation (2), Q_{IMF} is the product of V_{sw} and B_s (interplanetary electric field, IEFy) and α. Now substituting the value of α as 5.4 nT mV/m/h in equations (4) and (5) gives

$$\text{IEFy} = 0.19 \cdot Q_{Dst} + 1.08 \tag{7}$$

$$\text{IEFy} = 0.17 \cdot Q_{\text{ABG}} + 1.13 \tag{8}$$

It should be noted that the slopes and intercepts of the linear equations (7) and (8) are similar. This similarity in equations (7) and (8) and the similarity in correlation coefficients shown in Figures 5a and 5b indicate that the empirical relationship derived by *Burton et al.* [1975] between IEFy and *Dst* can also be applicable for ΔH_{ABG}. More importantly, these results suggest that one can estimate the probable interplanetary conditions (IEFy) for the intense geomagnetic storms using ΔH variations at Colaba-Alibag observatories using equation (8) when the *Dst* observations are not available. The RMSE between the observed Q_{IMF} (from ACE observations) and estimated from Q_{Dst} and Q_{ABG} are 10.21 and 10.47 mV/m (Figures 5a and 5b), respectively. The high correlation coefficients (0.79 and 0.74) and smaller RMSE (10.21 and 10.47 mV/m) indicate that the Q_{IMF} can be accurately estimated from the *Dst* and/or ΔH variations with minimal error (~±10–11 mV/m h) using linear relationship given by equations (7) and (8), respectively.

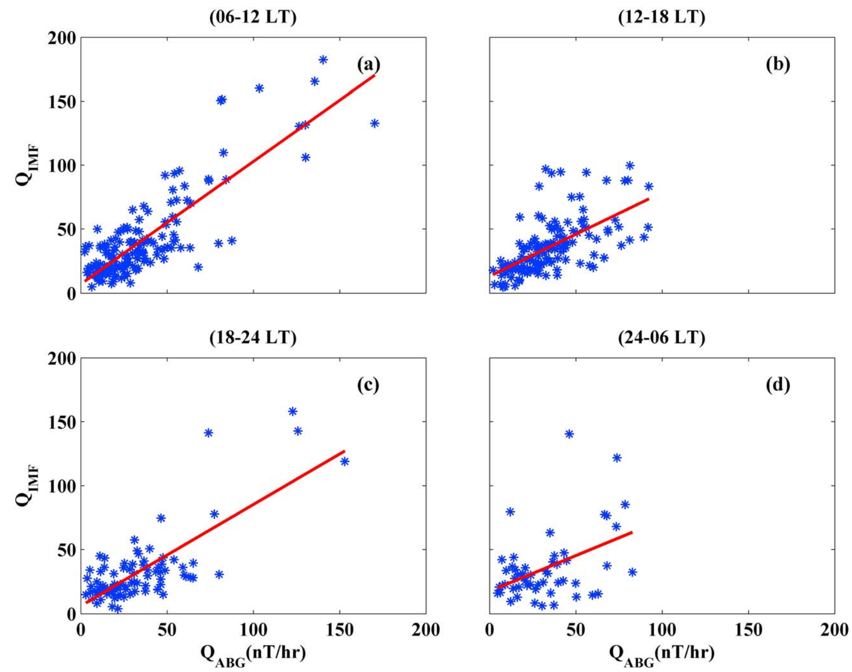

Figure 6. (a–d) Variation of Q_{ABG} with Q_{IMF} for different local time intervals.

It should be noted that the *Dst* index is derived from the mean variations of Δ*H* at four to five low-latitude stations that are spatially distributed at different longitudinal sectors. Hence, the local time effects on the Δ*H* variation at different longitudinal sectors will be averaged and minimized. However, when we consider the Δ*H* values from a single station at Colaba or Alibag, the local time effects may influence the estimation of IEFy from equation (8). In order to verify the local time influence on the Q_{ABG}, the scatterplots are shown between Q_{ABG} with Q_{IMF} for different local time intervals of 06:00–12:00, 12:00–18:00, 18:00–24:00, and 24:00–06:00 LT in Figures 6a–6d, respectively. It can be observed from Figure 6 that the Q_{IMF} exhibits a similar linear relationship with Q_{ABG} at all local times indicating the minimum effect of local time, except at 24:00–06:00 LT interval. It could be due to less number of data points in this range. Hence, Δ*H* ABG can be consider as a proxy parameter for Colaba and Alibag, for old historic magnetic storms where the *Dst* data are not available.

Table 1 shows the list of some of intense historic magnetic storms including Carrington storm with MP onset time, range, and the estimated time-integrated interplanetary electric fields which is computed from equation (8). Among all these interesting magnetic storms recorded at Colaba observatory, Bombay, only Carrington event is reported [*Tsurutani et al.*, 2003], the rest of the intense events are not analyzed, and there are no other supporting data available during the period. By investigating these intense magnetic storms, the predictability of intense events during solar cycle will be studied. *Tsurutani et al.* [2003] estimated the interplanetary electric field ~200 mV/m for Carrington storm on 1 September 1859 using the empirical equations given by *Cane* [1985] and *Gonzalez et al.* [1998]. We have estimated time-integrated electric field for Carrington storm by using equation (8), to be 273 mV/m which is closer to the value of estimated electric field by *Tsurutani et al.* [2003] (200 mV/m). We have also estimated integrated IEFy for 13 March 1989 storm, which is 275 mV/m (see Table 1). For 20 November 2003 magnetic storm ACE satellite observed integrated IEFy to be 175 mV/m, and the estimated value by using equation (7) is 125 mV/m. The IEFy during the main phase of the other intense magnetic storms calculated based on these equations are given in the Table 1. It is observed that time-integrated IEFy is very high for particular intense events, where the MP range is high and decrease in main phase is very fast.

Gonzalez et al. [2007] have studied intense storms of solar cycle 23 based upon their interplanetary structures. They showed that the magnetic clouds are most geoeffective and the CIR storms are less geoeffective. An attempt has been made to study the dependency of ring current injection rate on the interplanetary structures like MC, sheath, and ejecta. In the present work, we classified the magnetic storms which occurred during solar cycle 23 into two categories, viz., MC and sheath and ejecta based upon their interplanetary structure.

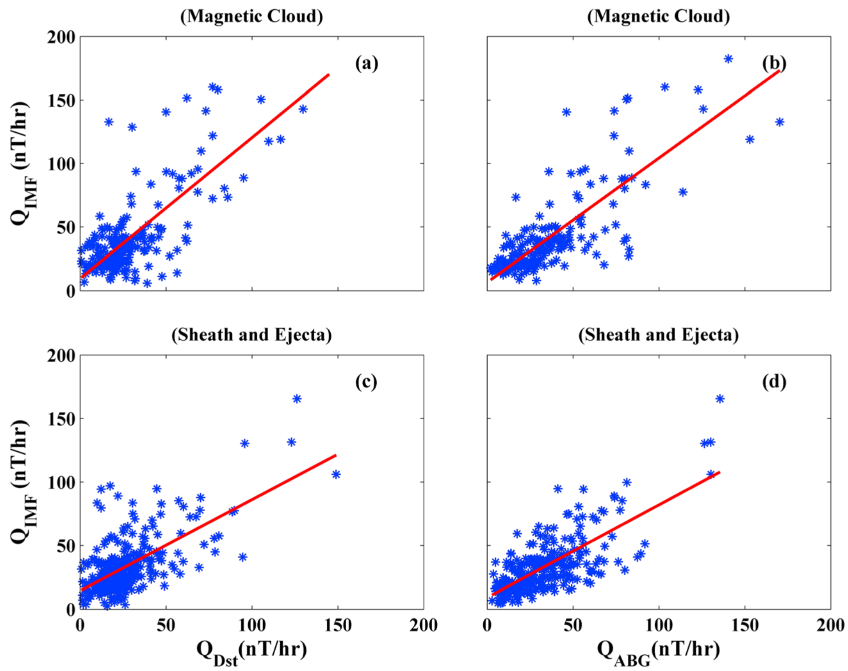

Figure 7. The relationship between the Q_{Dst}/Q_{ABG} and Q_{IMF} for different interplanetary structures. The Q_{Dst}/Q_{ABG} with Q_{IMF} for (a and b) magnetic clouds and (c and d) for sheath and ejecta.

The Q_{Dst} and Q_{ABG} values for both MC and sheath and ejecta categories storms were calculated using *Dst* and ΔH ABG. Then the relationship between Q_{Dst}/Q_{ABG} and Q_{IMF} was established for MC, sheath, and ejecta. Figures 7a and 7b show the relationship between Q_{Dst}/Q_{ABG} and Q_{IMF} for MC events, respectively. Similarly, Figures 7c and 7d show the relationship between Q_{Dst}/Q_{ABG} and Q_{IMF} for sheath and ejecta events, respectively. The correlation coefficients are 0.80 and 0.76 (Figures 7a and 7b) for MCs and 0.64 and 0.73 (Figures 7c and 7d) for sheath and ejecta. Figures 7a and 7b show that MC events are well correlated than the sheath and ejecta events; i.e., the magnetic storms produced by MC have more input energy as they are more geoeffective.

4. Discussion

There are several parameters and physical mechanisms responsible for producing the intense magnetic storms depending on solar, interplanetary, and magnetospheric conditions. The steady IMF B_z with higher solar wind velocity at CME front plays a pivotal role in the intense interplanetary cross-tail electric field ($-V_{\mathrm{sw}} \times$ IMF B_z) that causes intense geomagnetic storms at ground [*Balan et al.*, 2014]. However, it is found empirically that the IMF B_z plays relatively important role than solar wind speed for the creation of major storms because the variability of *Q* to the magnitude of solar wind speed is less than the variability due to IMF B_z [*Tsurutani et al.*, 1988]. Apart from interplanetary, the fast CMEs are one of main causes for the origin of geomagnetic storms during the solar maximum years. The counterparts of ICMEs, especially MC, show the existence of a relationship between their peak magnetic field strength and peak velocity values suggesting a possible intrinsic property of magnetic clouds and imply geophysical consequence [*Gonzalez et al.*, 1998]. Based on the detailed statistical study on geomagnetic storms ($Dst < -100$ nT) of solar cycle 23, it is found that most common structures leading to the development of an intense storm are magnetic clouds, sheath fields, sheath field followed by a magnetic cloud, and corotating interaction regions leading to high-speed streams that vary depending on the phase of the solar cycle [*Gonzalez et al.*, 2007]. However, the results therein are limited to only ICME structures and their significance during ascending, peak, and descending phases of solar cycle and do not consider intense magnetic storms of $Dst \le -250$ nT. Later, *Echer et al.* [2008] focused only on 11 super intense geomagnetic storms of solar cycle 23 ($Dst \le -250$ nT) and their interplanetary conditions. Their statistical study reveals that one third of the superstorms were caused by MCs, one third by combination of MC and sheath, and one third by sheath fields alone. It is interesting to note that the time-integrated interplanetary electric field (IEFy) is best correlated with peak *Dst* during storm main phase, in contrast with peak IMF B_z or peak IEFy for less intense storms. Most of the super intense magnetic storms occurred only during maximum and declining phases of solar cycle. It is also confirmed that only MCs and/or interplanetary sheaths had enough intense fields with long durations to cause superstorms [*Echer et al*., 2008]. In the present work, we have computed the time-integrated IEFy using *Dst* and ΔH ABG which also shows good agreement for almost 69 intense geomagnetic storms of solar cycle 23. Hence, the time-integrated IEFy is a key parameter as it provides the information of the severity of magnetic storms and an estimate of *Dst*.

A detailed investigation on SEP events associated with intense magnetic storms and the low-latitude geomagnetic response is analyzed by *Rawat et al*. [2006]. They found a close correspondence between the persistence of a high level of proton flux after the shock in some events and the ensuing intense magnetic storm and confirmed the key role of the preshock southward IMF B_z duration in generating a strong main phase. Recently, *Opera et al*. [2013] examined the solar and interplanetary parameters of CMEs causing major geomagnetic storms during solar cycle 23. They found a strong dependence of the *Dst* index on IMF B_z and on the Akasofu coupling function, demonstrating the significant role played by the reconnection between interplanetary and geomagnetic fields and thus the amount of the energy injected into the magnetosphere in the main phase of each geomagnetic storm. In the present analysis, the time-integrated IEFy derived from *Dst* and ΔH ABG for the intense magnetic storms of solar cycle 23 are well in concurrence with the calculated IEFy. Based on this methodology, we have used ΔH ABG to estimate the key parameter, time-integrated IEFy for historical events of Colaba observatory. *Tsurutani et al*. [2003] estimated the value of IEFy to be ~160 mV/m and 200 mV/m by assuming the velocity of shock (V_{shock}) to be ~2380 km/s and also the estimated solar wind speed to be approximately 1850 km/s for 1–2 September 1859 Carrington magnetic storm event. *Akasofu and Kamide* [2005] commented on the same event [*Tsurutani et al*., 2003] and pointed out that Colaba *H* component cannot be regarded as a *Dst* value as it will be function of local time, longitude, and main phase decrease. Considering the comment, we have examined the ring current injection parameter dependence on local time using ΔH ABG with different local time sectors (Figure 6) for some of intense magnetic storms observed at Colaba and clearly show significant linear relationship. The time-integrated interplanetary electric field IEFy estimated for the same event, 273 mV/m, which is near to the value of estimated electric field by *Tsurutani et al*. [2003], and other values cannot be compared due to lack of observations of old events. However, the estimated results obtained can give us an insight of prevailing interplanetary conditions during old super intense magnetic storms of Colaba. The further investigation will be taken up by considering the superintense magnetic storms which were also observed by other magnetic observatories in the world like Kew, Greenwich, and Potsdam. We will extend our study on occurrence of super intense magnetic storms during different solar cycle since 1900.

5. Conclusions

The main objective of the present study is to examine and estimate the integrated electric field of historical geomagnetic storms recorded at Colaba, India, during the eighteenth century. The variation in ring current rate (*Q*) is computed using *Dst* and ΔH ABG by analyzing 69 intense geomagnetic storms of solar cycle 23. The main findings are

1. The ring current injection rate variation depends on IMF B_s and V_{sw}. Its intensity is more dependable on IMF B_s strength and duration.
2. The ring current injection rate computed using *Dst* and ΔH ABG is almost in good agreement. The empirical equations are obtained from that linear relationship, which are used to estimate the integrated electric field of historical magnetic storms.
3. The magnetic cloud events show the significant correlation with *Dst* and ΔH ABG rather than sheath and ejecta events.
4. Based on the empirical analysis of 69 intense magnetic storms, the integrated electric field is estimated for historical geomagnetic storms recorded at Colaba. The IEFy obtained for Carrington event, 1–2 September 1859, is close to the value computed by *Tsurutani et al*. [2003].

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