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Posted Date: 9 January 2026

doi: 10.20944/preprints202601.0687.v1

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Investigations on the Extreme Space Weather Conditions During the Years 1841-1877 Using Geomagnetic Observations in Trivandrum, Singapore, Bombay and Madras

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Abstract

We have collected geomagnetic observations from low and equatorial latitudes during the 19th century to infer the intensity of geomagnetic storms during the years 1841-1877. Daily mean H observations during the above years in Trivandrum, Singapore and Madras is first scaled to Bombay observations and subsequently to the Dst index to infer the intensity of storms in modern units . These results are also compared with the intensity of these storms derived from mid latitudes. Extreme space weather events (ESW) are identified from the list of intense storms inferred during this period. The annual number of ESW events shows the characteristic double peak structure during the sunspot cycles 9-11. Space weather conditions during the sunspot cycle 11 (1867-1877) is found to be exceptional. A discussion on the true intensity of geomagnetic storms is also included.

Keywords : geomagnetic storms; 19th century; Trivandrum; Singapore; Madras; space weather

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1. Introduction

Geomagnetic storms are important manifestations of space weather changes near Earth (Mandea and Chemboldt, 2021.) The severity of space weather conditions generally increase with the intensity of these storms. Direct records of extreme space weather events dates back to middle of the 19th century (Cliver and Svaalgaard,2004 and the pr)oxy records of the same is available back to the 16th century (Cliver et al., 2022). The intensity of geomagnetic storms is related to the strength of the magnetospheric ring current whose effects are prominent in both low and equatorial magnetic latitudes in Earth (Ganuskina et al., 2017). Both Dst and Sym H indices are now used to determine intensity of geomagnetic storms (Villaverde etal, 2024). Dst index is currently derived from H variations in four low latitude stations after making necessary Sq corrections. (Geomagnetic Equatorial Dst index, available in : https://wdc.kugi.kyoto-u.ac.jp/dstdir/) Records of mid latitude geomagnetic observations are well documented and dates back to the19th century (Jones, 1955; Stamper et al., 1999;Nevanlinna, 2004).This is not however true for observations from low and equatorial magnetic latitudes.

Systematic and long term geomagnetic observations started for the first time in the Greenwitch observatory in London during the year 1840. Magnetic observations in British colonies were coordinated by the Royal Society of London during the 1840's . It is quiet interesting to find that magnetic observatories were established in Singapore, Trivandrum and Madras during the year 1841. Continuous geomagnetic observations started in Colaba observatory in Bombay (now Mumbai) began later from the year 1846 onwards (Moos, 1910 a).Magnetic observations in these observatories were carried out following the standards and instructions of the royal society (Royal Society, 1840).Only part of the 19th century magnetic observations in the above colonial observatories were either studied or published. Rest of them is possibly available in manuscript form in different archives of the world.

The observatories covered in this chapter are mainly low or equatorial latitude observatories which were functioning at Trivandrum, Madras, Bombay and Singapore during the British administration periods. Early geomagnetic observations made in these observatories are by and large hourly eye readings of different magnetic elements which can be reduced to old British geomagnetic units (and further to SI units) if the constants of measurements are known.There are several challenges in analysing geomagnetic data during the 19th century (Blake etal, 2020; Hejda et al., 2023). In order to study hourly H observations of that period we should know i) the type of bifilar magnetometer used for H measurements ii) the magnetometer constants (unit or scale coefficient and temperature coefficient) which will vary from time to time and iii) absolute measurements of H (at least on monthly or yearly basis) in that observatory (Broun, 1862). These details are studied in detail for the daily mean H observations from the Trivandrum observatory during the years 1855-1877.

In this paper using daily mean H observations in Singapore (1841-1845), Madras (1846-1855) and Trivandrum (1855-1877) we have attempted to infer the intensity of major geomagnetic storms during the years 1841-1877. Intensity of the storms are(in units of nT) are initially determined by scaling with Bombay H observations. Subsequently intensity of storms (in units of nT) are scaled to Dst values using the Carrington storm observations a reference. The results are then compared with We have identified occurrences of extreme space weather events (ESW) during the years 1841-1877 from the list of extreme intense and super intense storms inferred during this period . Annual number of ESW events show characteristic solar cycle variations during the sunspot cycles 9-11. Exceptional space weather activity during solar cycle 11 (1867-1877) is a new result from this study. After pointing out the limitations in the modern Dst index the need for determining true intensity of geomagnetic storms are also discussed.

2. Details of Data Used

2.1 Published values of daily mean horizontal intensity (H) of geomagnetic (as ratio relative to absolute H) of the Singapore magnetic observatory (ref) during years 1841-1845 (Eliot, 1850)

2.2 Published values of daily mean horizontal intensity (H) of geomagnetic (as ratio relative to absolute H) of the Madras magnetic observatory (ref) during years 1846-1855 (Taylor et al., 1854; Jacob, 1884)

2.3 (a) Geomagnetic storm intensity derived for selected list of geomagnetic storms during 1852-63 adopted from Table of the PhD thesis (Eapen, 2009) using published hourly values of H (in British units) from Bombay (Colaba) observatory during the years 1852-1863 (Chambers, 1852; Fergusson, 1860 etc)

(b) Selected values of storm decrease in hourly values of H in Bombay(Colaba) observatory during the years 1847-1877 (Lakhina and Tsuratani, 2018; Kumar et al., 2015; Moos, 2010b).

2.4 Daily mean H values in Trivandrum magnetic observatory (in scale divisions) obtained in manuscript form from National Library of Scotland during the years 1855-1877. (NLS, 2007a; NLS, 2007b).

2.5 International yearly mean Sunspot number (classic values) during the years 1841-1877 (available in : https://www.sws.bom.gov.au/Educational/2/3/6).

2.6 Geomagnetic storm data from the Greenwitch observatory during the years 1841-1877 (Jones, 1955; Maunder, 1905; Airy, 1863).

2.7 Geomagnetic storm data from Russian magnetic observatories during the years (Ptisyna et al., 2012).

2.8 (a) 3 hourly aa indices during the years 1868-1877 and

(b) Yearly mean aa indices during the years 1868-1877 (available in https://www.ngdc.noaa.gov/stp/space-weather/geomagnetic-data/AA_INDEX/AA_YEAR)

doi:10.20944/preprints202601.0687.v1

2.9 Information on extreme space weather events during 1841-2024 from different publications (Cliver and Svaalgaard, 2004; Cliver et al., 2022; Vennerstorm et al., 2010; Rao, 1964; Tulasi Ram et al., 2024).

3. Investigations on the Geomagnetic Observations in Low/Equitorial Latitudes During the Years 1841-1877

3.1. Bombay Geomagnetic Observations and Storm Intensity Calculations During 1852-1863

Even though Coloba (Bombay) magnetic observatory is established during the year 1841 regular observations were started only from the year 1845 (Gawali et al., 2015) Eye readings of geomagnetic elements continued till the year 1872 when photographic recordings were started (Moos, 1910a). Horizontal intensity is measured mainly with large horizontal force magnetometer with bifilar suspension whose details are available in early data books of the observatory (Chambers, 1852 etc)

Hourly values of horizontal component of the geomagnetic field (H) observed in Coloba observatory in Bombay (now Mumbai) is collected for selected geomagnetic storm periods during 1852-1863. This data is available in British units (BU) of intensity. The intensity of major geomagnetic storms observed in Bombay in modern units during the years 1852-63 is available in Eapen (2009). Let is discuss some examples in this list :-

First we will consider the intensity calculations for two outstanding geomagnetic storms during the period of study. For the Carrington storm of September 2, 1859 (Fergusson, 1860; see also Figure 1 in Hayakawa et al., 2022) the pre-storm maximum or baseline in hourly H of Colaba is found to be 8.0467 BU. The storm time minimum in Colaba H during September 2, 1859 is found to be 7.672 BU. The difference between the two values is ΔH (= 0.3747 BU) or decrease in H during the main phase the Carrington stoof rm. To convert in to modern units we will use the following expression (Chapman and Gupta, 1971; Eapen, 2009)

$\Delta H(nT) = \Delta H((BU) \times 36000 / 7.8$ (1)

For the Carrington storm we could find from (1)

ΔH (Colaba) = 1729.38 nT (2)

For the October 12, 1859 storm we have found

ΔH (Colaba) = 0.2097 BU = 967.85 nT (3)

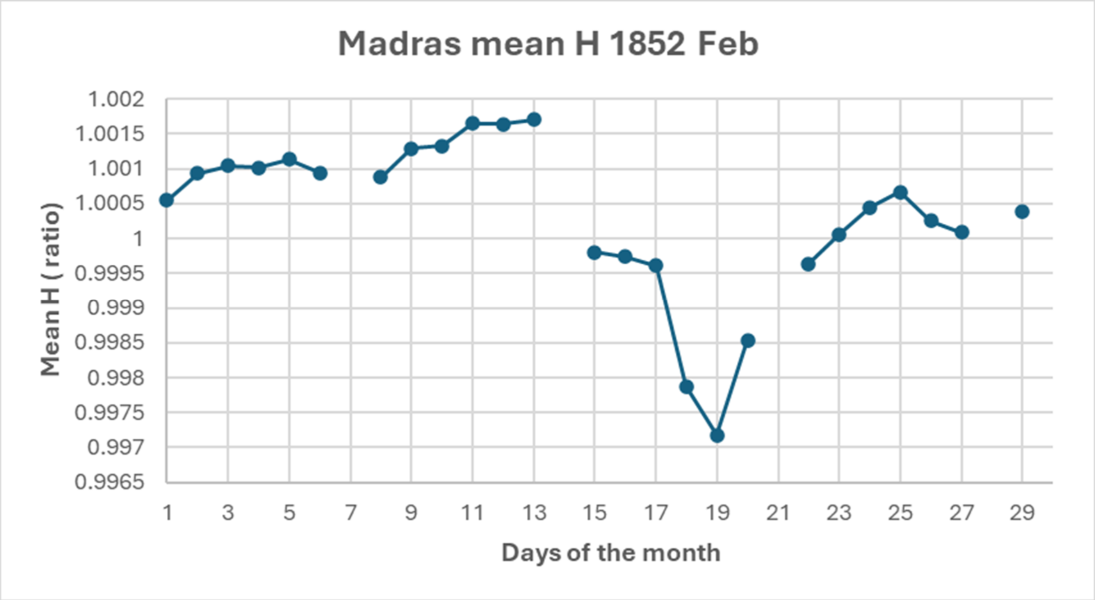


Figure 1. Daily mean H of Madras for the month of February 1852 expressed as fraction of absolute horizontal intensity in British Units**.** The decrease on Feb 19 is remarkable.

The values of ΔH for Colaba observatory published by Lakhina and Tsurutani (2018) for the Carrington storm is 1722 nT and for the October 12 (1859) storm is 984 nT. This justifies our calculations for the above two outstanding storms for Bombay. In a similar way we have calculated the intensity (ΔH) for more than 30 geomagnetic storms in Bombay during the years 1852-1863. The results are given in Table 2 and Table 5..

3.2 Madras Geomagnetic Observations and Storm Intensity Calculations

Earliest geomagnetic observations in Madras are made by TG Taylor (Govt Astronomer , Madras Observatory) along with John Caldecott (Director, Trivandrum Observatory) during 1837-38 period as a part of the magnetic survey of South India (Taylor, 1837;Taylor and Caldecott, 1839). The geographic coordinates of Madras is found (Taylor and Caldecott, 1839) to be 13^0 4′ 9″ N latitude and 80^0 17′ 12″ E longitude.The magnetic dip of Madras is determined as 6^0 50′ 9″ (north of dip equator) in 1838. The mean magnetic dip of Madras during January 1851 was 7^0 37′ 15″ which increased to 7^0 39′3″ during December 1855. The absolute horizontal intensity (H) of earths magnetic field measured in Madras varied between 8.1606 to 8.1970 BU during January 1851 and between 8.0682 to 8.1324 BU during December 1855.

Capt Ludlow (Madras Engineers) started geomagnetic observations in Madras Observatory

during March 1841. Observations during 1841-1845 and 1856-61 are not published so far and is believed to be available in hidden archives in manuscript form in London. Madras geomagnetic observations during 1846-1850 (Taylor et al., 1854) and 1851-1855 (Jacob, 1884) are however published . These later observations are used for the present study. The horizontal intensity data of Madras are given in these publications as hourly eye readings. This needs to be corrected for atmospheric temperature variations and required conversion in to relative intensity or British units which is not straight forward. However temperature corrected mean daily values of H in relative intensity values (as a fraction of the absolute H in Madras) are however available. We have used these values to determine the H decreases (ΔH) during magnetic storms in Madras during the years 1846-1855. Mean H values of Madras (in relative intensity units) given in the data books during February 1852 is shown in Figure 1. The MDS H_d in relative units for this storm is found to be 0.00452 . As an approximation we can assume 8.1 BU is the mean absolute H in Madras during our period of study so that for the February 18-19 storm of 1852 we have :

MDS Hd (BU) = MDS Hd X 8.1 = 0.00452 X 8.1 =0.03661 BU (4)

We have identified important geomagnetic storms during 1846-1855 using published Greenwich geomagnetic results (ref) . For each of these storm periods we have determined MDS Hd in BU using (4) These results are shown in Table 1 and Table 2

. In order to find the intensity of the storms in terms of modern units we have done a linear regression fit of MDS Hd (BU) values of Madras (1852-1855) with corresponding ΔH (hourly) values from Bombay observations (see Table) , The results are shown in Figure 2.

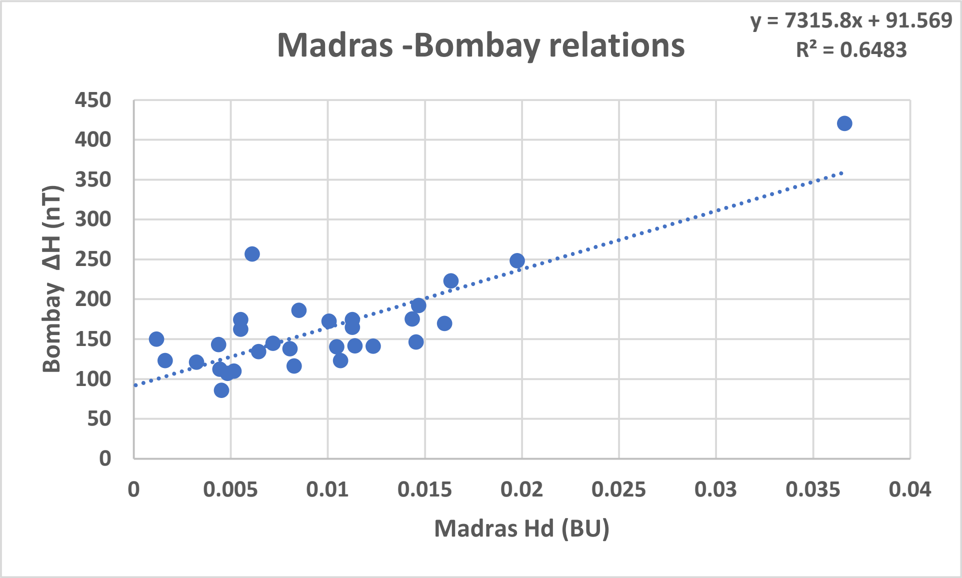


Figure 2. Regression relation between values of storm time change in daily mean H of Madras (BU) and Bombay hourly ΔH (nT) for selected geomagnetic storms during 1852-1855.

The yields the following linear regression equation :.

MDS ΔH (nT) = 7315.8 Hd (BU) +91.569 (R^2 = 0.6483, r = 0.81) (5)

Here MDS ΔH is the magnitude of storm time decrease in Madras scaled to Bombay observations in modern units (nT) and Hd is the observed magnitude of storm time decrease in Madras in BU .

Using (5) we have determined ΔH (nT) of Madras storms in modern units during the years 1846-1855. The results are shown in Table 1 and Table 2. The Greenwich classification of intense (A) and Great storms (G) are also included in these Tables (Maunder, 1905; Jones, 1955).

Table 1. Geomagnetic storm parameters in Madras Observatory during the years 1846-1851.

Sr No	Year	Storm Date	GW Class	MDS Hd	MDS Hd (BU)	MDS ΔH (nT)	Tvm Dst (nT)
1	**1846**	24-Jan		0.000489	0.0039609	120.54	105.9056221
2	1846	9-Feb		0.001072	0.0086832	155.0945546	176.1215008
3	1846	13-Mar		0.001795	0.0145395	197.9380741	263.1988255
4	1846	6-Apr		0.002101	0.0170181	216.071016	300.0531289
5	1846	7-Apr		0.001503	0.0121743	180.6347439	228.0306667
6	1846	12-May		0.00162	0.013122	187.5679276	242.122018
7	1846	11-Jul		0.000678	0.0054918	131.7469104	128.6685742
8	1846	7-Aug		0.001357	0.0109917	171.9830789	210.4465873
9	1846	4-Sep		0.001161	0.0094041	160.3685148	186.8405629
10	1846	11-Sep		0.001226	0.0099306	164.2202835	194.6690914
11	1846	22-Sep	G	0.000541	0.0043821	123.6285672	112.1684449
12	1846	8-Oct		0.000624	0.00505359	128.5410537	122.1528297
13	1846	17-Nov		0.001832	0.0148392	200.1306194	267.6550648
14	1846	26-Nov		0.001408	0.0114048	175.0052358	216.5889712
15	1846	23-Dec		0.00084	0.006804	141.3467032	148.179676
16	**1847**	22-Feb		0.001904	0.0154224	204.3971939	276.3266656
17	1847	1-Mar		0.001948	0.0157788	207.004545	281.6259772

18	1847	**19-Mar**	G	0.00364	0.029484	307.2690472	485.408596
19	1847	8-Apr		0.002145	0.0173745	218.6783671	305.3524405
20	1847	21-Apr		0.002932	0.0237492	265.3143974	400.1378548
21	1847	8-May		0.002313	0.0187353	228.6337077	325.5861757
22	1847	10-Jul		0.001306	0.0105786	168.9609219	204.3042034
23	1847	**24-Sep**	G	0.005122	0.0414882	395.0893736	663.8990458
24	1847	27-Sep		0.003436	0.0278316	295.1804193	460.8390604
25	1847	1-Nov		0.004743	0.0384183	372.6305991	618.2527027
26	1847	23-Nov		0.000515	0.0041715	122.0878597	109.0370335
27	1847	17-Dec	G	0.000116	0.0009396	98.44392568	60.9819124
28	1847	**20-Dec**	G	0.005587	0.0452547	422.6443343	719.9031343
29	**1848**	12-Jan		0.001115	0.0090315	157.6426477	181.3003735
30	1848	21-Feb	G	0.003551	0.0287631	301.995087	474.6895339

Table 1 (Madras 1846-1851) Contd..

Sr No	Year	Storm Date	GW Class	MDS Hd	MDS Hd (BU)	MDS ΔH (nT)	Tvm Dst (nT)
31	1848	20-Mar	A	0.002659	0.0215379	249.1369688	367.2580351
32	1848	25-Mar		0.001004	0.0081324	151.0650119	167.9316556
33	1848	16-Apr	A	0.001416	0.0114696	175.4792997	217.5524824
34	1848	11-Jul	A	0.002737	0.0221697	253.7590913	376.6522693
35	1848	23-Oct	A	0.002384	0.0193104	232.8410243	334.1373376
36	1848	17-Nov	G	0.005241	0.0424521	402.1410732	678.2312749
37	1849	30-Jan		0.000903	0.0073143	145.0799559	155.7673267
38	**1849**	**13-Sep**		0.000836	0.0067716	141.1096713	147.6979204
39	1849	31-Oct	A	0.000926	0.0075006	146.4428895	158.5374214
40	1849	13-Nov		0.001035	0.0083835	152.9020093	171.6652615
41	1849	29-Nov	A	0.001713	0.0138753	193.0789197	253.3228357
42	**1850**	22-Feb	A	0.001646	0.0133326	189.1086351	245.2534294
43	1850	11-Mar		0.00091	0.007371	145.4947618	156.610399
44	1850	25-Mar		0.001555	0.0125955	183.7161589	234.2934895
45	1850	4-May		0.00067	0.005427	131.2728466	127.705063
46	1850	2-Jul		0.000786	0.0063666	138.1467723	141.6759754
47	1850	1-Oct		0.002151	0.0174231	219.033915	306.0750739
48	1850	17-Dec		0.001588	0.0128628	185.6716722	238.2679732
49	1850	27-Dec		0.000976	0.0079056	149.4057885	164.5593664
50	1851	20-Jan	A	0.002813	0.0227853	258.2626977	385.8056257
51	1851	6-Feb		0.000637	0.0051597	129.3173333	123.7305793
52	1851	19-Feb	A	0.001762	0.0142722	195.9825608	259.2243418
53	1851	24-Aug	A	0.001116	0.0090396	157.7019057	181.4208124
54	1851	3-Sep	A	0.001297	0.0105057	168.4276001	203.2202533
55	1851	29-Sep	G	0.00247	0.020007	237.9372106	344.495083
56	1851	3-Oct	G	0.001298	0.0105138	168.486858	203.3406922
57	1851	28-Oct	A	0.001008	0.0081648	151.3020438	168.4134112

doi:10.20944/preprints202601.0687.v1

58	1851	8-Dec	G	0.001033	0.0083673	152.7834933	171.4243837
59	1851	28-Dec	A	0.001545	0.0125145	183.1235791	233.0891005

Table 2. Geomagnetic storm parameters in Madras and Bombay Observatory during 1852-1855.

Sr No	Year	Storm Date	GW class	MDS Hd	MDS Hd (BU)	MDS ΔH (nT)	Bom ΔH (nT)	Tvm Dst (nT)
1	1852	7-Jan		0.000397	0.003216	115.0954		94.82524
2	1852	20-Jan	A	0.001389	0.011251	173.8793	164.77	214.3006
3	1852	Feb 18,19	G	0.00452	0.036612	359.4161	1575	591.3948
4	1852	7-Mar		0.000678	0.005492	131.7469	108.46	128.6686
5	1852	12-Mar		0.000992	0.008035	150.3539		166.4864
6	1852	26-Mar	A	0.000455	0.003686	118.5324		101.8107
7	1852	21-Apr	A	0.002066	0.016735	213.997	228.92	295.8378
8	1852	2-May		0.001033	0.008367	152.7835		171.4244
9	1852	20-May					110.77	
10	1852	27-May	A	0.00119	0.009639	162.087		190.3333
11	1852	Jun 11,12	A	0.001644	0.013316	188.9901		245.0126
12	1852	Jun,17,18	A	0.001322	0.010708	169.909		206.2312
13	1852	Jul,10		0.000852	0.006901	142.0578		149.6249
14	1852	Aug 10,11		0.000413	0.003345	116.0435		96.75227
15	1852	24-Aug		0.000793	0.006423	138.5616	134.31	142.519
16	1852	9-Sep		0.000546	0.004423	123.9249	112.15	112.7706
17	1852	22-Sep					85.85	
18	1852	29-Sep		0.000555	0.004496	124.4582		113.8546
19	1852	Oct 18,19		0.001017	0.008238	151.8354	116.31	169.4974
20	1852	12-Nov	G	0.001049	0.008497	153.7316	186	173.3514
21	1852	11-Dec					142.62	
22	1852	29-Dec		0.001065	0.008627	154.6797		175.2784
23	**1853**	Jan 9,10		0.000892	0.007225	144.4281		154.4425
24	1853	14-Feb		0.001975	0.015998	208.6045	169.85	284.8778
25	1853	21-Feb		0.001677	0.013584	190.9456		248.987
26	1853	8-Mar		0.001017	0.008238	151.8354		169.4974
27	1853	Apr 5,6		0.001479	0.01198	179.2126		225.1401
28	1853	3-May		0.001487	0.012045	179.6866		226.1036
29	1853	24-May	A	0.00181	0.014661	198.8269	192	265.0054
30	1853	2-Jun		0.001364	0.011048	172.3979		211.2897
31	1853	22-Jun	A	0.000454	0.003677	118.4731		101.6903
32	1853	12-Jul	G	0.001182	0.009574	161.6129		189.3698
33	1853	26-Aug		0.000463	0.00375	119.0064		102.7742
34	1853	2-Sep	A	0.001769	0.014329	196.3974	175.38	260.0674
35	1853	27-Sep					170.77	

Table 2 **Madras** 1852-55 Contd..

Sr No	Year	Storm Date	GW class	MDS Hd	MDS Hd (BU)	MDS ΔH (nT)	Bom ΔH (nT)	Tvm Dst (nT)
36	1853	15-Oct		0.000711	0.005759	133.7024		132.6431
37	1853	31-Oct		0.001652	0.013381	189.4642		245.9761
38	1853	9-Nov	A	0.001338	0.010838	170.8572		208.1582
39	1853	6-Dec	A	0.002437	0.01974	235.9817	248.31	340.5206
40	1853	21-Dec	A	0.000669	0.005415	131.1875		127.5316
41	**1854**	Jan 2,3		0.001794	0.014531	197.8788	146.31	263.0784
42	1854	Jan 8,9		0.000282	0.002284	108.2808		80.97477
43	1854	20-Jan		0.000438	0.003548	117.525		99.76324
44	1854	29-Jan		-8.6E-05	-0.0007	86.47381		36.65325
45	1854	11-Feb		0.001388	0.011243	173.8201		214.1802
46	1854	16-Feb	A	0.001057	0.008562	154.2057		174.3149
47	1854	Feb 24,25	G	0.001065	0.008627	154.6797		175.2784
48	1854	Mar 15,16	G	0.000967	0.007833	148.8725		163.4754
49	1854	28-Mar	A	0.001389	0.011251	173.8793	174.46	214.3006
50	1854	11-Apr	A	0.002016	0.01633	211.0341	222.92	289.8158
51	1854	24-Apr		0.000884	0.00716	143.9541	144.92	153.479
52	1854	9-May		0.000827	0.006699	140.5763		146.614
53	1854	16-May		0.000538	0.004358	123.4508	143.08	111.8071
54	1854	Jun 12,13		0.000892	0.007225	144.4281		154.4425
55	1854	10-Jul		0.001166	0.009445	160.6648		187.4428
56	1854	24-Jul		0.000703	0.005694	133.2284		131.6795
57	1854	4-Aug		0.000859	0.006958	142.4726		150.468
58	1854	20-Aug		0.000752	0.006091	136.132		137.5811
59	1854	Sep 11,12	A	0.001313	0.010635	169.3757	123.23	205.1473
60	1854	26-Sep		0.00057	0.004617	125.347		115.6612
61	1854	8-Oct	A	0.00124	0.010044	165.0499	172.62	196.3552
62	1854	Oct 25,27		0.000893	0.007233	144.4874		154.5629
63	1854	8-Nov		0.000636	0.005152	129.2581	109.85	123.6101
64	1854	2-Dec						47.011
65	1855	12-Jan		0.000248	0.002009	106.266		76.8799
66	1855	24-Jan		0.000356	0.002884	112.6658		89.88726
67	1855	9-Feb		0.000752	0.006091	136.132	256.62	137.5811
68	1855	13-Mar	A	0.00152	0.012312	181.6421	141.23	230.0781
69	1855	18-Mar						

Table 2 **Madras** 1852-55 Contd..

Sr No	Year	Storm Date	GW class	MDS Hd	MDS Hd (BU)	MDS ΔH (nT)	Bom ΔH (nT)	Tvm Dst (nT)
70	1855	5-Apr		0.001405	0.011381	174.8275	141.69	216.2277
71	1855	12-Apr						

72	1855	8-May		0.000454	0.003677	118.4731		101.6903
73	1855	28-May		0.000198	0.001604	103.3031	123.23	70.8579
74	1855	7-Jun						
75	1855	22,23 Jun		0.000265	0.002146	107.2734		78.92731
76	1855	20-Jul		0.000678	0.005492	131.7469	162.41	128.6686
77	1855	4-Sep						
78	1855	12-Sep		0.000346	0.002803	112.0733		88.68286
79	1855	28-Sep		0.000594	0.004811	126.7692	107.08	118.5517
80	1855	4-Oct		0.001289	0.010441	167.9535	140.31	202.2567
81	1855	20-Oct		0.001214	0.009833	163.5092		193.2238
82	1855	6-Nov		0.000347	0.002811	112.1325		88.8033
83	1855	7-Dec		0.000166	0.001345	101.4068		67.00386
84	1855	18-Dec		0.000158	0.00128	100.9328		66.04035
85	1855	30-Dec		0.000142	0.00115	99.98463	150	64.11332

3.3. Singapore Magnetic Observations and Storm Intensity Calculations

Singapore magnetic observatory was established during December 1840 whose coordinates are reported to be 1^{0} 18’32” (Eliot, 1851). Geomagnetic observations carried out in this observatory during 1841-1845 was published (Eliot, 1850) by Capt Eliot (the first Director of the observatory and belonging to the Madras Engineers). The magnetic observations and instruments in Singapore is a replica of the Madras Observatory during the above period. The geographic coordinates of Singapore is

The magnetic dip of Singapore during 1841-1844 is found very between 12^{0} 43.3’ S and
12^{0} 39.3’ S (Eliot, 1851).

The mean absolute horizontal intensity of H in Singapore during 1845 is 8.095 BU (Eliot, 1850). This value is almost similar to that of Madras during 1851-1855.

Similar to Madras observations (as described in 3.2) we have determined ΔH (BU) of Singapore during the geomagnetic storm periods in 1841-1845 (identified from Greenwitch data) using published daily mean values of H in relative intensity units similar to Madras.

Based on the following assumptions (i) the decrease of daily mean H in Singapore during magnetic storm periods (Sing Hd in BU) is almost identical to that of Madras and (ii) the regression relation (5) of Madras magnetic observations with Bombay H observations is also valid for Singapore . Hence we have estimated the Sing ΔH in modern units for Singapore storms for the years 1841-1845. The results are given in Table 3.

Table 3. Observed and derived geomagnetic storm parameters in Singapore 1841-1845.

Year	**Storm Date**	**GW Class**	**Sing Hd**	**Sing Hd (BU)**	**Sing ΔH (nT)**	**Tvm Dst**
1841	24-Sep	G	0.003000	0.0242757	269.16617	407.96638
1841	Oct-25		0.001690	0.0137052	191.83450	250.79362
1841	Nov-18	G	0.001828	0.0148068	199.89359	267.17331
1841	Dec-03		0.001148	0.0092988	159.59816	185.27486
1841	Dec-14		0.000467	0.0037827	119.24348	103.25597
1842	Jan-01		0.001653	0.0133893	189.52344	246.09650
1842	Feb-24		0.001137	0.0092097	158.94632	183.95003
1842	Jul-02	G	0.001422	0.0115182	175.83485	218.27512

1842	Nov-10		0.001401	0.0113481	174.59043	215.74590
1842	Nov-21		0.001133	0.0091773	158.70929	183.46827
1842	Dec-09		0.000952	0.0077112	147.98360	161.66883
1843	Jan-02		0.000156	0.0012636	100.81424	65.79947
1843	Feb-06		0.000623	0.0050463	128.48772	122.04443
1843	May-06		0.001868	0.0151308	202.26391	271.99087
1844	Oct-01		0.000390	0.0031590	114.68061	93.98217
1844	Oct-21		0.000701	0.0056781	133.10984	131.43867
1844	Nov-22		0.000720	0.0058320	134.23575	133.72701
1845	Jan-09		0.001170	0.0094770	160.90184	187.92451
1845	Feb-19		0.000331	0.0026811	111.18439	86.87628
1845	Mar-21		0.000937	0.0075897	147.09473	159.86225
1845	Aug-28		0.007126	0.0577206	513.84237	905.25860
1845	Dec-03		0.000700	0.0056700	133.05059	131.31823

3.4. Trivandrum Magnetic Observations and Geomagnetic Storm Investigations

Earliest magnetic observations in Trivandrum were carried out as a part of magnetic survey of South India during 1837-38 (Taylor and Caldecott, 1839). Regular magnetic observations was started in the Maharaja's Observatory in Trivandrum with the help of TG Taylor from August 1841 onwards (Sabine, 1842).

The geographic coordinates of Trivandrum measured during 1837 is 8^0 30'35" N latitude and 76^0 59' E longitude (Taylor and Caldecott, 1839). The magnetic dip in Trivandrum during 1837 is found to be 3^0 15'24'' S which changed to 2^0 30' S during 1860 (Eapen, 2009). Broun (1861) estimated the absolute H of Trivandrum during 1844-1845 as 7.8 BU or 36000 nT. Chapman and Gupta (1971) inferred that absolute H of Trivandrum varied between 36134 and 36734 nT during 1854-1869.

3.4.1. Estimation of Storm Time Change in Daily Mean H of Trivandrum During the Years 1855-1877.

The description of the Trivandrum magnetic observatory , instruments used and observations made during 1841-1879 is given in Appendix. Daily mean values (mean H) of the measurements of horizontal intensity of the geomagnetic field in Trivandrum observatory for years 1855-1877 is procured from the personnel archives of John Allan Broun in manuscript form preserved in the National Library of Scotland (NLS 2007a;NLS, 2007b). For selected geomagnetic storm periods our aim is to first tabulate the storm time change in mean H of Trivandrum (H diff) during the above years. Tvm daily mean H data is from (a) Adies Bifilar 1 observations during the years 1855-1868 (b) Adies Bifilar 1 and Adies Bifilar 2 observations during 1869-1872 (c) Adies Bifilar 2 observations during 1873-1877. All these data is temperature corrected (Broun, 1862).

We have determined the storm time in change daily mean H (Hd in scale divisions) observed in Trivandrum observatory i) making used of ABF1 observations for the years 1855-1869 and ii) ABF 1 and ABF 2 observations for the years 1869-1872. In Table 4 we have given Hd values determined from both ABF 1 (Hd1) and ABF 2 (Hd2) observations in Trivandrum for 10 selected intense geomagnetic storms during the years 1869-1972. The ratio of the two Hd values is also shown in this Table . Let the mean value of the ratio be k then:

Hd1 = k Hd2 = 0.6 X Hd2 (6)

So we can normalise Hd2 values by multiplying with k.

Table 4. Storm time change of daily mean H in Trivandrum observatory deduced from Adies BF 1 and Adies BF 2 measurements during selected geomagnetic storms in the years 1869-1872.

Date of the magnetic storm	**ABF 1 Mean H (Sc Div)**	**ABF 2 Mean H (Sc Div)**	**Ratio of the values (ABF 1)/(ABF 2)**
1869 April 15-16	86.64	128.8	0.673
1869 May 13-14	94.772	148.56	0.67
1870 Aug 20-21	37	76.44	0.484
1870 Sep 24-26	82.63	143.78	0.575
1870 Oct 24-25	77.58	148.95	0.521
1871 Feb 10-11	84.37	100.288	0.84
1872 Feb 4	94.376	180	0.524
1872 Aug 15	98	170.1	0.576
1872 Oct 15	99.8	160.164	0.623
1872 Oct 17-18	93.86	161.26	0.582
Mean Ratio			**0.6**

The estimated storm time decrease in daily mean H in Trivandrum (Hd) for the Carrington storm during September 2, 1859 is 133.53 Sc div and Hd for August 29th, 1859 storm is found to be 144.24.

We have tabulated the values of Hd (storm change in daily mean H in Sc div) of Trivandrum in Table 5 which is derived from a) AFM 1 observations during the years 1855-1872 and b) AFM 2 observations during 1873-1877 after normalisation as per details given in first para.

Table 5. Geomagnetic storm parameters in Trivandrum and Bombay during 1855-1877.

Sr No	Year	Storm Date	GW Class	Tvm Hd (Sc div)	Tvm ΔH (nT)	Bom ΔH (nT)	Tvm Dst (nT)
1	1855	12-Jan		2.21994	135.3186		15.78069
2	1855	24-Jan		9.939932	176.9054		70.65914
3	1855	9-Feb		17.25	216.284		122.6236
4	1855	13-Mar	A	34.13	307.2149		242.617
6	1855	5-Apr		30.17	285.8828		214.4669
8	1855	8-May		11.72	186.4945		83.31296
9	1855	28-May		22.75	245.912		161.721
10	1855	7-Jun		2.73	138.0662		19.40652
11	1855	22,23 Jun		8.92	171.4111		63.40884
12	1855	20-Jul		32.89	300.5351		233.8023
13	1855	12-Sep		8.87	171.1418		63.05341
14	1855	28-Sep		7.5	163.7618		53.31461
15	1855	4-Oct		24.67	256.2548		175.3695
16	1855	20-Oct		28.81	278.5566		204.7992
17	1855	6-Nov		13.9	198.2379		98.80974
18	1855	18-Dec		6.53	158.5365		46.41925
19	1855	30-Dec		13.93	198.3995		99.023
20	**1856**	13,14 Jan		7.43	163.3847	156.46	52.817
21	1856	18-Jan		7.44	163.4385	118.62	52.88809
22	1856	6,7 Feb		6.12	156.3278		43.50472
23	1856	21-Feb		6.41	157.89		45.56622
24	1856	27-Mar		21.19	237.5084	132.92	150.6315
25	1856	22,23 Apr		20.4	233.2528		145.0157
26	1856	15-May		18.39	222.4251		130.7274
27	1856	11-Jun		16	209.5504	84.46	113.7378
28	1856	18-Jul		5.69	154.0115		40.44801
29	1856	23,24 Aug		29.05	279.8494	135.23	206.5052
30	1856	8,9 Sep		10.34	179.0605	169.85	73.50307
31	1856	27-Sep		7.3	162.6844		51.89288
32	1856	23-Oct		12.88	192.7433	166.62	91.55895
33	1856	6,7 Nov		11.19	183.6394	103.38	79.54539
34	1856	3,4 Dec		13.46	195.8677		95.68195
35	1856	29-Dec		24.65	256.1471		175.2273

Table 5 Contd..

Sr No	Year	Storm Date	GW Class	Tvm Hd (Sc div)	Tvm ΔH (nT)	Bom ΔH (nT)	Tvm Dst (nT)
36	**1857**	17,18 Jan		20.68	234.7611		147.0061
37	1857	26-Jan		10.99	182.562		78.12367
38	1857	12,13 Apr		20.15	231.906		143.2386
39	1857	8,9 May	G	47.41	378.7529	264.92	337.0194
40	1857	7-Jun		5.43	152.6109		38.59978
41	1857	23,24 Jun		5.45	152.7186		38.74195
42	1857	9-Jul		13.04	193.6052		92.69633
43	1857	28-Jul		17.4	217.0921		123.6899
44	1857	13-Aug		4.18	145.8772		29.71401
45	1857	3,4 Sep	A	37.37	324.6685	282	265.6489
46	1857	21-Sep				259.38	0
47	1857	12-Nov		22.63	245.2655		160.8679
48	1857	16-Nov		31.28	291.8622		222.3575
49	1857	16,17 Dec	G	75.24	528.6704		534.8521
50	**1858**	8-Jan	A	35.7	315.6723	266.77	253.7775
51	1858	16,17 Feb	A	25.32	259.7563	191.08	179.9901
52	1858	3-Mar		30.99	290.3		220.296
53	1858	13,14 Mar	A	34.14	307.2688		242.6881
54	1858	29-Mar		34.63	309.9083	252.46	246.1713
55	1858	9,10 Apr	G	47.02	376.652	601.38	334.247
56	1858	9-May		37.76	326.7693		268.4213
57	1858	25-May		37.51	325.4226	200.77	266.6441
58	1858	24,25 Jun	A	14.06	199.0998	213.69	99.94712
59	1858	5,6, Jul		14.76	202.8706		104.9231
60	1858	10-Aug		8.73	170.3876		62.0582
61	1858	25-Aug		11.98	187.8951	114.92	85.1612
62	1858	20-22 Sep		36.24	318.5813		257.6162
63	1858	19-Oct				159.69	0
64	1858	27-Oct	A	48.51	384.6785	218.31	344.8389
65	1858	1-2, Nov		28.03	274.3548		199.2545

Table 5 Contd..

Sr No	Year	Storm Date	GW Class	Tvm Hd (Sc div)	Tvm ΔH (nT)	Bom ΔH (nT)	Tvm Dst (nT)
66	1858	19-Nov		29.1	280.1188	233.08	206.8607
67	1858	5-6 Dec	A	34.57	309.5851	212.77	245.7448
68	1858	24-Dec		22.01	241.9257		156.4606
69	**1859**	11-Jan		24.84	257.1706	243.69	176.578
70	1859	16-Jan		20.5	233.7915		145.7266
71	1859	9,10 Feb	A	37.15	323.4833		264.085
72	1859	24-Feb		51.08	398.5229	303.23	363.108
73	1859	27-Feb				418.62	0

doi:10.20944/preprints202601.0687.v1

74	1859	4-Mar		11.43	184.9323		81.25146
75	1859	17-Mar		15.67	207.7727		111.392
76	1859	26-Mar		20.09	231.5828		142.8121
77	1859	22-Apr	A	70.88	505.1835	478.15	503.8586
78	1859	29-Apr	A	52.6	406.7109	330.92	373.9131
79	1859	3-May		9.46	174.3201		67.24749
80	1859	19-May		30.39	287.0679	319.38	216.0308
81	1859	8-Jun	A	43.66	358.5521	294	310.3621
82	1859	11-Jul	A	43.24	356.2896	309.23	307.3765
83	1859	18-Jul		38.86	332.6949	286.15	276.2407
84	1859	16-Aug		23.2	248.3361		164.9199
85	1859	29-Aug	G	144.24	900.3665	681.23	1025.347
86	1859	2-Sep	G	133.53	842.6728	1729.38	949.2133
87	1859	3-Oct		35.95	317.0191	296.31	255.5547
88	1859	11,12 Oct	G	116.85	752.8193	967.85	830.6416
89	1859	17,18 Oct	A	57.11	431.0059	325.38	405.973
90	1859	13-Nov		30.69	288.684	169.38	218.1634
91	1859	13-Dec	A	61.9	456.8091	492	440.0232
92	1860	12-Jan		18.54	223.2331		131.7937
93	1860	10-Feb		18.15	221.1322		129.0213
94	1860	21-22,Feb	A	41.94	349.2866	227.54	298.1353
95	1860	9-Mar				288	0

Table 5 Contd..

Sr No	Year	Storm Date	GW Class	Tvm Hd (Sc div)	Tvm ΔH (nT)	Bom ΔH (nT)	Tvm Dst (nT)
96	1860	12,13 Mar				294.92	0
97	1860	28-Mar	A	84.89	580.6539	539.54	603.4503
98	1860	9-10 Apr	A	29.4	281.7349	285.67	208.9933
99	1860	13-14 Apr	A	23.45	249.6828		166.697
100	1860	6-May		12.8	192.3123		90.99026
101	1860	12-May		13.92	198.3456		98.95191
102	1860	25-May		12.69	191.7198		90.20831
103	1860	10-Jun		29.98	284.8593		213.1163
104	1860	29-30 Jun	A	21.3	238.101		151.4135
105	1860	4,5 Jul	A	40.18	339.8056	219.69	285.6241
106	1860	11-Jul		15.12	204.8099		107.4822
107	1860	6-7 Aug	A	35.03	312.0631	365.54	249.0148
108	1860	14-Aug	G	74.75	526.0308		531.3689
109	1860	6,7 Sep	G	65.62	476.8484	344.77	466.4673
110	1860	3-4 Oct		26.04	263.6349		185.1083
111	1860	30-Oct		22.89	246.6661		162.7162
112	1860	4-5 Nov		13.3	195.0058		94.54457
113	1860	25-Nov		9.53	174.6972		67.74509

114	1860	10-11 Dec		42.42	351.8723	274.57	301.5474
115	1860	16-Dec		20.36	233.0373		144.7314
116	1861	25-Jan	A	53.04	409.0812	230.77	377.0409
117	1861	27-Feb	A			294	0
118	1861	9-10 Mar		27.85	273.3852		197.9749
119	1861	26-Mar		23.42	249.5212		166.4837
120	1861	15-Apr		24.79	256.9013	248.39	176.2225
121	1861	17-May		17.74	218.9236		126.1068
122	1861	13,14 Jun		19.74	229.6974		140.324
123	1861	11-Jul		16.92	214.5063		120.2778
124	1861	26-Jul		17.53	217.7924		124.614
125	1861	18-19 Aug		26.48	266.0051	188.38	188.2361

Table 5 Contd..

Sr No	Year	Storm Date	GW Class	Tvm Hd (Sc div)	Tvm ΔH (nT)	Bom ΔH (nT)	Tvm Dst (nT)
126	1861	15-Sep		34.33	308.2923		244.0387
127	1861	10,11 Oct	A	33.86	305.7604	357.23	240.6977
128	1861	25-Oct		41	344.2229	259.85	291.4532
129	1861	8-Nov		35.99	317.2345		255.839
130	1861	10-Dec		27.56	271.823		195.9134
131	1861	19-Dec	A	38.85	332.6411	328.15	276.1697
132	1862	15-Jan	A	23.2	248.3361		164.9199
133	1862	23-Jan		12.71	191.8275		90.35049
134	1862	8-Feb		19.32	227.4349		137.3384
135	1862	21-Feb	A	20.73	235.0304		147.3616
136	1862	6,7 Mar		34.47	309.0464	311.08	245.0339
137	1862	2,3 Apr		28.05	274.4625		199.3966
138	1862	11-Apr		43.79	359.2524		311.2862
139	1862	20-May		17.16	215.7992		121.9838
140	1862	7-8 Jul	A	20.9	235.9462		148.57
141	1862	4-Aug	G	61.65	455.4624	389.08	438.2461
142	1862	27-Aug				146.31	0
143	1862	10-Sep		17.64	218.3849	344.31	125.396
144	1862	24,25 Sep	A	24.3	254.2617		172.7393
145	1862	3,4 Oct	G	61.27	453.4154	327.23	435.5448
146	1862	10-Oct				198.46	0
147	1862	22-Oct	A	26.73	267.3518	333.69	190.0133
148	1862	4-5 Nov		21.93	241.4947		155.8919
149	1862	18-Nov	A	8.36	168.3945		59.42801
150	1862	27-Nov		9.81	176.2055		69.73551
151	1862	15-Dec	A	62.81	461.7112	251.54	446.4921
152	1862	25-Dec		36.75	321.3286		261.2416

153	1863	24-Jan	A	27.01	268.8602		192.0037
154	1863	31-Jan		18.45	222.7483		131.1539
155	1863	25-Feb	A	31.32	292.0777		222.6418
156	1863	21-22 Mar		7.3	162.6844		51.89288
157	1863	8-Apr			123.36		0
158	1863	9,11 Apr		21.86	241.1176		155.3943
159	1863	15,17 Apr		19.91	230.6132		141.5325
160	1863	11,12 Jun		23.46	249.7367		166.7681

Table 5 Contd..

Sr No	Year	Storm Date	GW Class	Tvm Hd (Sc div)	Tvm ΔH (nT)	Bom ΔH (nT)	Tvm Dst (nT)
161	1863	10-Jul		15.16	205.0254		107.7666
162	1863	15,16 Jul		32.7	299.5116	218.77	232.4517
163	1863	14,15 Aug		14.85	203.3555	206.77	105.5629
164	1863	11-Sep		25.72	261.9111		182.8336
165	1863	8,9 Oct	A	29.11	280.1727	357.23	206.9318
166	1863	5,6 Nov		18.08	220.7552		128.5237
167	1863	15-Nov		12.76	192.0968		90.70592
168	1863	27-Nov		14.12	199.423		100.3736
169	**1864**	12-Jan		13.33	195.1674		94.75783
170	1864	15,16 Jan		11.34	184.4474		80.61169
171	1864	27-Jan		3.81	143.8841		27.08382
172	1864	10,11 Feb		21.12	237.1313		150.1339
173	1864	6-Mar		17.15	215.7453		121.9127
174	1864	10,11 Mar	A	18.32	222.048		130.2298
175	1864	27-Apr		15.97	209.3888		113.5246
176	1864	5,6 May		20.66	234.6534		146.864
177	1864	25-May		9.19	172.8656		65.32816
178	1864	7,8 Jun	A	41.2	345.3003		292.8749
179	1864	23-Jun	A	26.33	265.1971		187.1698
180	1864	20-Jul	A	39.07	333.8262		277.7336
181	1864	14-Aug		19.18	226.6807		136.3432
182	1864	17,18 Sep		14.99	204.1096		106.5581
183	1864	21-Sep	A	21.97	241.7102		156.1763
184	1864	13,14 Oct	A	25.92	262.9884		184.2553
185	1864	11-Nov		20.75	235.1382		147.5037
186	1864	15-Nov		15.06	204.4867		107.0557
187	1864	12-Dec		10.2	178.3064		72.50787
188	1864	15-Dec		7.82	165.4856		55.58936
189	1864	23,24 Dec		10.38	179.276		73.78742
190	1865	15,16 Mar		22.39	243.9727		159.1619
191	1865	20-Mar		28.69	277.9102		203.9461
192	1865	14-May		23.61	250.5447		167.8344

193	1865	10,11 Jun	A	25.59	261.2108		181.9094
194	1865	8-Jul		**34.68**	310.1777		246.5267
195	1865	14-Jul		19.89	230.5054		141.3903

Table 5 Contd..

Sr No	Year	Storm Date	GW Class	Tvm Hd (Sc div)	Tvm ΔH (nT)	Bom ΔH (nT)	Tvm Dst (nT)
196	1865	2,3 Aug	G	**69.93**	500.0659		497.1054
197	1865	8,9 Sep		15.4	206.3183		109.4727
198	1865	6,7 Oct	A	26.5	266.1129		188.3783
199	1865	13-Oct		**31.63**	293.7476		224.8455
200	1865	19-Oct	A	23.87	251.9453		169.6826
201	1865	26-Oct		29.92	284.536		212.6897
202	1865	31-Oct	A	24.91	257.5477		177.0756
203	1865	1-Nov		47.4	378.6991		336.9483
204	1866	7-Feb	A	27.69	272.5233		196.8375
205	1866	20,21 Feb	G	79.75	552.9653		566.912
206	1866	25-Feb	A	43.17	355.9125		306.8789
207	1866	7,8 Mar		27.01	268.8602		192.0037
208	1866	19,20 Mar		28.38	276.2402		201.7425
209	1866	5-Apr		16.77	213.6983		119.2115
210	1866	14,15 May		25.06	258.3557		178.1419
211	1866	13,14 Jul		24.72	256.5242		175.7249
212	1866	23,24 Aug		35.9	316.7497		255.1993
213	1866	4,5 Oct	A	9.08	172.2731		64.54622
214	1866	11,12 Oct		14.72	202.6552		104.6388
215	1866	28-Nov		25.03	258.1941		177.9286
216	**1867**	13-Jan		19.31	227.381		137.2673
217	1867	8,9 Feb		31.85	294.9328		226.4094
218	1867	13-Feb		24.08	253.0766		171.1754
219	1867	7-Mar	A	21.64	239.9325		153.8304
220	1867	11-Mar		19.04	225.9266		135.348
221	1867	7,8 Apr		26.72	267.298		189.9422
222	1867	28-May		35.77	316.0494		254.2751
223	1867	1,2 Jun		24.07	253.0227		171.1043
224	1867	21,22 Jul		15.95	209.2811		113.3824
225	1867	18,19 Sep		13.59	196.568		96.60607
226	1867	25,26 Sep		31.69	294.0709		225.272
227	1867	2-Oct		50.34	394.5365		357.8476

Table 5 Contd..

Sr No	Year	Storm Date	GW Clas (aap)	Tvm Hd (Sc div)	Tvm ΔH (nT)	Bom ΔH (nT)	Tvm Dst (nT)
228	1867	26-Nov		16.56	212.5671		117.7187

229	**1868**	24-Jan		10.96	182.4004		77.91041
230	1868	6,7 feb		27.04	269.0218		192.2169
231	1868	20-Feb		19.73	229.6435		140.253
232	1868	20-Mar		30.21	286.0982		214.7512
233	1868	23,24 Mar		37.52	325.4765		266.7152
234	1868	2-Apr		37.3	324.2914		265.1513
235	1868	19,20 Apr		34.58	309.639		245.8159
236	1868	27-Apr		42.92	354.5657		305.1017
237	1868	20-May		29.86	284.2128		212.2632
238	1868	24-May		17.89	219.7316		127.1731
239	1868	8-Jun		35.78	316.1033		254.3462
240	1868	10,11 Jul	A(74)	41.79	348.4786		297.069
241	1868	15-Jul		40.33	340.6137		286.6904
242	1868	30-Aug	A(179)	46.82	375.5747		332.8253
243	1868	15,16 Sep		48.56	384.9479		345.1943
244	1868	27-Sep		17.92	219.8932		127.3864
245	1868	1-Oct	160	59.74	445.1734		424.6686
246	1868	18-Oct		27.2	269.8837		193.3543
247	1868	22,23 Oct	A(126)	48.49	384.5708		344.6967
248	1868	19-Nov		22.84	246.3968		162.3607
249	1868	13-Dec	95	42.01	349.6637		298.6329
250	**1869**	21-Jan		53.24	410.1586		378.4626
251	1869	3,4 Feb	A(126)	81.27	561.1534		577.7171
252	1869	10,11 Mar	A(126)	32.87	300.4274		233.6601
253	1869	18-Mar		29.72	283.4587		211.268
254	1869	15,16 Apr	G(286)	97.68	649.5524		694.3694
255	1869	13,14 May	G(531)	94.78	633.9304		673.7545
256	1869	7-Jun	A	31.29	291.9161		222.4285
257	1869	5-Sep		43.03	355.1583		305.8837
258	1869	14,15 Sep	A(179)	38.54	330.9711		273.634
259	1869	27,28 Sep	A	35.35	313.7869		251.2895
260	1869	6-Oct		22.56	244.8885		160.3703

Table 5 Contd..

Sr No	Year	Storm Date	GW Clas (aap)	Tvm Hd (Sc div)	Tvm ΔH (nT)	Bom ΔH (nT)	Tvm Dst (nT)
261	1869	25-Oct		15.99	209.4965		113.6667
262	1869	9,10 Nov		19.39	227.812		137.836
263	1869	6,7 Dec		40.11	339.4286		285.1265
264	1869	15,16 Dec		30.76	289.061		218.661
265	1870	3-4 Jan		72.05	511.4861		512.1757
266	1870	1-2, Feb	G(179)	25.97	263.2578		184.6107

267	1870	12-Feb		62.7	461.1186		445.7101
268	1870	5-6 April	A(211)	38.95	333.1798		276.8805
269	1870	21-May		116.086	748.7037		825.2106
270	1870	20-21 Aug	A(262)	72	511.2168		511.8202
271	1870	24-26 Sep	334	82.63	568.4795		587.3848
272	1870	24-25 Oct	464	77.58	541.2757		551.4863
273	1870	17-Dec	158	56.48	427.6121		401.4945
274	1871	10-11 Feb	G(334)	84.37	577.8528		599.7538
275	1871	9-10 Apr	G(337)	63.64	466.1823		452.3922
276	1871	24-25 Aug	G(262)	47.8	380.8538		339.7918
277	1871	3-Nov	G(211)	39.8	337.7586		282.9228
278	1871	9-11 Nov		76.7	536.5352		545.2307
279	1872	6-Jan				107	0
280	1872	4-Feb	G(658)	94.376	631.7541	1023	670.8826
281	1872	20-Feb				192	0
282	1872	2-Mar				195	0
283	1872	10-Apr	A(158)			238	0
284	1872	15-Apr	A			195	0
285	1872	4-Jun	A(209)	40.66	342.3914	169	289.0363
286	1872	9-Jun	G			120	0
287	1872	7-Jul		74.328		221	528.3691
288	1872	19-Jul			123.36	156	0
289	1872	3-Aug	G(211)			253	0
290	1872	9-Aug	A	62.99	462.6808	183	447.7716

Table 5 Contd..

Sr No	Year	Storm Date	GW Clas (aap)	Tvm Hd (Sc div)	Tvm ΔH (nT)	Bom ΔH (nT)	Tvm Dst (nT)
291	1872	15-Aug	A(179)	98	651.2762	198	696.6442
292	1872	25-Aug				184	0
293	1872	2-Sep				222	0
294	1872	29-Sep				114	0
295	1872	15-Oct	456	99.8	660.9726	430	709.4397
296	1872	17-18 Oct	262	93.86	628.9744	265	667.2145
297	1872	24-Nov				156	0
298	1873	8-Jan	A	61.54	454.8698		437.4641
299	1873	19-Jan				205	0
300	1873	10-Feb	A(126)	19.22	226.8962		136.6276
301	1873	10-Mar	A(262)	60.69	450.291	288	431.4218
302	1873	24-Mar		20.71	234.9227		147.2194
303	1873	1-3 Apr	107	39.03	333.6107	143	277.4492

304	1873	Apr-19	A(126)	50.031	392.872		355.6511
305	1873	Jun-01		21.57	239.5554		153.3328
306	1873	Jun-19		26.63	266.8131		189.3024
307	1873	Jun-27	A(158)	38.7	331.833		275.1034
308	1873	Jul-10		11.37	184.6091		80.82494
309	1873	Aug-06		22.35	243.7572		158.8775
310	1873	Nov-27		17.84	219.4623		126.8177
311	1873	Dec-15		26.72	267.298		189.9422
312	1874	Jan-28		43.63	358.3904		310.1488
313	1874	4-5 Feb	G(286)	53.6	412.0978	294	381.0217
314	1874	Mar 7-9	A(92)	48.31	383.6011	144	343.4172
315	1874	2-Apr	A(105)	44.11	360.9762		313.561
316	1874	8-Apr	A(105)	42.81	353.9732		304.3198
317	1874	13-Apr				147	0
318	1874	29-Apr		30.6	288.1991		217.5236
319	1874	5-May		14.99	204.1096		106.5581
320	1874	3-6 Oct	G(176)	56.4	427.1812	299	400.9258

Table 5 Contd..

Sr No	Year	Storm Date	GW Clas (aap)	Tvm Hd (Sc div)	Tvm ΔH (nT)	Bom ΔH (nT)	Tvm Dst (nT)
321	1875	Feb 26-27	209	31.6	293.586	381	224.6322
322	1875	7-Apr	94	25.89	262.8268	285	184.042
323	1875	15-16 Sep	125	31.9	295.2021	109	226.7648
324	1876	25-Mar	88	24.56	255.6623		174.5876
325	1876	23-Oct	74	19.93	230.7209		141.6747
326	1876	10-11 Dec	74	21.57	239.5554	141	153.3328
327	1877	26-Jan		16.14	210.3046		114.733
328	1877	12-May	125	26.1	263.9581		185.5348
329	1877	28-29 May	A(74)	41.5	346.9164	125	295.0075
330	1877	12-Oct		31.26	291.7545		222.2153

3.4.2. Inferring the Intensity of Geomagnetic Storms During 1855-1877 Based on Trivandrum Hd Data Scaled to Bombay Observations.

We have given the ΔH (nT) values of Bombay during selected magnetic storm periods during 1855-1863 in Table 2 and Table 5. A linear regression fit between ΔH in Bombay with Hd values in Trivandrum given in Table 5 is done for selected geomagnetic storm periods for the 1855-1863 is done. See also Figure 4.

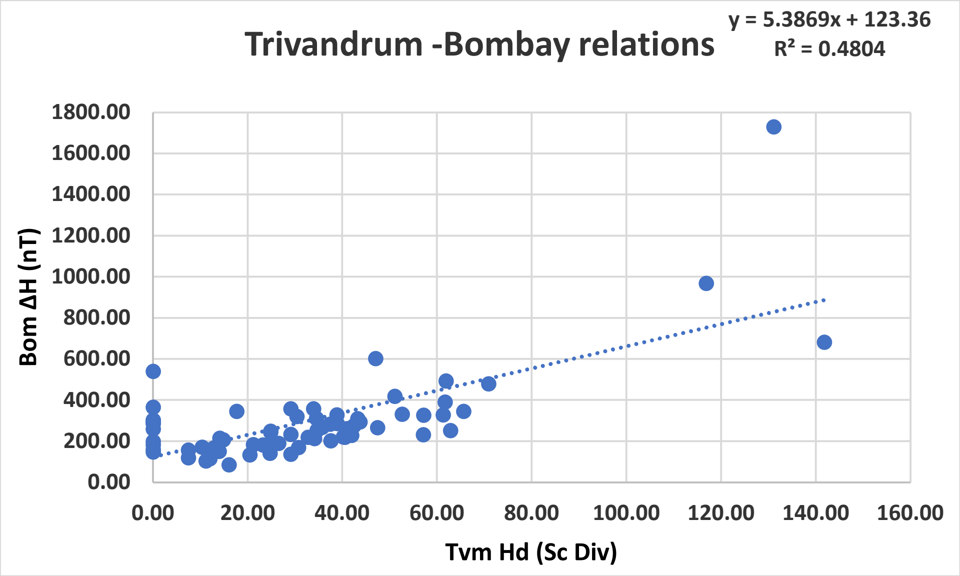


Figure 4. Regression relation between values of storm time change in daily mean H of Trivandrum (Sc div) and Bombay hourly ΔH (nT) for selected geomagnetic storms during 1855-1863.

The regression relation is found to be

Tvm ΔH (nT) = 5.3809 Tvm Hd (Sc div) + 124.48 (R^2 =0.4794 , r=0.69) (7)

Tvm ΔH is the intensity of storms scaled to Bombay observations as derived from above regresion relation using Hd values of Trivandrum for these storms.

Using relation (6) we have estimated the Tvm ΔH values based on Trivandrum Hd values during different storm periods in modern units (nT) for the years 1855-1877. These results are tabulated in Table 5. It is interesting to find that for the out standing geomagnetic storms of August 28-29 and Sep 2 in 1859 and Feb 4-5 in 1872 the estimated storm intensity in Trivandrum scaled to Bombay observations is found to be >800 nT.

3.4.3. Storm Time Changes in Trivandrum Magnetic Declination and the Dst Index

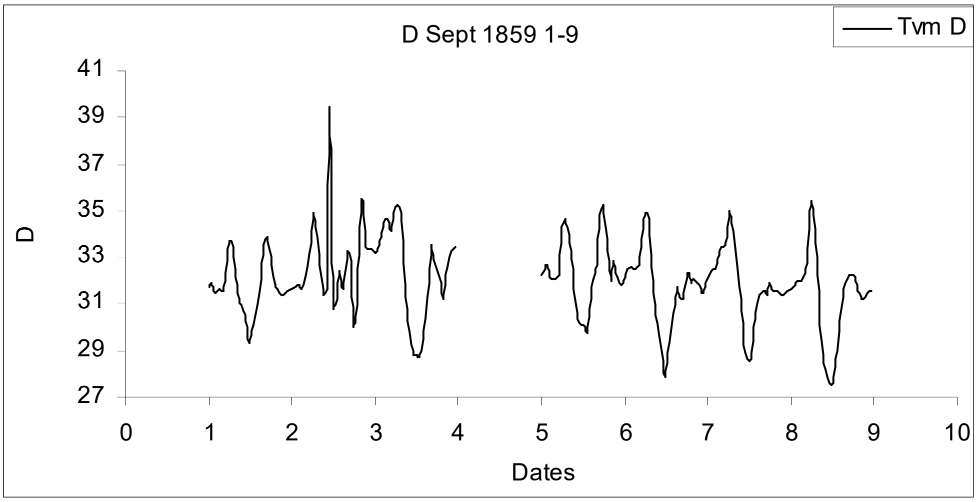
In Figure 5 we have storm time changes in hourly magnetic declination (D) and %D (change in parentage of D from the pre-storm reference value) during the Carrington storm of September 2, 1859 (after Eapen, 2009). For comparison we have also shown storm time changes in hourly Bombay 1/H values for the same storm. Correlation between storm time change in Trivandrum magnetic declination and Bombay 1/H observations is quite remarkable. Similar result is obtained in a recent publication (Jayakrishnan et al., 2025) based on minute values of Trivandrum magnetic declination published by JA Broun for this outstanding storm (Broun, 1874). Maximum daily range of Trivandrum magnetic declination (Rd) and maximum hourly valuields e of % D for selected geomagnetic storm periods during 1852-1869 is given in Table 6 (adopted from Eapen, 2009).

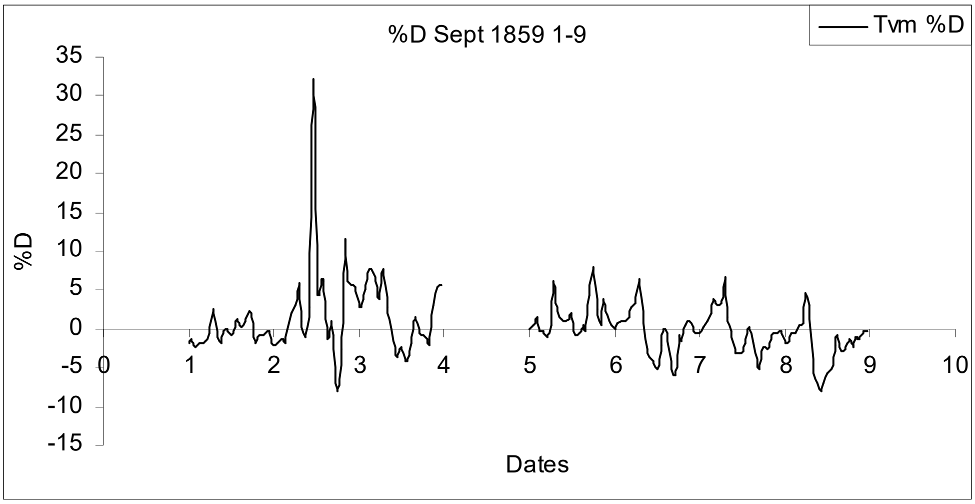
doi:10.20944/preprints202601.0687.v1

Table 6. Maximum storm time change (%D) and daily range (Rd) found for magnetic declination observations at Trivandrum for Greenwich great geomagnetic storm periods during 1852-1869. The maximum values of Greenwich (GW) H , Helsinki (HEL) Ak and daily sunspot number corresponding to these storm dates are also given (adapted from Eapen, 2009).

No	Date of Great Storm	Maximum value of Rd	% D Maximum	Date & Time of %D Max	GW H (nT)	HEL Ak (nT)	R
1	1852 Nov 11-14	5.9	12.98%	1852 Nov 12, 1.30pm	150	65	73
2	1853 Jul 12-13	6.03	13.99%	1853 Jul 13, 7.30 am	275	53	71
3	1854 Mar15-16	2.29	9.96%	1854 Mar 16, 7.30 am	200	33	33
4	1857 May 7-8	5.83	10.69%	1857 May11, 10.30am	>325	82	24
5	1857 Dec16-17	10.65	21.16%	1857 Dec 17 3.30pm	450	139	79
6	1858 Apr 9-11	7.94	18.26%	1858 Apr 10, 2.30am	>475	159	44
7	1859 Aug 28-29	9.83	21.78%	1859 Aug 29, 6.30am	275	55	108
8	1859 Sep 2-5	9.43	32.07%	1859 Sep 2, 8.30pm	>>625	75	154
9	1859 13-Oct	5.53	16.49%	1859 Oct 12, 10.30pm	>500	55	141
10	1860 Aug 8-11	8.42	18.84%	1860 Aug 8, 7.30pm	450	92	154
11	1860 Aug 12-13	8.88	17.08%	1860 Aug 11, 4.30am	600	85	126
12	1860 Sep 6-7	6.62	16.59%	1860 Sep 7, 12.30pm	425	105	102
13	1862 5-Jul	4.45	6.6%	1862 Jul 5, 1.30pm	350	53	55
14	1862 Aug 4-5	4.1	11.05%	1862 Aug 5, 4.30pm	350	105	118
15	1862 Oct 3-6	5.14	9.25%	1862 Oct 6, 5.30pm	425	109	40
16	1865 Aug 2-5	6.47	5.63%	1865 Aug 3, 6.30am	500	123	90
17	1866 Feb 21-22	5.98	5.63%	1866 Feb 21, 4.30 pm	400	108	118
18	1868 30-Sep	4.09	7.91%	1868 Oct 1 4.30pm	200	56	64

19	1869 Feb 3-4	3.87	6%	1869 Feb 4, 11.30am	250	60	127
20	1869 Apr 15-16	16.34	12.33%	1869 Apr 16, 6.30am	400	99	45
21	1869 May 13-14	12.1	11.13%	1869 May 14 6.30am	700	71	163





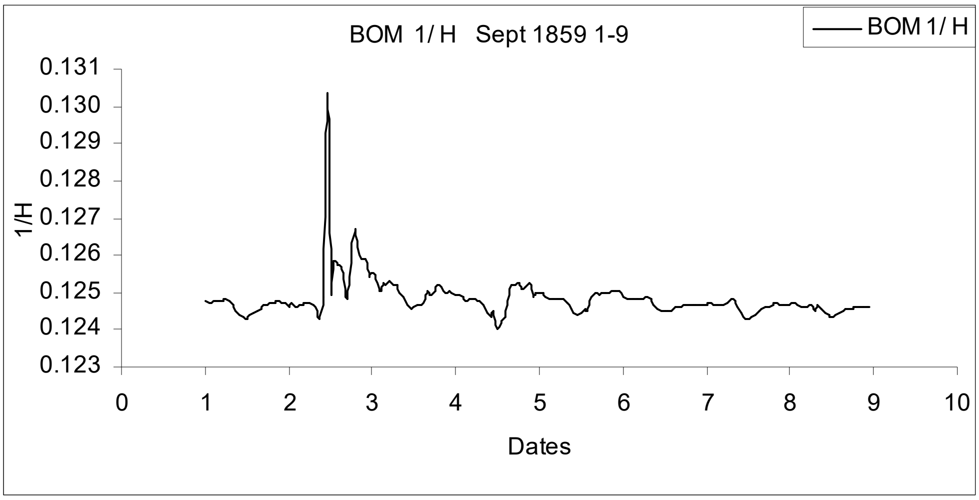
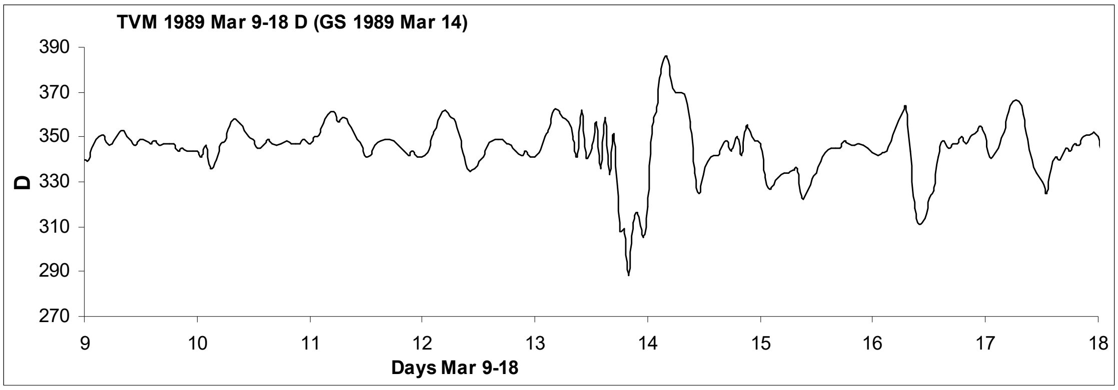


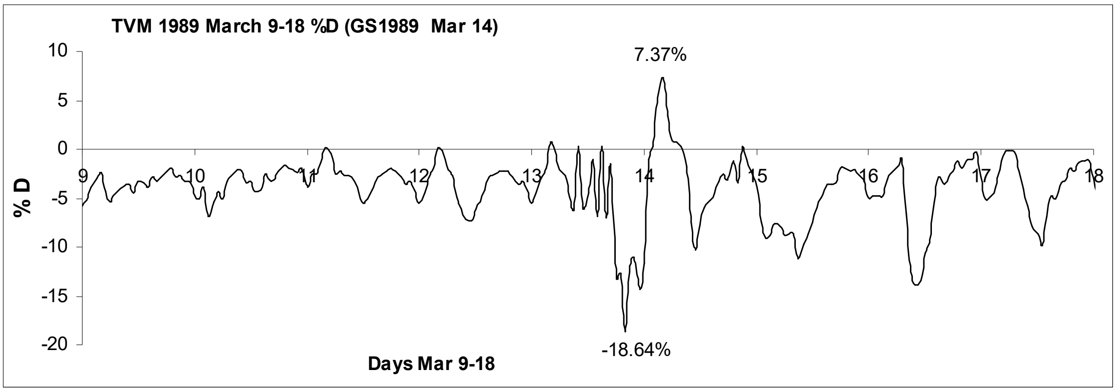
Figure 5. Variations of Trivandrum magnetic declination (D and % D) and Bombay1/H during the Carrington geomagnetic storm of September 2, 1859.

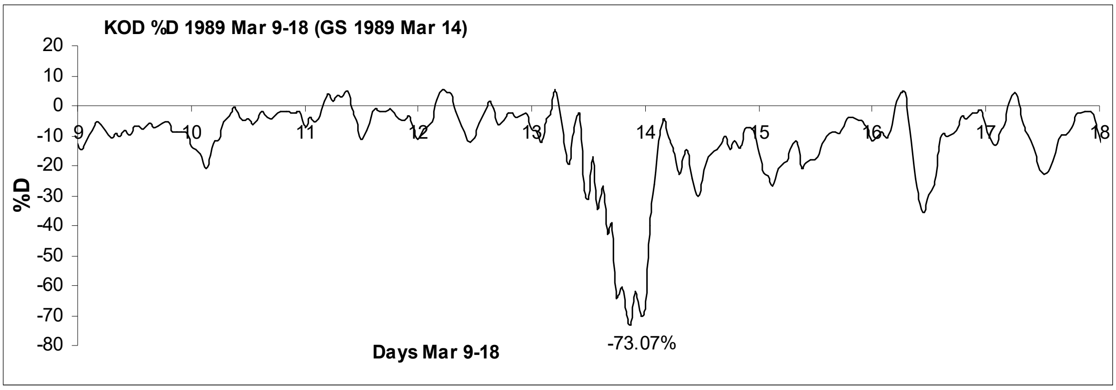
In Figure 6 we have plotted storm time changes in magnetic declination observed at the equatorial stations Trivandrum, Kodaikanal and Annamalai Nagar during the modern outstanding storm of March 14 1989 (Eapen, 2009). Maximum values of %D in Trivandrum and Kodaikanal during selected extreme storm periods (Dst >250nT) during the years is shown in Table 7 (adopted from Eapen, 2009). A least square fit between minimum Dst values and Trivandrum %D for these storms yields the following relation:

Dst = 21.961%D + 94.208 (8)

See also Figure 7.







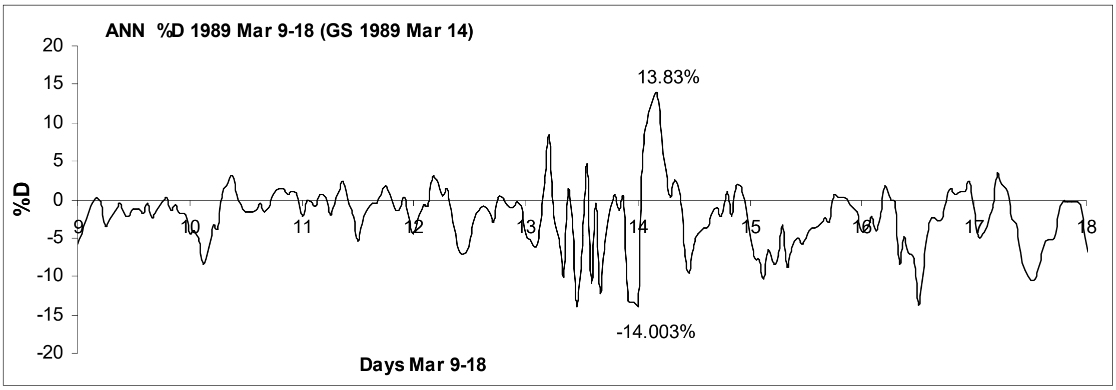


Figure 6. Variation of D and its storm time differences (%D) observed during the great geomagnetic storm of March 14, 1989 (a) at Trivandrum (b) at Kodaikanal and Annamalai Nagar (adopted from Eapen, 2009).

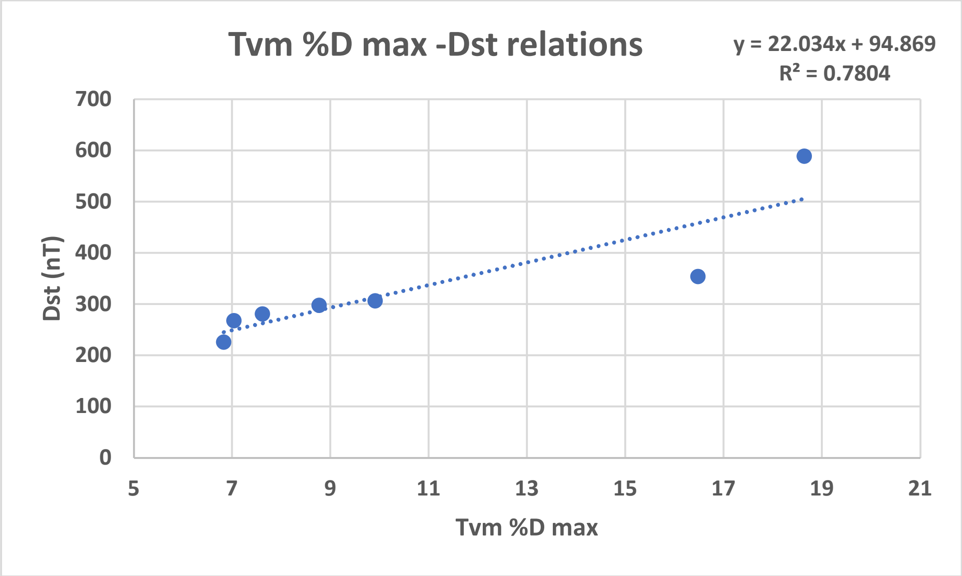


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Figure 7. Linear regression relation between Tvm %D max (maximum storm time hourly change in magnetic declination in Trivandrum) and magnitude of Dst minimum for selected intense geomagnetic storms during the modern period.

Table 7. Maximum storm time changes in hourly magnetic declination (%D) in Trivandrum and Dst during selected severe magnetic storm periods during the years 1981-1991 (after Eapen, 2009).

Date of magnetic storm	Date and time of maximum %D	Value of max %D	Max Dst (nT)
1981 July 25	1981 July 25,15 hr	-6.83	-226
1986 February 8	1986 Feb 8th, 22 hr	-9.91	-307
1989 March 13-14	1989 Mar 13, 21 hr	-18.64	-589
1989 Oct 20-21	1989 Oct 20, 7 hr	-7.04	-268
1990 April 10-12	1990 Apr 12, 9 hr	-7.626	-281

1991 March 24-25	1991 Mar 24, 23 hr	-8.77	-298
1991 November 8-9	1991 Nov 8, 23 hr	-16.48	-354

Applying equation (7) for the Carrington storm of Sep2, 1859 given in Table 6 we find that Dst for this storm is inferred to be only 798 nT . An update of the Dst calculations for this storm will be discussed in Section

4. Dst Equivalent Values of Geomagnetic Storms During 1841-1877 Estimated from Daily Mean H Values Trivandrum, Madras and Singapore

It is always preferable to find the relations between geomagnetic storm intensity in the colonial stations during the 19th century and the modern Dst index. In this context we will first scale the storm time mean H changes in Trivandrum in term of the Dst values. The Hd of Trivandrum found for the Carrington storm (Sep 2, 1859) from Table is 133.5. The median Dst value inferred for the Carrington storm is reported to be 949 nT (Hayakawa et al., 2022).

We define Tvm Dst for a given geomagnetic storm during 1855-1877 as :

Tvm Dst = (949/133.5) X H_d (9)

Using equation (9) we have determined Tvm Dst values for all the geomagnetic storms in Table and the results are given in the same Table. It is surprising to find that the Tvm Dst values for the Aug 29, 1859 and Feb 4, 1972 storms exceeded the value for the Carrington storm.

We have done a linear regression fit between H_d (in BU) of Madras storms given in Table 2 during the year 1855 with the corresponding Tvm Dst values given in Table 5

The equation is :

Tvm Dst (nT) = 14840 MDS Hd (BU) + 46.922 (R^2 =0.6052, r = 0.78) (10)

See also Figure 8.

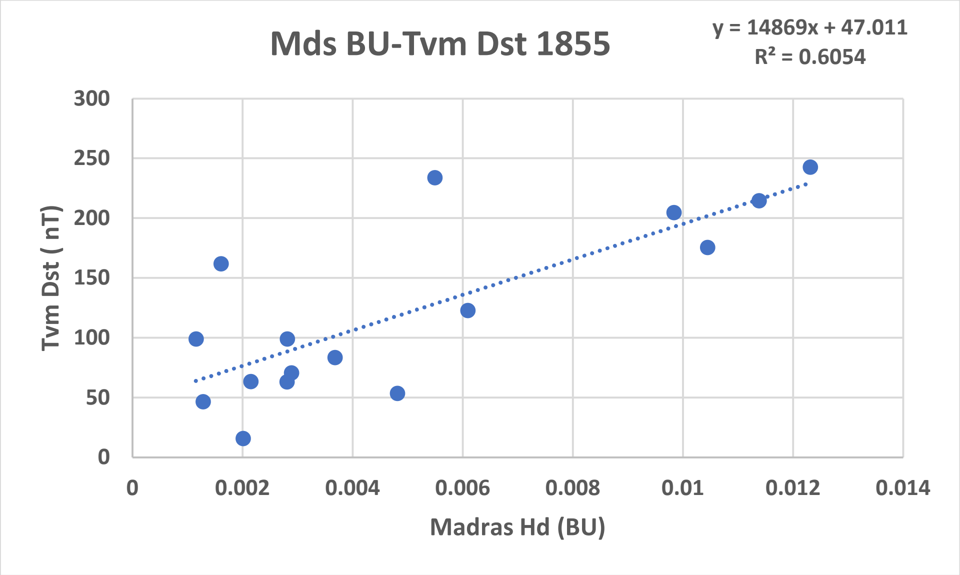


Figure 8. Regression relation between values of storm time change in daily mean H of Madras (Hd in BU) and Tvm Dst for selected geomagnetic storms during the year 1855.

The estimated Tvm Dst values of the Madras storms is given in Tables 1 and 2. .

For Singapore storms we assume that equation (9) is valid so that we find

Tvm Dst (nT) = 14840 Sing Hd (BU) + 46.922 (11)

Here Sing Hd values are adopted from Table 3 . The Tvm Dst values estimated for the geomagnetic storms observed in Singapore during 1841-1845 is also given in the same Table.

We have included Maunder classification of geomagnetic storms derived from Greenwich data in the strom Tables . The values of observed peak in 3 hourly aa index for selected storms during the period 1868-1877 is also included in Table 5.

5. Investigations on the Relations Between Geomagnetic Parameters in Low and Equatorial Latitudes and the Dst Index

5.1. Relation Between Daily Mean H Changes in Trivandrum and Dst Index During Modern Magnetic Storms

James et al. (2004) studied the relation between deviation of daily mean H during magnetic storm periods from its respective monthly means for low/equatorial stations during the IGY (1957-58) period. They found high correlation between these parameters (r>0.9) including Trivandrum (r=0.95). For selected storm periods between 1974-1996 we have determined the % change in storm time minimum daily mean H from its monthly means (% ΔH) in Trivandrum (Indian magnetic data, 2005) and compared with minimum Dst index during these storms The relevant data is given in Table 8. A linear regression fit between these parameters for Trivandrum yields :

Dst = 7.4832 X (% ΔH) + 45.233 (R^2 =0.942) (12)

See also Figure 9.

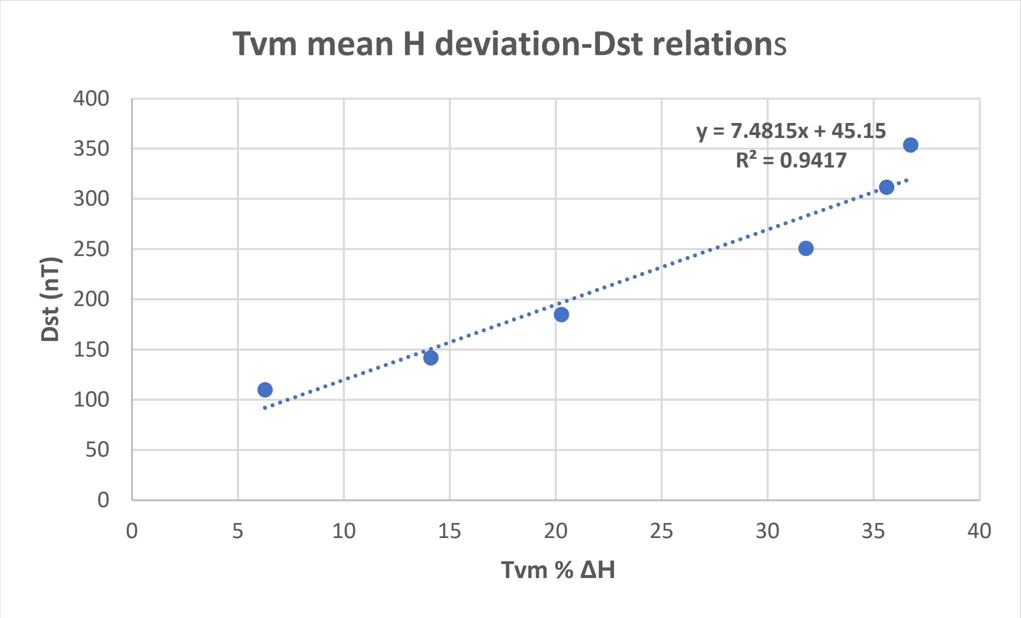


Figure 9. Linear regression fit between Tvm % ΔH (Devitiation of Storm time value of daily mean H from monthly mean in Trivandrum) and magnitude of minimum Dst during selected storms in the modern period.

Table 8. Deviation of storm time value daily mean H observed in Trivandrum from the respective monthly mean (% ΔH) for selected modern storms compared with Storm time minimum Dst index.

storm date	% ΔH	Dst
1988 Jan 14	20.2	-185
1989 Feb 8	35.6	-312
1991 Oct 29	31.8	-251
1991 Nov 9	36.74	-354
1995 Apr 7	14.1	-142

1996 Oct 23	6.27	-110

Our result is in good agreement with the findings of James et al. (2004) even though the sample size is small. This result justifies our proposed relation between storm time changes in daily mean H values of Trivandrum (H_{diff}) and Dst index during the years 1855-1877 in section

5.2.. Relations Between Hourly H Decreases (ΔH) in Bombay (Mumbai) During Severe Magnetic Storms and the Dst Index.

From the list of intense geomagnetic storms along with H decreases observed in Alibag, Mumbai [ΔH (A)] and minimum Dst values published by Lakhina and Tsuratani(2018) we have done a linear regression fit for these storms during 1957- . The results are given in Figure 10.

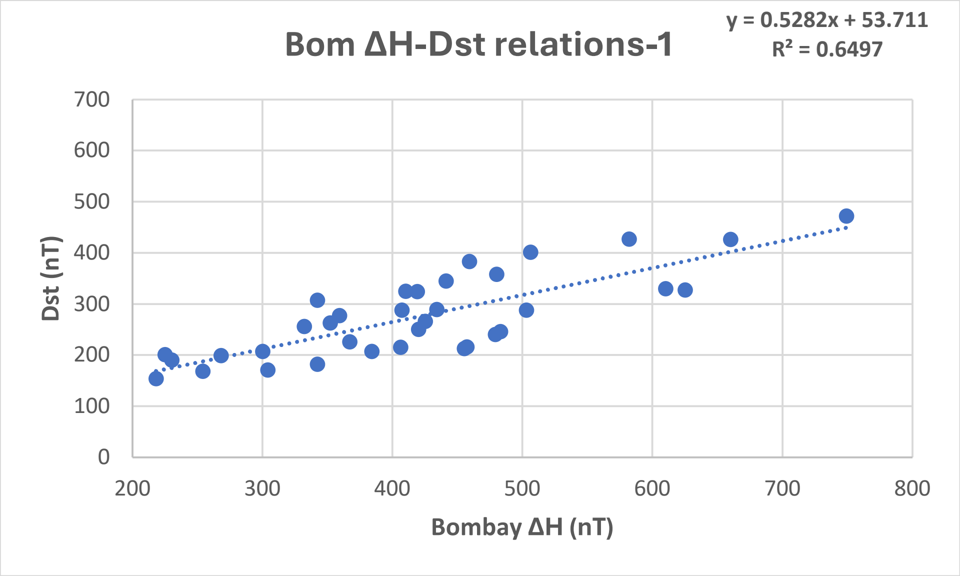


Figure 10. Linear regression relation between Bombay ΔH (maximum hourly storm time decrease in Bombay - Alibag observatory) and magnitude of minimum Dst index during selected super intense storms during the years… (after Lakhina et al.).

The regression relation found i

Dst = 0.5282 ΔH (A) + 53.71 (R^2 =0.6497) (13)

Similar relation is determined for 18 intense storms (with Dst <200 nT) observed in Alibag during the years 1996-2006 i (Rawat et al., 2020) in sunspot cycle 23

For this case the regression relation is found as:

Dst = 0.5292 ΔH (A) + 101.41 (R^2 = 0.67) (14)

See also Figure 11.

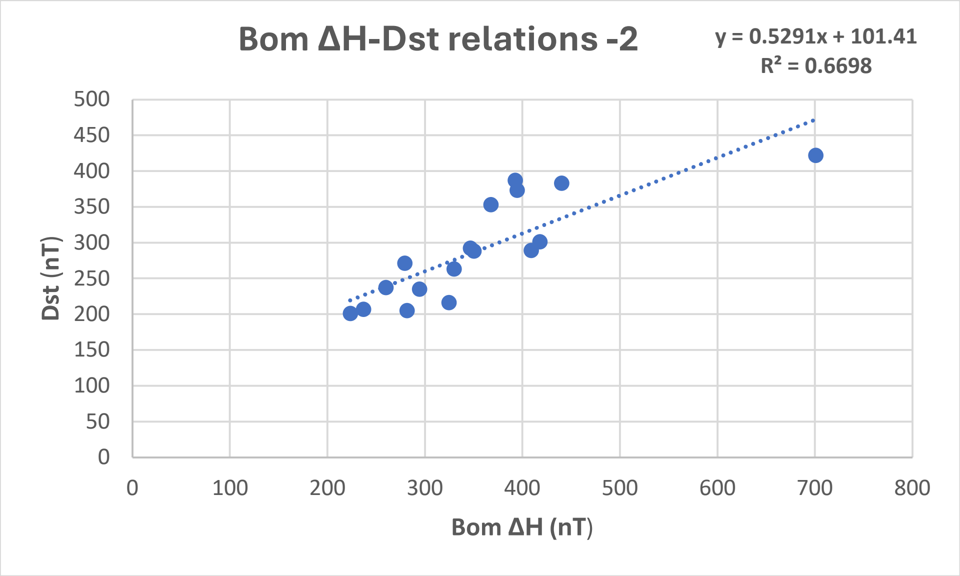


Figure 11. Linear regression relation between Bombay ΔH (maximum hourly storm time decrease in Bombay - Alibag observatory) and magnitude of minimum Dst index during selected intense storms during the years… (after Rawat et al., 2020).

5.3.. Storm Time H Decreases (ΔH) in Dip Equator Stations in India and Dst Index

The intensity of geomagnetic storms are controlled by the strength of the magnetospheric current system called ring current. The manifestations of ring current is maximum for latitude and equatorial stations during these storms. In Table we have shown values of storm time hourly H decreases in dip equator stations in India (ΔH_E) from published literature (Kotadia, 1964; Rastogi, 1999; Veeenadhri and Alex, 2006; Pande etal, 2014) along with Dst values for selected severe geomagnetic storm periods during the years 1957-2003. We have done a linear regression fit between magnitudes of ΔH_E (nT) and corresponding Dst values.

The relation is found to be :

Dst (nT) = 0.729 ΔH_E + 24.085 ($R^2 = 0.9524$) (15)

See also Figure 12.

Table 9. Equatorial Delta H in Indian stations compared with Dst for modern storms.

Date of Storm	Eq Station	Mag latitude	Delta H (nT)	Dst (nT)
13 Sept 1957	Kodaikanal		570	426
19 Dec 1980	Ettayapuram		350	250
13 Sep 1986	Kodaikanal		270	170
14 Mar 1989	Kodaikanal		740	589
6-7 Apr 2000	Ettayapuram		317	314
30-31 March 2001	Tirunelveli		525	383
20 Nov 2003	Tirunelveli		650	491

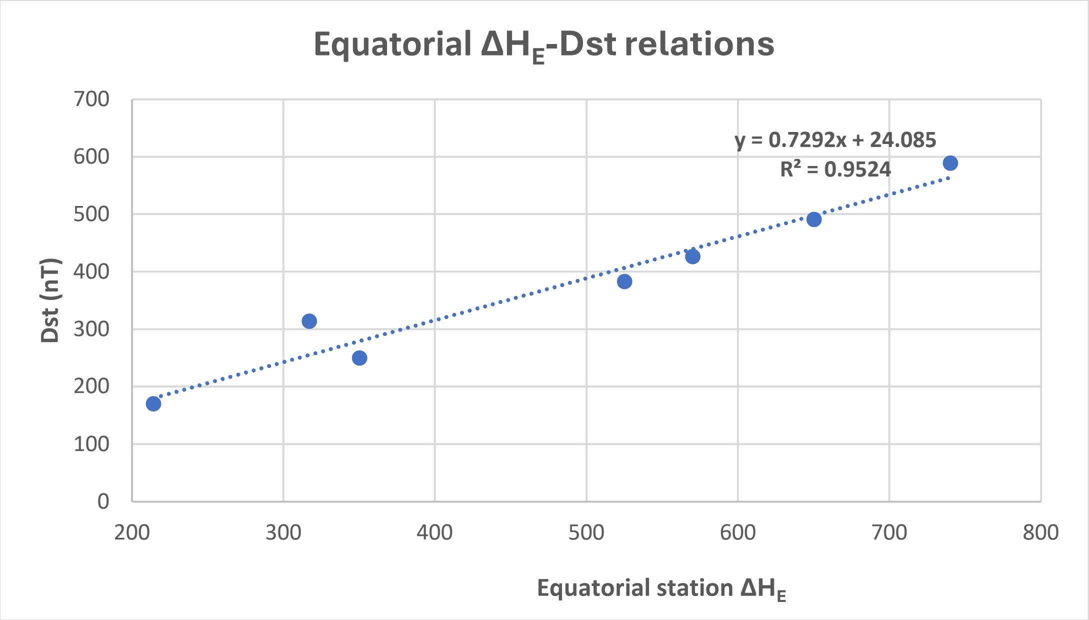


Figure 12. Regression fit between ΔH_E (Maximum storm time decrease in hourly H in equatorial stations) and magnitude of minimum Dst values for selected modern geomagnetic storms.

6. Occurences of Intense and Super Intense Storms During the Sunspot Cycles 8-11

Let us adopt the following criteria for the identification of intense, extreme intense and super intense geomagnetic storms based on the magnitude of Tvm Dst index:
i) Intense geomagnetic storms : Tvm Dst is between 150-299 nT
ii) Extreme intense geomagnetic storms : Tvm Dst is between 300-599 nT
iii) Super intense geomagnetic storms : Tvm Dst is between 600-799 nT
iv)Carrington class geomagnetic storms : Tvm Dst is 800 nT or above

In Tables .. we have shown extreme intense storms in blue colour and super intense storms in red colour in the last columns. The statistics of extrema and super intense storms which occurred during the sunspot cycles 8-11 (covering years 1841-1877) is given in Table 10. Details of some outstanding storms inferred during different sunspot cycles is given below

Table 10. Number of extreme intense and super intense geomagnetic storms inferred during the sunspot cycles 8-11 inferred using low/equatorial latitude observations.

Sunspot Cycle	No of Extreme-intense GM storms	No of Super intense GM storms	Total No of Severe storms
8 (1841-1843)	1	0	1
9 (1844-1854)	15	7	22
10 (1855-1866)	22	4	26
11 (1867-1877)	30	7	37

Some outstanding storms in different sunspot cycles
Sunspot cycle 8

We could collect geomagnetic data only for only three years (1841-1843) during solar cycle 8. Only one extreme geomagnetic storm is identified during this period : Sep 24, 1841. The storm time decrease in H during this storm in Trivandrum is inferred to be only 235 nT (see Appendix for details). However the inferred Tvm Dst value for this storm is found to be high (407 nT). According to Sabine (1842) this storm is an outstanding one whose effects are felt world wide.

Sunspot cycle 9

During solar cycle 9 (1844-1855) we could identify the occurrence of at least 5 super intense storms in Madras (Trivandrum Dst >600 nT) during the sunspot maximum epoch (1847-48). These storms and some additional outstanding storms will be discussed below.

i)The storm on September 24th 1847 : This is recorded as a great storm in Greenwitch (ΔH=1100 nT) and Russia (ΔH>1043 nT) in the mid latitudes . This is included in the list of super storms in Bombay published by Lakhina and others ( )

ii)The storm on 1st Nov 1847 (not reported in other locations).

Iii) The storm on 20th December 1847: This is reorded as a Great strorm in Greenwich (ΔH =675 nT) . From inferred daily aa index data this storm is suggested to be the one with maximum intensity inhere sunspot cycle 9 (ref)

iv)The storm on 1847 October 23 : There is data gap for Madras for this storm so Tvm Dst could not be estimated. This is recorded as an outstanding great storm in Greenwich (ΔH =1900 nT). It is also part of great storms recorded in Russia (ΔH >816 nT). This is included as a super storm in Bombay.

v) The storm on 1852 February 18-19 : Tvm Dst estimated for this storm suggests this as an extreme storm. However Bombay hourly H decrease for this storm (Eapen, 2009) suggest a very large value (ΔH =1500 nT, see our Table in Sec). It is recorded as great storm in Greenwich and Russia (ΔH>819 nT).

vi) The storm on 1845 August 30-31 : We could find a very large value for Tvm Dst (905 nT) for this storm which occurred near sunspot minima. In Fig we have shown daily mean H observations in some equatorial , low and mid latitude stations(after Broun, 1861) along with daily Ak index and sunspot number around this storm period (after Eapen, 2009). The variations of daily mean H in relative units in Singapore ( ) during August 1845 is shown in Fig .

Sunspot cycle 10

During this cycle we could infer the occurrence of 22 extreme intense storms and at least 4 super intense storms.Details some of them are given below.

i)The storm on 1857 December 17-18 : This is inferred as an extreme intensity storm (Tvm Dst= 534.85 nT) Included in the list of super storms (Lakhina 2018) observed in Bombay (ΔH=306 nT) . Recorded as a great storm in Greenwich.

ii) The storm on 1858 April 9-10 : This is inferred as an extreme magnetic storm (Tvm Dst =334 nT). Recorded as a great storm in Greenwich. We could infer a high storm time decrease of H in Bombay (ΔH=601 nT).

iii) The storm on 1859 April 22 : This is inferred as an extreme intensity storm (Tvm Dst=503.2 nT). The inferred intensity is Bombay is also high (ΔH=478 nT).

iv) The storm on 1859 August 28-29: This is recorded as a great double storm along with the Carrington storm in Greenwich. The inferred intensity exceeds the Carrington storm in Trivandrum (Tvm Dst: 1025 nT). Recorded as a great storm in Russia. The inferred decrease of H in Bombay by us (ΔH=681 nT) can be an underestimate due to data gaps.

v) The storm on 1859 September 2 : This is the historic Carrington storm, widely reported in modern literature. The storm is used as a reference to estimate Tvm Dst for other storms in this paper. It is recorded as a great storm in Greenwich and Russia (ΔH>980 nT).In Bombay we could infer a very large H decrease (ΔH=1729 nT).

vi) The storm on 1859 October 12 : This is inferred as a super intense storm (Tvm Dst=830 nT). Recorded as a great storm in Greenwich. We could infer relatively a large H decrease for this storm in Bombay (ΔH=967 nT).

vii) The storm on October 17-18: This is possibly a dual storm to the previous one. It is recorded as an extreme intensity (ΔH=475 nT) storm in Bombay (Kumar et al., Veeendhari etc). Our inference also supports this result (Tvm Dst=405 nT).

viii) The storm on 1859 December 13th : Inferred as an extreme magnetic storm by us (Tvm Dst=440 nT). This is supported by Bombay H observations (ΔH=492 nT).

ix) The storm on 1860 March 28th : This is inferred as a super storm by us (Tvm Dst=603.45 nT) . The inferred H decrease in Bombay is also high ((ΔH=539 nT).

x) The storm on 1866 February 20-21 : This is inferred to be an extreme intensity storm (Tvm Dst= 556.9 nT) occurring near sunspot minima. Recorded as a great storm in Greenwich.

Sunspot cycle 11

During this cycle we could infer the occurrence of 30 extreme intense storms and 7 super intense storms.Details some of them are given below.

i)The storm on 1869 February 3-4: This is inferred to be a extreme intensity storm (Tvm Dst=577.7 nT) . Recorded as a great storm in Greenwich.

ii) The storm on 1869 April 15-16 : This is inferred to be a super intense storm (Tvm Dst=694 nT). Recorded as a great storm in Greenwich. The peak 3 hrly aa index (aap) is found to be 286 nT..

iii) The storm on 1869 May 13-14 : This is inferred to be a super intense storm (Tvm Dst=673.75 nT) . Recorded as a great storm in Greenwich (ΔH>700 nT) The peak 3 hourly aa index (aap) is found to be 531 nT.

iv) The storm on 1870 September 24 : The is inferred as an extreme storm in Trivandrum (Tvm Dst= 587.38 nT). Recorded as a great storm in Greenwich . The 3 hourly aa peak value (aap) is found to be 334 nT.

v) The storm on 1870 October 24-25 : Inferred to be an extreme intensity storm (Tvm Dst=551.48 nT). Recorded as a great storm in Greenwich and Russia (Ptitsyna et al., 2012) The observed peak 3 hourly aa index (aap) is found to be 464 nT.

vi)The storm on 1871 February 10-11 : Infered to be an extreme intensity storm (Tvm Dst=599.75 nT). The observed maximum 3 hourly aa index (aap) is found to be 334 nT.Recorded as a great storm in Greenwich.

vii) The storm on 1871 April 9-10 : Inferred to be an an extreme intensity storm (Tvm Dst =452.39 nT). The observed peak 3 hourly aa index (aap) is found to be 337 nT. Recorded as a great storm in Greenwich.

viii) The storm on 1871 November 9-11 : Inferred to be an extreme intensity storm (Tvm Dst=545.2 nT).Recorded as a great storm in Greenwich.

ix) The storm on 1872 Feb 4 : This is inferred as a super storm in Trivandrum (Tvm Dst=670.88 nT) even though this is expected to be a Carrington class storm during which low latitude Aurora is seen in Bombay. It is recorded as a great storm in Greenwich (ΔH=800 nT). The observed maximum 3 hourly aa index (aap) is found to be 658 nT. Large H decrease is observed in Bombay (ΔH=1023 nT).

x) The storm on 1872 August 15 : Inferred to be a super intense storm (Tvm Dst=696.64 nT).

xi) The storm on 1872 October 15 : This inferred to be a super intense storm in Trivandrum (Tvm Dst=709.43 nT) . Recorded as a great storm in Greenwich (ΔH=600 nT). The observed maximum 3 hourly aa index (aap) is found to 458 nT. H decrease observed in Bombay is significant (ΔH=430 nT).

xii) The storm on 1872 October 17-18 : This inferred to be super intense storm (Tvm Dst=667.21 nT) It appears be part of a dual storm related to the previous one. Recorded as a great storm in Greenwich. The observed maximum 3 hourly aa index (aap) is found to 262 nT.

xiii) The storm on 1873 January 8th : This is inferred to be a extreme intense storm (Tvm Dst=437.46 nT).

xiv) The storm on 1873 March 10 : This is inferred to be a extreme intense storm (Tvm Dst=431.42 nT). The observed maximum 3 hourly aa index (aap) is found to 262 nT.

xv) The storm on 1873 April 19 : This is inferred to be an extreme intense storm (Tvm Dst=355.65 nT).

xvi) The storm on 1874 February 4-5: Thisis inferred to be a extreme intense storm (Tvm Dst =381.02 nT). Recorded as a great storm in Greenwich. The observed maximum 3 hourly aa index (aap) is found to 286 nT.

xvii) The storm on 1874 March 7-9 : This is inferred to be an extreme intense storm (Tvm Dst=566 nT).

xviii) The storm on 1874 April 2 : Inferred to be an extreme intense storm (Tvm Dst=517 nT)

xix) The storm on 1874 April 8 : Inferred to an extreme intense storm (Tvm Dst=343.41 nT).Appears to be a dual storm related to the previous one.

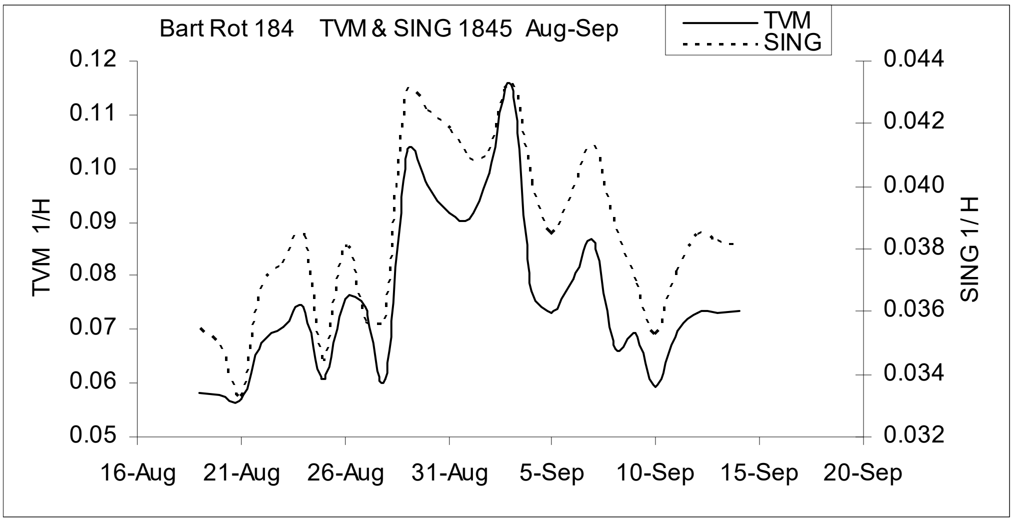
xx) The storm on 1874 October 3-6 : Inferred to be a extreme intense storm (Tvm Dst=400.92 nT)

7. Occurences of Extreme Space Weather Events and Its Sunspot Cycle Variations During the Years 1841-1877

There are different criteria adopted to identify extreme space weather events. Intensity of geomagnetic storms is one such criteria. We suggest that extreme intense and super intense geomagnetic storms discussed in the previous section can be identified with extreme space weather (ESW) events.

Thus geomagnetic storms with a value of Tvm Dst equal to 300 nT or more can be considered as ESW events during the period of our study.

Total number of ESW events (sum of the number of extreme and super intense storms for the year) for each year between 1841-1877 is plotted in Figure 13 along with international classic sunspot numbers. Characteristic sunspot cycle changes can be seen from this Fig which will be discussed in detail in the next section.



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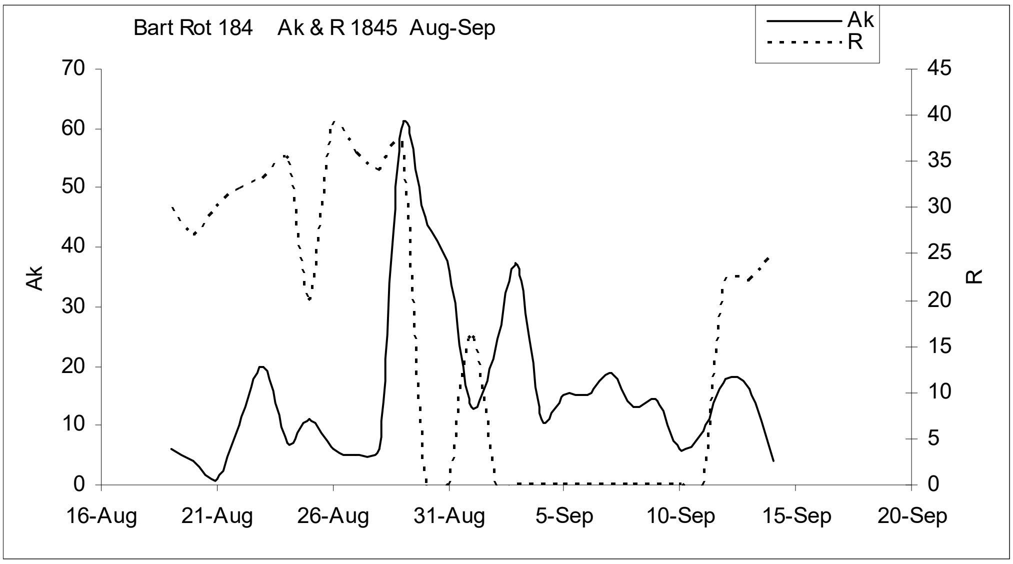


(b)

Figure 13. (a) Daily mean values of H observed in Trivandrum and Singapore calculated by Broun (1861) during August-September 1845 (b) Daily mean values of Helsinki Ak and international sunspot number (R) during August-September 1845 (adopted from Eapen, 2009).

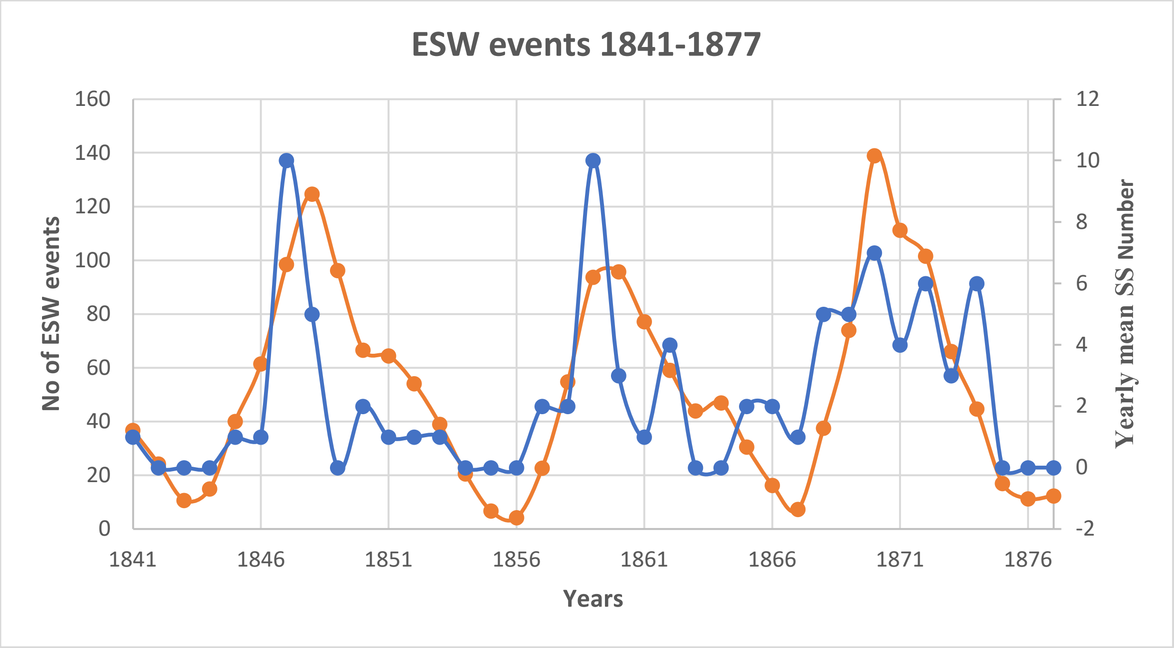


Figure 13. Annual number of extreme space weather (ESW) events plotted along with yearly mean international sunspot number for the years 1841-1877.

8. Discussion

Geomagnetic observations made at British colonial observatories in low/equatorial latitudes during the 19th century under the directions of Royal society of London forms an important resource for inferring the characteristics of extreme space weather events during this period. We aim to identify extreme space weather events during the years 1841-1877 using hitherto unexplored geomagnetic observations in Trivandrum, Madras, Singapore and Bombay located in m either low or equatorial magnetic latitudes.

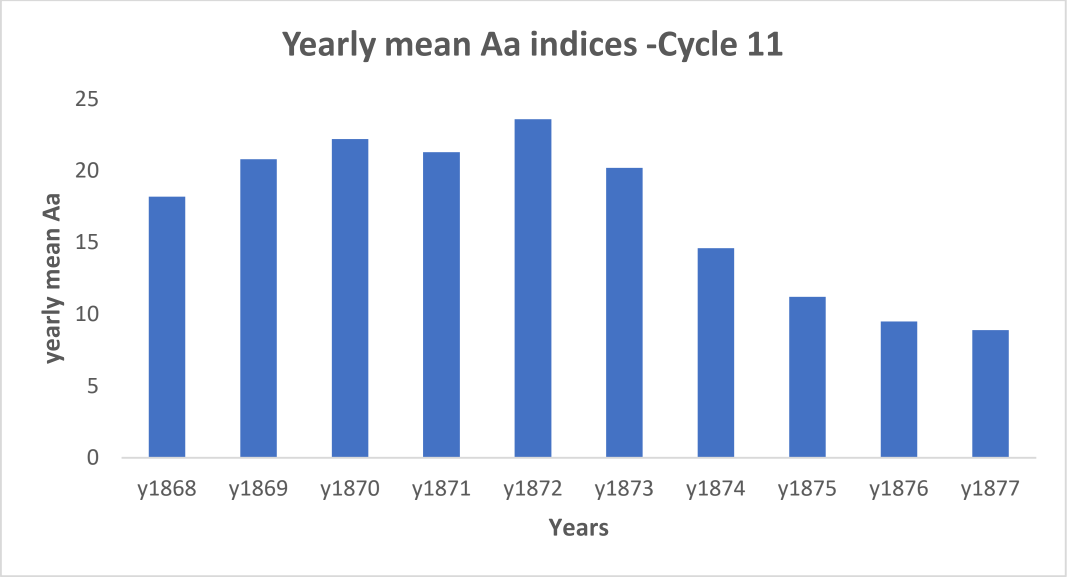
Only part of Bombay and Trivandrum magnetic observations during the 19th century are studied so far and reported. Ours is a detailed study making use of most of the available archival/published observations related to the above observatories. One of our key objectives is to estimate the intensity of major geomagnetic storms during the period of study and also determine its relation with modern Dst index. During 1841-1855 we have used low latitude observations from Singapore and Madras . We have used of Trivandrum observations which is situated close to the dip equator during the years 1855-1877. Our work will add more light on the results of previous works based on mid latitude observations

The intensity of geomagnetic storms observed in Madras, Singapore and Trivandrum is first determined by scaling storm time changes in daily mean H values in these places to Bombay hourly H observatios . Such an attempt is done by us earlier using limited data series (Eapen and Girish, 2010; Eapen and Girish, 2012) . Subsequently we have scaled storm time changes in daily mean H values in Trivandrum (1841-1845) Madras (1846-1855) and Singapore (1841-45) to modern Dst values by defining a new index called Tvm Dst.

We have taken care to minimise errors when we determine the intensity of geomagnetic storms in the Dst scale. Reliable Dst estimates are available in literature only for few outstanding storms (Hayakawa et al., 2022; Hayakawa et al., 2023) . during the period of our investigation in the 19th century. Tvm Dst values are estimated by us using Carrington storm Dst value as a reference. For the Feb 4, 1872 storm, Tvm Dst estimated using Adies Bifilar 1 observations in Trivandrum obslueervatory is found to be 671 nT. If we use normalised Adies Bifilar 2 observations in Trivandrum for the same storm (see Table) Tvm Dst value increases to 767 nT. Both these values are found to be less than the Dst value estimated for this outstanding storm (852 nT) from low latitude observations (Hayakawa et al., 2023).Further we have normalised the Adies Bifilar observations in Trivandrum during the years 1873-1877 as explained in Sec . and Appendix. So it appears that we have not over estimated the values of Tvm Dst in the present study.

From Figure 13 we can find that the sunspot cycle variations in the annual number of extreme space weather events (Nsw) during the years 1841-1877 suggest several interesting features. The period of our study covers the solar cycles 9-11. The most prominent peak in Nsw occurs during the epoch of sunspot maxima in these sunspot cycles. During sunspot cycle 9 the maximum or prominent peak in Nsw occurs during the years 1847 and 1859 in the solar cycles 9 and 10 repectively. These years falls one year prior to the sunspot maximum years. It is interesting to find that occurrences of super/extreme intense storms of 1946 March in sunspot cycle 18 (Hayakawa et al., 2020), 1989 March in sunspot cycle 22 (Tsurutani et al., 2024) and 2024 May in current 25th sunspot cycle (Tula si Ram et al., 2024) happens during the late ascending or sunspot maximum epoch.

Let us consider the peaks in Nsw which occurred during the post sunspot maximum or declining phase of these sunspot cycles. Let us consider the peaks in Nsw which occurred during the years 1851 in sunspot cycle 9, during the year 1862 in sunspot and during the year 1872 in sunspot cycle 11. The double peak structure in geomagnetic storm activity during a sunspot cycle is reported in literature (Gonzalez et al., 1990) A distinct peak in geomagnetic activity is found to occur during solar polar magnetic reversal (SPR) periods and this feature is used to infer the epoch of SPR during every sunspot cycle back to early 18th century (Haritha et al. 2018; Haritha, 2023). From these cited studies we can find that the years 1851, 1862 and 1872 fall during the epoch of solar polar magnetic reversal. A recent example is the distinct peak in geomagnetic activity during the year 2003 in sunspot cycle 23 which coincides with SPR during that cycle . In Figure 14 we have plotted annual mean values of geomagnetic aa indices during sunspot cycles 11 and 23 where the distinct peaks during the solar polar reversal years can be clearly seen. These results suggest that the pattern of double peak structure of intense geomagnetic storm activity during a sunspot cycle can be used to predict occurrences of super intense storms in future sunspot cycles.



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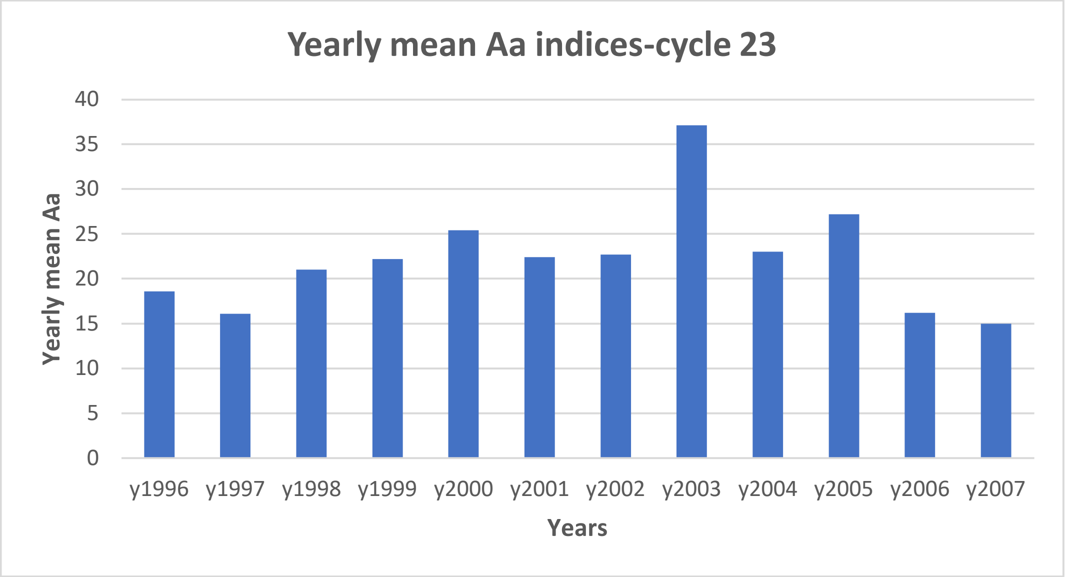

(b)

Figure 14. Yearly mean geomagnetic aa indices for (a) the sunspot cycle 11 and (b) sunspot cycle 23.

Sunspot cycle 11 is found to be associated with outstanding space weather activity. The number of ESW events (37) inferred to have occurred during this cycle from the present study is possibly a maxima during the past 185 years. For comparison during sunspot cycle 19 (most active cycle in recent times) only 23 ESW events are recorded (see Figure 15). Sunspot cycle 10 where Carrington storm occurred is also a cycle with severe space weather activity with 25 ESW events. preceded by solar cycle 9 with 21 ESW events.

doi:10.20944/preprints202601.0687.v1

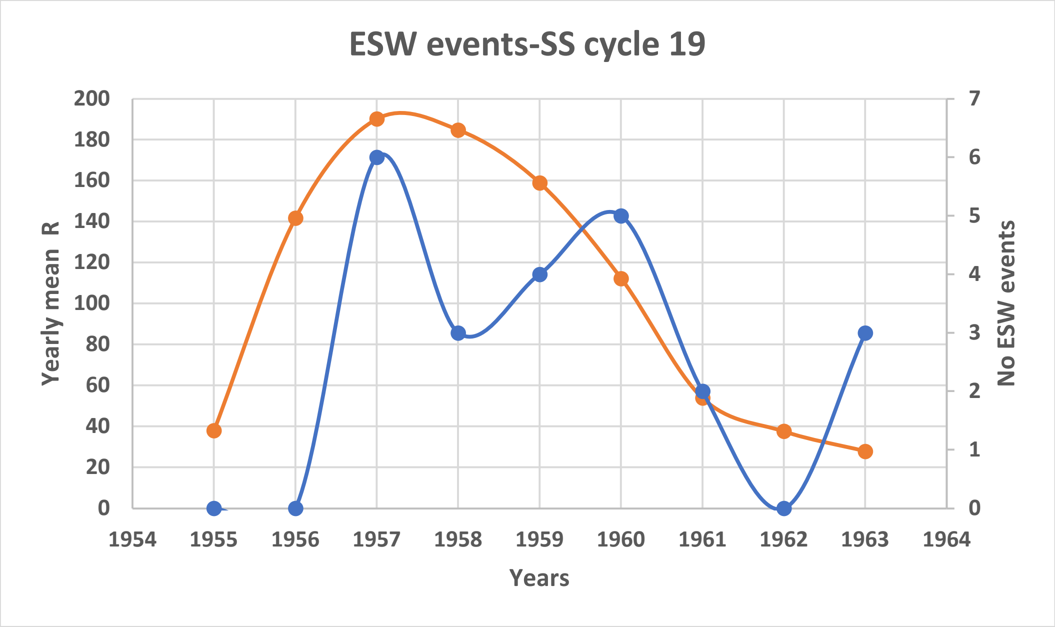

Figure 15. Annual number of extreme space weather (ESW) events (blue) during the sunspot cycle 19 plotted along with yearly mean classic sunspot numbers (orange).

Limitations in the Dst index to define the intensity of extreme geomagnetic storms and allied space weather phenomena is pointed in several studies (Borovsky and Shprits, 2017; Blake et al., 2021; Manu et al., 2024). Both mid latitude and low latitude indices are used to identify extreme space weather events since the 19th century (Cliver and Svaalgaard, 2004;Vennerstorm et al., 2016) In the space craft era March 13-14: 1989 geomagnetic storm is found to be associated with maximum decrease of Dst index (589 nT) . Space weather effects related to this storm is often compared with the same expected during Carrington class super intense storms. Sym H index is suggested as an alternative to Dst index. (Solovyev et al., 2005) While Dst index is an hourly index, Sym H is a high resolution(making use of 1 minute geomagnetic observations) storm index. During the main phase of March 1989 storm , maximum H decrease (ΔH=752 nT) is observed in the equatorial station Kodaikanal in Indian longitudes. Unfortunately there are data gaps for this extreme storm day in Trivandrum and Mumbai magnetic observatories so that accurate ΔH determination becomes impossible. In Figure 16 we have shown remarkable H decrease in Kodaikanal during the Maerch 14 1989 storm. It is interesting to observe that the maximum decrease in Sym H index for this storm is reported to be 715 nT. This value is comparable to the Kodaikanal ΔH if make corrections for the Sq amplitude for this station. So ΔH observations in dip equator stations in different longitudes will help us to determine true intensity of extreme intense geomagnetic storms

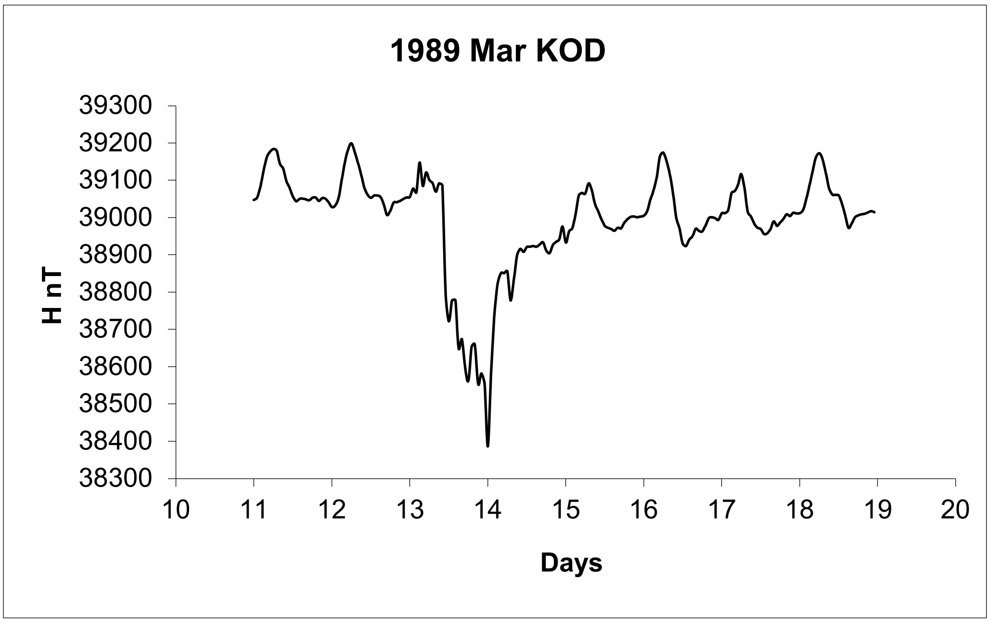

Figure 16. Remarkable H decrease (752 nT) in Kodaikanal during the March 14 1989 super geomagnetic storm.

The ratio of the magnitude of minimum Dst of Carrington storm (949 nT) with the magnitude minimum Dst of March 1989 storm (589 nT) can be found to be 1,6. This implies that :

Sym H (Carrington Storm) = 1.6 X Sym H (March 1989 storm) = **1152 nT**

From the minute (every 2-5 minutes eye readings) magnetic declination data of Trivandrum observatory published by Allan Broun (Broun, 1874) during the Carrington storm we have found that the revised storm time change %D during this storm can be inferred to be 47%. Applying this value to the regression relation (8) we can find a new estimate of Dst to this outstanding storm. It yields a Dst value of 1120 nT which is comparable to the estimates given in literature. So the true mean intensity of the Carrington storm is likely to between 1100-1200 nT from these resuts. As a typical solar-terrestrial relation we have plotted storm time changes in cloud cover observed in Trivandrum during the Carrington storms in Figure 17.

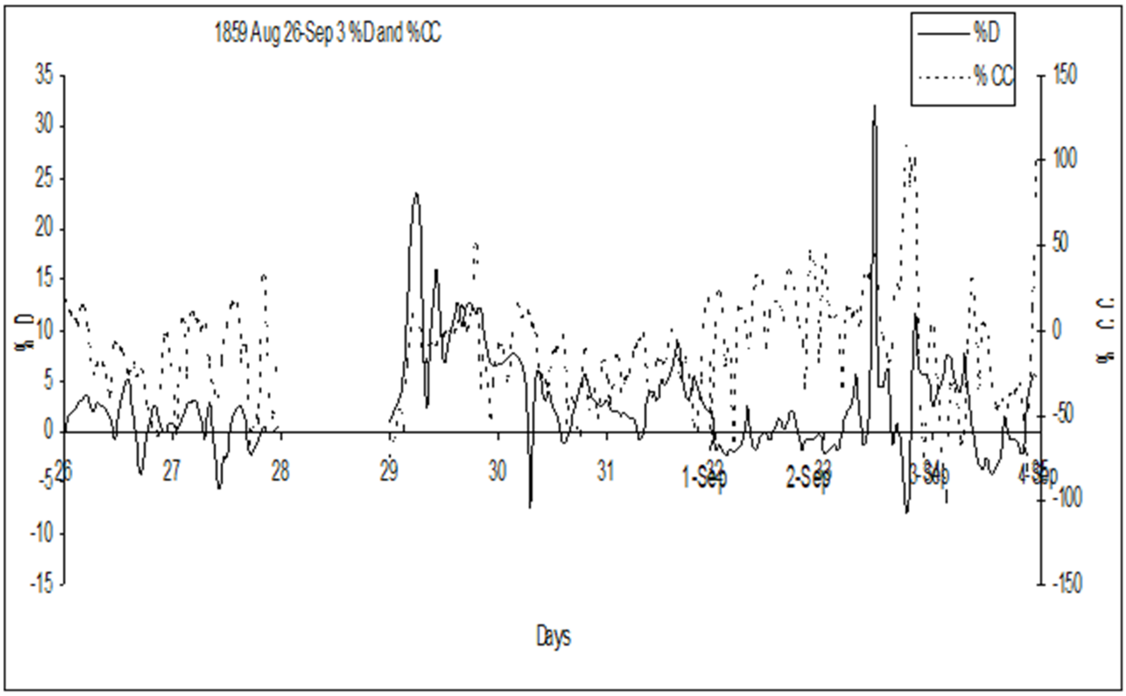

Figure 17. Storm time deviations in hourly values of cloud cover (%C) and magnetic declination in Trivandrum (%D) during the Carrington storms of August 29 and September 2 in 1859 (adopted from Eapen, 2009).

9. Summary of Results

1. Using daily mean H observations in the low/equatorial latitude stations : Trivandrum, Singapore and Madras we have inferred the intensity of geomagnetic storms scaled to Dst indices in modern units during the years 1841-1877. Our results are also compared with Bombay and mid latitude geomagnetic observations during these storm periods.
2. Extreme space weather (ESW) events are then identified from the list of extreme or super intense geomagnetic storm periods during 1841-1877 .
3. Solar cycle evolution of annual number of ESW events during the sunspot cycles 9-11 is found to show a characteristic double peak structure
4. Sunspot cycle 11 is found to be a cycle with exceptional space weather activity if consider relevant data for the past 185 years.
5. The limitations of the geomagnetic Dst index in deciding the true intensity of geomagnetic storms is also pointed out.

Author Contributions: P.E.Eapen (Formal analysis, data curation, writing-original draft preparation). **T.E.Girish** (Conveptia;ization, methodology, validation, writing-review and editing). **G.Gopkumar** (supervision, project administration, resources, writing-review and editing). **V.G.Haritha** (methodology, data curation, software, visualization).

Funding: This research received no external funding.

Data Availability Statement: Data will be made available on request.

Acknowledgments: Authors are grateful to National Library of Scotland for providing selected manuscripts of J.A.Broun related to Trivandrum Observatory.

Conflicts of Interest: The authors has no conflict of interest to declare.

Appendix

TRIVANDRUM MAGNETIC OBSERVATORY :DETAILS OF INSTRUMENTS AND OBSERVATIONS (1841-1879)

The magnetic observatory in Trivandrum was established during April 1841 .Early geomagnetic observations (eye readings) were made once in two hours which later changed to hourly observations during 1855-1864 and finally 5 times a day during 1865-1879. Most of the geomagnetic observations during this period remain unpublished except for the observations of magnetic declination during the years 1852-1869.

John Caldecott period

The instruments and geomagnetic observations during the period 1841-1849 in Trivandrum made under the supervision of John Caldectott (first director of the observatory) is shown in Table. The organisation of the Trivandrum magnetic observatory during this period is shown in Fig A1

Allan Broun's period

The instruments and geomagnetic observations during the period 1852-1864 in Trivandrum made under the supervision of J.A Broun (first director of the observatory) is also shown in Table Further the organisation o Trivandrum magnetic observatory during this period is shown in Fig A2. The details of this plan is given in Addendum

Period after Broun's retirement (1865-1879)

After retirement of Broun, two scientific assistants (Kochu Kunju and Cohervay Pillai) trained by him was entrusted to continue geomagnetic observations in Trivandrum . MJ Kochu kunju (KK) was in charge of the magnetic observatory between the years 1865-1874. After the death of him (KK) Cochervay pillai was in charge of the observatory between the years 1874-1880. The instruments and magnetic observations during the years 1865-1879 is also given in Table.A1 and values of scale coefficients (k) of the bifilar magnetometers is given in Table A2.

Table A1. Details of magnetic instruments and observations made under different directors of Trivandrum magnetic observatory during the 19th century.

Director and period of magnetic observations	**Instruments used during this period and nature of observations**
1 John Caldecott (1841-1849) *Bi-hourly eye observations*	i)Bifilar magnetometers for horizontal force measurements ii)Grubbs declinometer for magnetic declination measurements iii)Grubbs vertical force magnetometer iv) Absolute intensity magnetometer for absolute H measurements
2. J.A Broun (1852-1864) *Hourly eye observations*	i)Bifilar magnetometers for horizontal force measurements ii)Robinson and Adies balance magnetometers for vertifical force mesurements iii)Grubbs and Adies declinometers iv) Magnetic survey intsruments
3 Assistants of Broun (1865-1879) *Eye observations made 5 times daily*	i)Bifilar magnetometers for horizontal force measurements ii)Adies balance magnetometer for vertical force measurements iii) Adies and Grubbs unifilar magnetometers for declination measurements

Table A2. Details of Bifilar magnetometers used in Trivandrum observatory and estimated unit constants for different years during 1841-1877.

Period of measurement/use	**Type of the Bifilar magnetometer**	**Estimated Unit coefficient (k)**
1841-1847	1) Grubbs bifilar with silver wires	0.000133-0.00014
1852	-do-	0.0001365-0.0001370

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1854	2) Grubbs bifilar with platinum wires	0.0001503-0.0001505
1854	3) Adies Bifilar No1: Platinum wires	0.0000692-0.00007
1855	4)Adies Bifilar used in Augustia Obv: Platinum wires	0.000044-0.0000451
1869 May to 1872 December	5) Adies Bifilar No 1 & Adies Bifilar No 2	see section in this paper
1873 -1877	6) Adies Bifilar No 2	-do-

Adies Bifilar Magnetometer

The main components included an eyepiece for observing the magnet located on a pillar a few meters away and a magnet that was hung from above by two cables. This suspended magnet was free to rotate according to the varying horizontal geomagnetic field; the angle at which the magnet came to rest caused the cables holding it to twist. A scale, reflected off a mirror attached to the suspended magnet, was visible through the eyepiece. The eyepiece would show a different marking on the scale depending on the angle of the magnet. This setup enables the calculation of the percentage change in the strength of the horizontal magnetic field relative to the overall horizontal magnetic field at that location.

Equation of Adies bifilar magnetometer in the equilibrium position (after Broun, 1861a) is $mX = (Wab/l) \sin v$ (A1)

From this we can find

$X = (Wab/ml) \sin v$ (A2) (

m is the moment of the magnet, X is the horizontal component of earths magnetic field at the location, W is the weight suspended , a and b are the distances between bifilar wires from the top and bottom, l is the length of the bifilar wire and v is the angle of twist .

Storm time change in horizontal force from the base line in modern units is given by :

$\Delta H\,(nT) = H_A(nT)\ k\ H_{diff}$ (A3)

Here H_A is the absolute value of H in the location

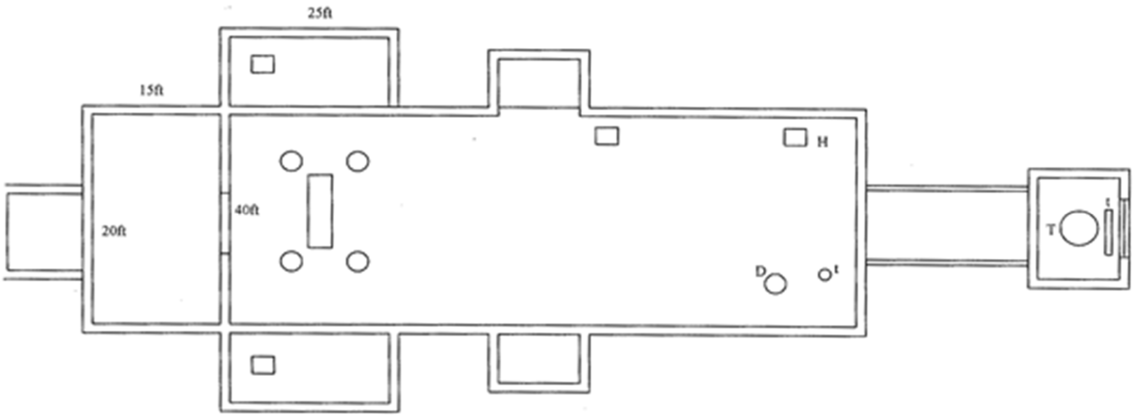

Figure A1. Plan of Trivandrum magnetic observartory established by J.Caldecott during the year 1841 (after Eapen, 2009). The explanation of symbols in this Plan: D : Position of the Declination Magnetometer. H : Position of the Bifilar Magnetometer. V : Position of the Vertical Component Magnetometer. t : Reading Telescopes. Λ : Table of Osseler's Anemometer. Γ : Library and Computing Room.

Inference of the intensity of the 1841 storm using Trivandrum H observations

The change in horizontal intensity (Hd) at Trivandrum during a geomagnetic storm is given by the expression (Eapen, 2009)

Hd (nT) = (36000/7.8) X Ha X Hd (sc dev) X k (A4)

Here Ha is the absolute value of H measured in Trivandrum and k is the unit coefficient of the bifilar magnetometer used for the measurement of H variations in this station.

The magnetic observations in 1841 under the supervision of John Caldecott consisted of measurements of magnetic declination, horizontal component (H) and vertical component (Z) of the geomagnetic field for every two hours in Trivandrum. This is modified to hourly observations since 1852 by John Allan Broun , the second director if Trivandrum observatory.

We have some useful observations of horizontal intensity in Trivandrum during the September 24-25 magnetic storm period as published by British Astronomer Col. Sabine (Sabine, 1842).

Using Equation (A11) we can calculated the storm intensity for this storm in modern units

From Sabine (1842) we could find the following data for Trivandrum for this storm:

k= 0.000133

Ha= 7.77 BU

Maximum storm time change in bi-hourly H in Trivandrum is

Hd = 49.3 Sc div

Intensity of 1841 Sep 24-25 storm in Trivandrum from (A4) = **235.14** nT/.

Theory for simultaneous measurement of H with two different bifilars

Let Hd1 and Hd2 are the readings of the bifilar magnetometers 1 and 2 corresponding to change in H during a geomagnetic storm period expressed in scale divisions. Now from equation (x) we can write :

Hd (nT) = Q X Ha X Hd1 (sc div) X k1 = Q X Ha X Hd2 (sc div) X k2 (A5)

Here Q = 36000/7.8

Ha is the absolute value of H in the station close to the storm period

k1 and k2 are the unit coefficients of bifilar 1 and bifilar 2 respectively.

From (A5) we can find that

Hd1 k1 = Hd2 k2

(Hd1/Hd2) = (k2/k1) =k

Hd1= k X Hd2

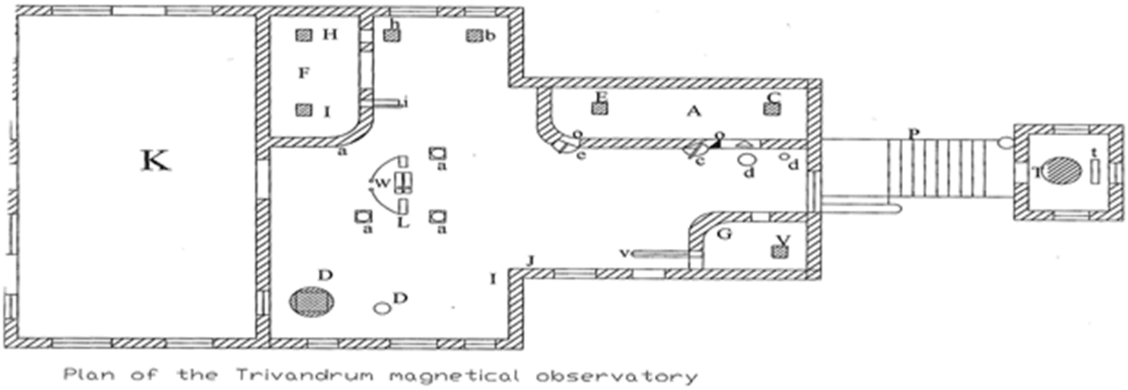

Figure A2. Plan of the Trivandrum magnetic observatory under the supervision of Broun.J.A (after Eapen, 2009).

Fig. A2 depicts the Trivandrum magnetic observatory's layout (Elliot, 1898) during the supervison of Broun in 1850's. Up until 1853, the declinometer (Dr. Lloyd's by Mr. Grubb of Dublin) and its reading telescope d' were located on pillar d. In the little transit house north of the observatory, a transit instrument was positioned on pillar T, slightly out of azimuth, but connected to it via the exposed tunnel P. The transit was so tuned that the declination telescope d' could serve as a collimator to transit when it was inverted on its Ys. The transit instrument was then used to observe stars in order to establish the azimuth of d' \

The pillars' locations with Grubb's bifilar and telescope up until 1853 are displayed at D, D'. Robinson's magnetometer was located in pillar H until its removal in 1859. The plan shows the various modifications made to the observatory in 1853. The bifilar and its telescope were put on the pillars constructed at b and h, while Grubb's declinometer and its telescope were moved from the previously designated pillars to those previously occupied by the latter.

In October 1853, room A was constructed inside the observatory. It was completely enclosed above by a ceiling made of well-joined, one-inch-thick teak planks, covered in plaster like a terraced roof, and had only one opening at Δ, which was closed by a double door that opened inward and outward, as well as at o o small apertures that were sealed by the ivory or glass scales and the object glass of the telescopes. At the end of 1853, two additional instruments built in accordance with Mr. Broun's directions by Mr. Adie of London occupied the pillars C and E in this closed room. The telescopes for these instruments were positioned on the pillars e and e, forming a portion of the well-founded wall.For a new balance magnetometer made for Mr. Broun, also by Mr. Adie of London, a comparable closed room was constructed at G; its telescopes are displayed at V and v.

A third closed room was constructed at F in 1859, with pillars H and I holding various instruments at different times.Adie's second bifilar, which had previously been used at the Agustia Malley Observatory, was installed on pillar H in 1859, while the balance from the same observatory was installed on pillar I. These instruments were identical in construction to those on pillars E and V (Figure 2.4). These two devices' telescopes were housed in pillars h and i. In order to conduct additional observations at the Agustia Observatory, these instruments

were taken out in 1864 and reinstalled in 1865.

During the period 1864-65

Dr. Lamont's small instruments, which were acquired from his Munich observatory earlier , occupied the pillars. H was used for the horizontal force instrument, while I was used for the induction apparatus. The former was used for variations of horizontal force, while the latter was used for vertical force.

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