Indian Journal of Radio & Space Physics
Vol 43, August - October 2014, pp 274-283

Equatorial and mid-latitude ionospheric currents over the Indian region based on 40 years of data at Trivandrum and Alibag

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Received 10 January 2014; revised received and accepted 23 July 2014

Forty years of geomagnetic data obtained from two Indian stations, Trivandrum (TRD) located near the magnetic equator; and Alibag (ABG) located away from the magnetic equator, for the period 1958-1998 are examined to study the daily ranges in H and in the strength of the equatorial electrojet (EEJ) obtained from the differences in the ranges at the two stations. Mean diurnal and seasonal variations in H, averaged over the 40 years are described for the two stations and for EEJ. The annual mean ranges in H show linear increases with sunspot number (Rz) and vary from 65 to 140 nT at TRD, 30 to 70 nT at ABG and from 40 to 72 nT for the EEJ. The rate of increase in H is faster at TRD than at ABG. Seasonal variations show equinoctial maxima for TRD and EEJ during the months of April and October. The range of H at ABG shows a weak secondary maximum during June-July, in addition to maxima during April and October. During the months of June-July, the range of H at ABG is stronger than that of EEJ. The occurrence of the afternoon counter electrojet is highest during low sunspot years and seasonally, during the June solstices.

Keywords: Equatorial electrojet, Equatorial ionosphere
PACS Nos: *94.20.dm; 94.20.dt*

1 Introduction

Graham[1] first described geomagnetic transient variations in London in 1722. By 1880, large amount of data were available regarding the diurnal, seasonal and solar cycle variations of geomagnetic field from about fifty observatories operating through the International Geomagnetic Union initiated by Gauss. Analysis of such global data led Stewart[2] to suggest the existence of a layer of ionized plasma (the ionosphere) and dynamo currents in the upper atmosphere due to heating by the Sun.

A geomagnetic observatory was commissioned at Trivandrum in India in 1841. A standard magnetic observatory recording all the three components of the geomagnetic field at a location near the magnetic equator was established at Kodaikanal in 1902 and was closed down in 1923. The observatory restarted in 1949 and has been providing excellent set of data for geomagnetic and ionospheric research in India.

The result described by Stewart[2] is equivalent to a dynamo action in which the Earth is the magnet, the moving air is the armature and the conducting ionosphere is the winding. Thus the Stewart hypothesis is called the atmospheric (or ionospheric) dynamo theory. Schuster[3] developed the dynamo theory and Chapman[4] gave the final formulation of the theory as it is today.

McNish[5] described that the daily range of the horizontal component of the geomagnetic field at Huancayo was larger than that anywhere in the world. Giesecke (unpublished) from a survey at 14 stations in Peru during September - November 1949 showed that the daily range of H slowly increased from 7°S latitude to a peak at 13°S latitude with a ratio of 2. Chapman[6] interpreted this as being due to a band of intense current flowing eastward during the daytime hours in the E-region of ionosphere and named it the equatorial electrojet (EEJ).

This presented a serious problem as it required a larger EMF for the EEJ. In the ionosphere over the magnetic equator, the daytime eastward electric field and northward geomagnetic field give rise to a vertical Hall current. Due to the finite conductivity in the vertical extent, an upward directed Hall polarization field is set up. This, in turn, generates an eastward Hall current, which is much larger than the eastward Pederson current. Baker & Martyn[7] showed that the enhanced effective conductivity or Cowling conductivity exists only within a narrow belt of ± 3° in dip latitude.

An enhancement of the daily range of H (ΔH) was found in India by Pramanik & Yegnanarayanan[8] and in the African zone by Forbush & Casaverde[9]. Seeing the importance of the equatorial electrojet, a number of observatories at low latitudes were established during the International Geophysical Year (IGY) 1957-58 in the American, Indian and Pacific regions. In India, new observatories were established at Trivandrum (dip latitude 0.6°S), Annamalainagar (dip latitude 2.7°N) and Kodaikanal (dip latitude 1.7°N). Based on IGY data, Rastogi[10] showed that EEJ has a significant longitudinal variation, being strongest at Huancayo (Peru) and weakest at Trivandrum (India).

A close association between EEJ and ionosphere was established by the special type of sporadic-E echoes over the magnetic equator[11]. The occurrence features of the equatorial type of sporadic-E (Esq) were similar to that of EEJ[12-14].

Gouin & Mayaud[15] described occasions of depression in the H field at Addis-Ababa around 0700 and 1500 hrs LT and explained these as a westward current in the E-region. This current system was named as the counter electrojet (CEJ). Similar CEJ events were later reported at Ibadan and Zaria by Hutton & Oyinloye[16] and at Trivandrum by Sastri & Jayakar[17]. Chandra[18] described the disappearance of Esq at Thumba and Kodaikanal in India associated with CEJ.

The major breakthrough in the understanding of the equatorial electrojet in relation to ionospheric irregularities, the interplanetary magnetic field and solar wind parameters came through the observations of spaced receiver HF drift measurements at Thumba, that started in January 1964 and VHF backscatter Doppler radar drift measurements at Jicamarca that started in 1967. The ground measurements of the geomagnetic field are affected by currents at various levels that include the ionospheric currents, induced currents in the sub-surface conducting regions, magnetospheric ring currents, magnetopause currents, tail currents and polar/auroral currents. The ionospheric drifts represent the dynamics of only the reflecting/backscattering region in ionosphere.

Ionospheric drift measurements at Thumba during January 1964 - December 1969 showed drifts to be westward during day and eastward during night[19]. The diurnal, seasonal and latitudinal variations (along with results reported at other latitudes) showed a close similarity with the variations of the geomagnetic H field[20]. Chandra *et al.*[20] showed high correlation between the range in H at Trivandrum and the midday drift speed at Thumba. The correlation improved when the difference in the range at Trivandrum and the range at Alibag (outside electrojet region) was used. Thus, in the absence of electric field measurements one can use electrojet strength as an index of the electric field in ionosphere (E-region). Anderson *et al.*[21] showed quantitative relationship based on the Jicamarca incoherent scatter radar drift observations and magnetometer data at Canete and Piura in Peru. It was, further, demonstrated for the Philippine longitude sector[22]. Denardini *et al.*[23] have recently studied features of CEJ events in Brazilian sector from the difference between ΔH at Sao Luis (equatorial) and Eusebio (away from equator), with ΔH normalized from the mean midnight value of 5 quiet days of the month, and named it as the electrojet ground strength.

On some occasions, drifts were shown to be eastward during day and these events were coincident with the occurrence of CEJ and disappearance of Esq[24]. Fambitakoye *et al.*[25] compared the latitudinal profiles of geomagnetic field from a chain of nine geomagnetic observatories in Africa along 17°E with corresponding ionograms from Fort-Archambault-Sarh (Chad), a station close to the magnetic equator. The disappearance of Esq coincided exactly with the period when ($\Delta H_{equator}$-$\Delta H_{tropics}$) was below the base level even though ΔH at equatorial station was positive.

Rastogi[26] compared the ionospheric drift at Thumba and H field at Kodaikanal and Alibag and showed that disappearance of Esq and CEJ occur when (ΔH_{KOD} - ΔH_{ABG}) is negative but ΔH_{KOD} may be above the night time base level. He suggested that the observed ΔH over the equator is due to the simultaneous flow of two currents in the E-region, an eastward current related to the mid-latitude Sq current and another current at a lower altitude in the electrojet region, flowing eastward during normal electrojet and westward during counter electrojet. At times an eastward electrojet current, weaker than the Sq current can cause a partial counter electrojet and the disappearance of Esq. Rastogi[27] showed that Esq at Huancayo disappears when the drifts at Jicamarca show an eastward E-region or downward F-region drift. Rastogi *et al.*[28] showed that the echoes on the modified range-time intensity (RTI) maps at Jicamarca disappear or reappear precisely at the time when ΔH at an equatorial station minus ΔH at a nonequatorial station is close to zero irrespective of the absolute value of ΔH over the magnetic equator.

During the second phase of ATS-6 program, the Beacon satellite was positioned at 34°E and the NOAA receiver system was operated from Ootacamund in India during October 1975 - July 1976. While studying Beacon receiver data along with ionosonde and geomagnetic data, it was found that during the summer months, especially in July 1976, there was a counter electrojet on almost every day. The daily variations of ΔH at Trivandrum minus ΔH at Alibag, representing ΔH of the equatorial electrojet are shown in Fig. 1 for each day of July 1976. CEJ is noted on 25 of the days and the monthly mean variation of the range in EEJ also shows CEJ in the afternoon. This is the motivation of studying the geomagnetic H data at Trivandrum and Alibag for an extensive period of 1958-1998.

2 Data

The hourly data of the geomagnetic H component at Trivandrum (TRD) and Alibag (ABG) were downloaded from the website of the World Data Center for Geomagnetism, Kyoto, Japan. The deviations in H for a day (0000 to 2300 hrs LT) were obtained by subtracting the data at 0000 hrs LT from the hourly H values of the day. The hourly values of the electrojet strength (EEJ) are obtained by subtracting the hourly values of the deviations in H at ABG from the hourly values of the deviations in H at TRD.

3 Results

The average diurnal variations of ΔH at Trivandrum, ΔH at Alibag and the EEJ strength ΔH_{EEJ} ($\Delta H_{TRD} - \Delta H_{ABG}$), for the entire period 1958-2008 are shown in Fig. 2. ΔH at ABG increases after 0200 hrs LT, reaching a peak value of 44 nT at 1300 hrs LT and thereafter, decreases to a minimum value at 2200 hrs LT. ΔH at TRD starts increasing at 0200 hrs LT, shows very small decrease between 0500 and 0700 hrs LT and then, increases rapidly around 0700 hrs LT, reaching a maximum value of 92 nT around midday and thereafter, decreases to a minimum value at 2200 hrs LT. The electrojet strength ($\Delta H_{TRD} - H_{ABG}$), as a consequence, shows a small negative value at 0600 and 0700 hrs LT, increasing to a maximum value of 51 nT at 1100 hrs LT and then decreasing to the base level by midnight. It must be noted that electrojet strength is slightly larger than Sq at Alibag (ΔH_{ABG}) and peaks about 2 hours earlier. It must be noted that ΔH (dependence on the product of electron density and velocity) peaks around 1100 hrs LT because the electric field at Thumba (E-region drift velocity) peaks around 0900 hrs LT[29], while the

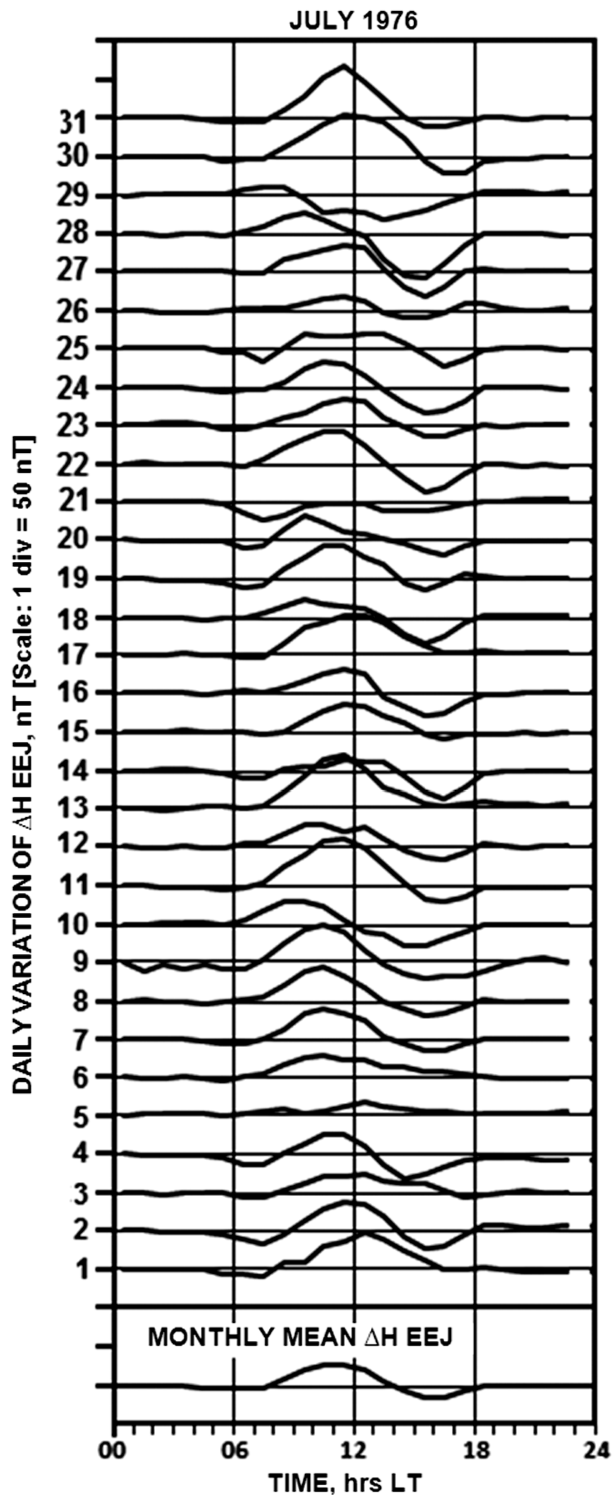

Fig. 1 — Daily variations of EEJ strength (ΔH Trivandrum - ΔH Alibag) for each of the days in July 1976

electron density (NmE) at Thumba peaks around midday[30]. Asymmetries in the variations of ΔH at low-latitudes in the afternoon and night hours is discussed earlier[31,32].

Figure 3 shows the yearly mean diurnal variations of ΔH_{TRD}, ΔH_{ABG} and ΔH_{EEJ} during years of low and high sunspot activity. During any of the low sunspot years, the diurnal variations are fairly symmetrical about noon. The range of ΔH_{EEJ} is slightly larger than that of ΔH_{ABG} and the peak occurs two hours earlier than that of ΔH_{ABG}. During high sunspot years, there is tendency of CEJ around sunrise.

Figure 4 shows the year-to-year variations of the yearly annual mean diurnal range of ΔH at TRD, ABG and EEJ, respectively. Year-to-year variation of the annual mean sunspot number is also shown in the figure. A close relation between the three ranges and the sunspot number is evident. Thus, both the mid latitude Sq and equatorial current strength increases with solar activity.

The dependence of the annual mean diurnal range of ΔH at TRD and ABG and EEJ with the corresponding annual mean sunspot number is shown in Fig. 5. A linear relation exists between the three ranges in H with the sunspot number (Rz). A straight line fit is obtained for all the three ranges, representing, R_H, the range as a function of Rz.

$$R_H = a + b\,Rz \qquad \ldots (1)$$

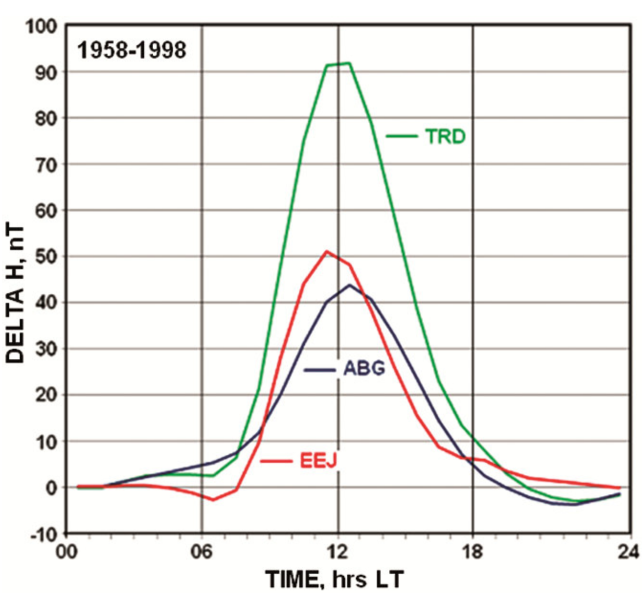

Fig. 2 — Yearly averaged daily variations of ΔH at Trivandrum, ΔH at Alibag and EEJ strength averaged over the forty years period 1958-1998

In Eq. (1), intercept ‘a’ represents the range for an Rz value of zero and b, the slope, represents the rate of increase with sunspot number Rz. The coefficients a, b are also listed in Table 1. The values of ‘a’ are 62.8 nT for TRD, 27.0 nT for ABG and 37.3 nT for EEJ. The slopes are 0.4145 for TRD, 0.2295 for ABG and 0.1902 for EEJ. The increase of range in ΔH with sunspot number is slightly faster for ABG than for EEJ.

To study the seasonal variation, monthly mean diurnal range of H at TRD, ABG and of EEJ are averaged for the entire period and shown in Fig. 6. As known, the range in H shows equinoctial maxima during April and October at TRD. The seasonal variation of range in H at ABG shows weak equinoctial maxima during March and October and in addition, a weaker maximum during summer months of June-July. These are in accordance with the earlier findings of James & Rastogi[33]. The EEJ range clearly shows equinoctial maxima during April and October. It is to be noted that ΔH_{EEJ} is smaller than ΔH_{ABG} during the months of June-July and probably during winter months of November-December. During the other months, the electrojet current is larger than the mid-latitude Sq current.

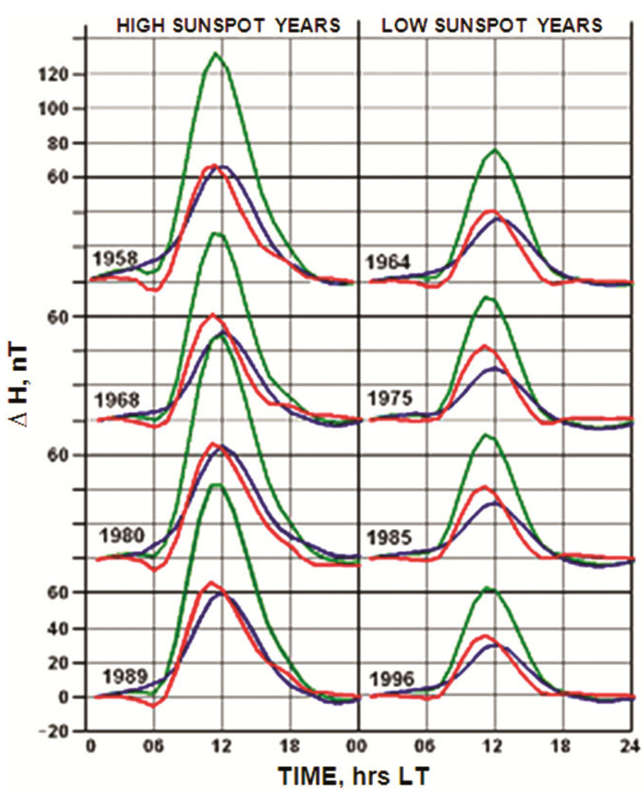

Fig. 3 — Yearly averaged daily variations of ΔH at Trivandrum, ΔH at Alibag and EEJ strength for selected high and low sunspot years during the period 1958-1998

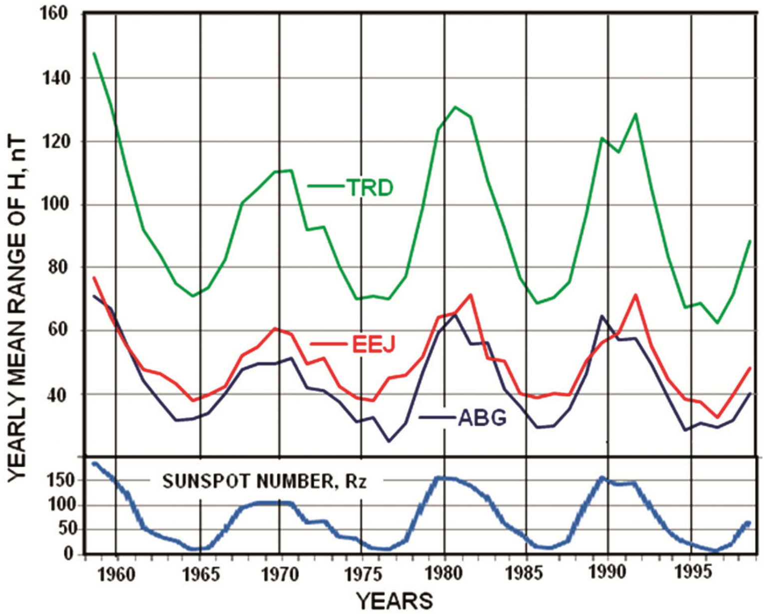

Fig. 4 — Relation between the yearly average ΔH at Trivandrum, ΔH at Alibag and EEJ strength with yearly average sunspot number based on 40 years of data over 1958-1998

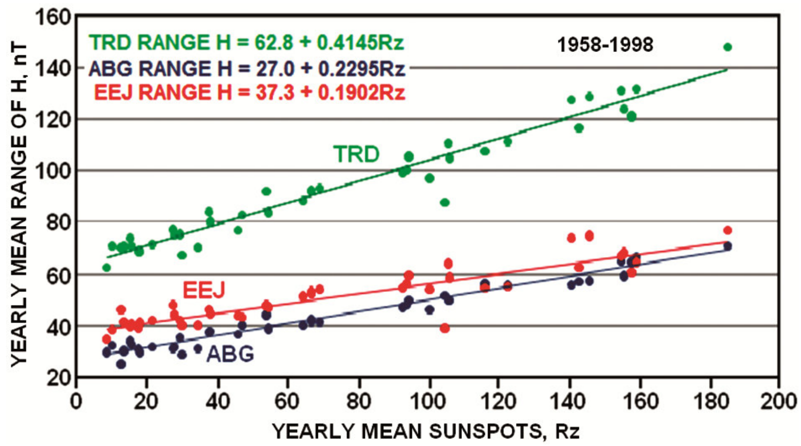

Fig. 5 — Variations of the maximum yearly mean ΔH at Trivandrum, ΔH at Alibag and EEJ strength and of yearly mean sunspot number Rz over the period 1958-1998

Table 1 — Coefficients a, b representing the linear sunspot dependence of the ranges in H

	Annual	March	June	January
Coefficient a, nT				
TRD	62.8	81.2	57.6	54.5
ABG	27.0	35.6	30.9	24.5
EEJ	37.3	45.6	27.6	30.0
Coefficient b				
TRD	0.4145	0.512	0.355	0.339
ABG	0.2295	0.256	0.206	0.188
EEJ	0.1902	0.256	0.135	0.150
Correlation coefficient				
TRD		0.93	0.87	0.85
ABG		0.85	0.89	0.79
EEJ		0.95	0.70	0.56

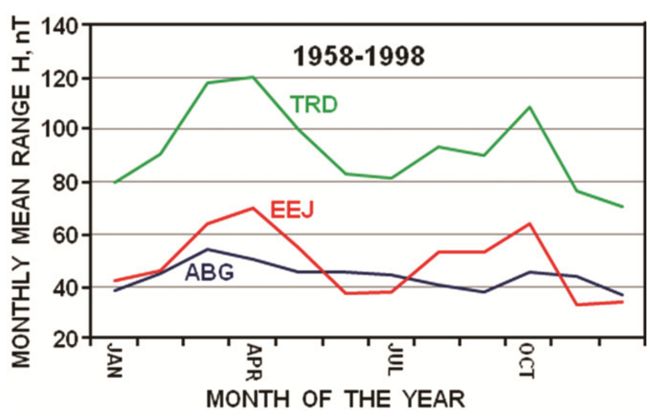

Fig. 6 — Month-to-month variations of the mean ΔH at Trivandrum, ΔH at Alibag and EEJ strength averaged over the period 1958-1998

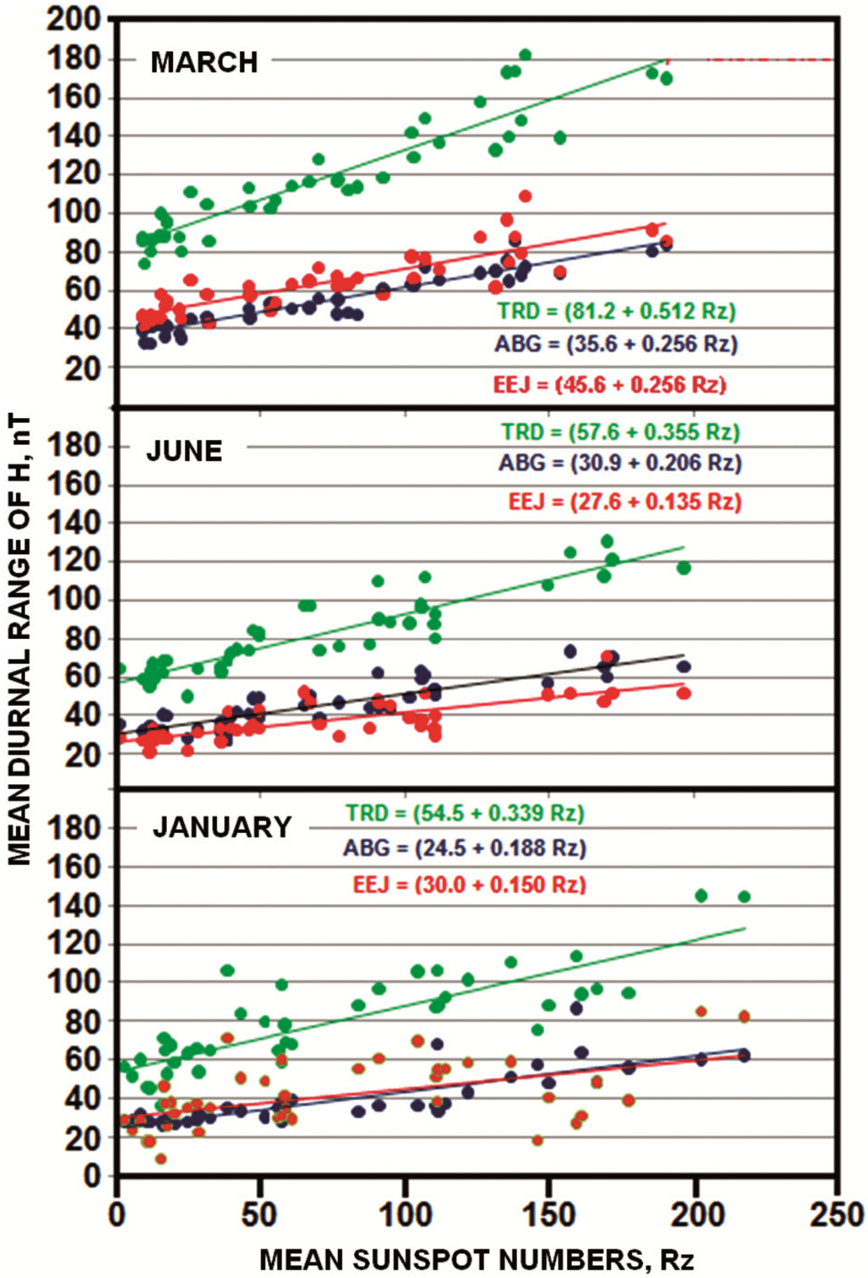

Fig. 7 — Variations of the monthly mean ΔH at Trivandrum, ΔH at Alibag and EEJ strength for each month, averaged over the period 1958-1998

To study the seasonal dependence of solar cycle related changes on the range in H at TRD, ABG and in EEJ variations, monthly mean maximum values are plotted as a function of the monthly mean Rz for three representative months *viz.* March, June and January. The scatter plots and the best fit lines are shown in Fig. 7. The coefficients ‘a’ and ‘b’ of the best-fit lines, with ‘a’ representing the range for an Rz value of zero and b representing the slope are also marked in Fig. 7 and listed in Table 1. For the range in H at TRD the values of ‘a’ are 81.2, 57.6 and 54.5 nT for the months of March, June and January, respectively. For the range of H at ABG the values are 35.6, 30.9 and 24.5 nT for the months of March, June and January, respectively. Thus, both at TRD and ABG, the values are largest during March and smallest during January. For the range EEJ, the values are 45.6, 27.6 and 30.0 nT for months of March, June and January, respectively indicating that electrojet strength is largest during March and smallest during June. The values of the slopes for any of the three months are larger for the range of H at TRD than for the range of H at ABG. For the range of EEJ, the slopes are largest for March and smallest for June. Seasonally, the slope values for the ranges at TRD and ABG are largest for March, smaller for June and smallest for January. The range in EEJ is largest in March and smallest in June. The correlation values of the relationship listed in Table 1 are between 0.85 and 0.95 for March, between 0.70 and 0.89 for June, and between 0.56 and 0.85 for January. Thus, the correlation values are highest during the month of March and lowest during January for each of the three ranges.

These features of the seasonal differences are clearly shown in Fig. 8, where the monthly mean diurnal variations of ΔH at TRD, ABG and ΔH_{EEJ} for each month of the year and averaged over the entire period of 1958-1998 are shown. ΔH_{EEJ} is much larger than ΔH_{ABG} during the equinoctial months and during May and August. ΔH_{EEJ} is slightly larger than ΔH_{ABG} during January and February but is smaller than ΔH_{ABG} during June, July, November and December.

Figure 9 shows the monthly mean diurnal variations of ΔH_{TRD}, ΔH_{ABG} and ΔH_{EEJ} for each month of the year 1976. The maximum range in H varies from 50 to 90 nT at TRD and from 20 to 35 nT at ABG. The maximum in EEJ strength varies from 30 to 70 nT. ΔH_{EEJ} is seen larger than ΔH_{ABG} for all months except January, June, July and November.

Looking at the phenomenon of weak electrojet during June and July as seen from the diurnal variation of ΔH_{EEJ} for each day of July 1976 in Fig. 1, it is interesting to note that there was counter electrojet on 25 days in the afternoon hours with a maximum of ΔH_{EEJ} in the pre-noon hours. Figure 10 shows the monthly mean diurnal variation of ΔH_{ABG} and ΔH_{EEJ} during the months of July and January of few low sunspot years and few high sunspot years. During July, the ΔH_{EEJ} is, generally, lower than ΔH_{ABG} for any of the low or high sunspot years. For the month of January, the effect is not the same for different years.

4 Discussion

Solar cycle dependence of the daily range in H at equatorial electrojet stations has been studied earlier. Misra *et al.*[34] reported coefficients a, b (sunspot sensitivity index) of 89 nT and 0.5607, respectively for the range in H at Huancayo based on data of the years 1940-45. Rastogi & Iyer[31] examined geomagnetic data at Trivandrum (TRD), Kodaikanal (KDK, dip 3.4°N), Annamalainagar (ANM) and Alibag (ABG) in India for 1958-1972 to study solar cycle dependence. The values of the coefficient ‘a’ were 67, 63, 51 and 28 nT, respectively at the four stations. The values of the coefficient ‘b’ were 0.40, 0.35, 0.31 and 0.21, respectively for the four stations. Thus, the values of both a, b decreased with increasing dip latitude. Solar cycle dependence of the daily range in H at Kodaikanal in India was later studied by Rastogi[35] based on data from 1954 to 1968. The coefficients ‘a’, ‘b’ were 60.1 nT and 0.3606, respectively. Thus, the values of the coefficients ‘b’ (0.4145 and 0.2295) obtained from the present work based on 40 years of geomagnetic data at TRD and ABG are slightly higher than the values of 0.40 and 0.21 obtained from the data during 1958-1972. The

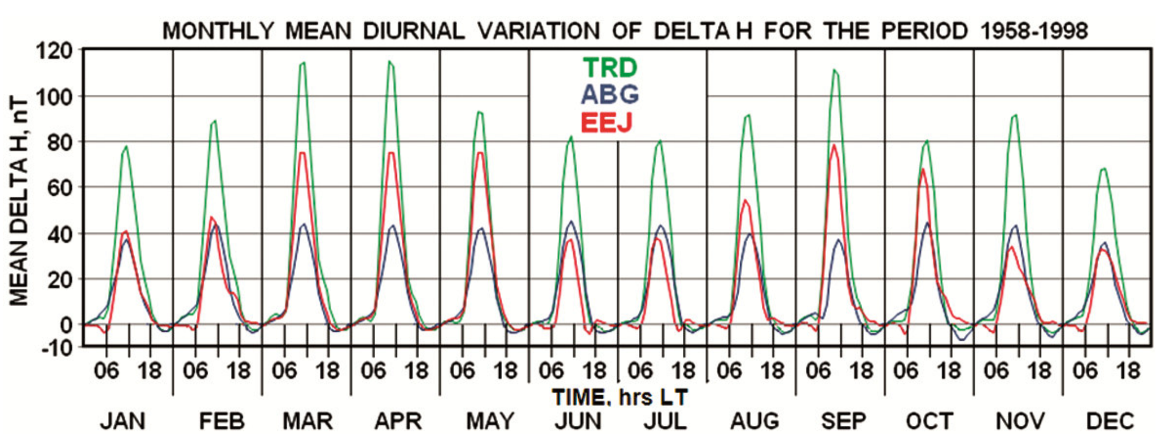

Fig. 8 — Monthly mean diurnal variations of ΔH at Trivandrum, ΔH at Alibag and EEJ strength, averaged over the period 1958-1998 for each month

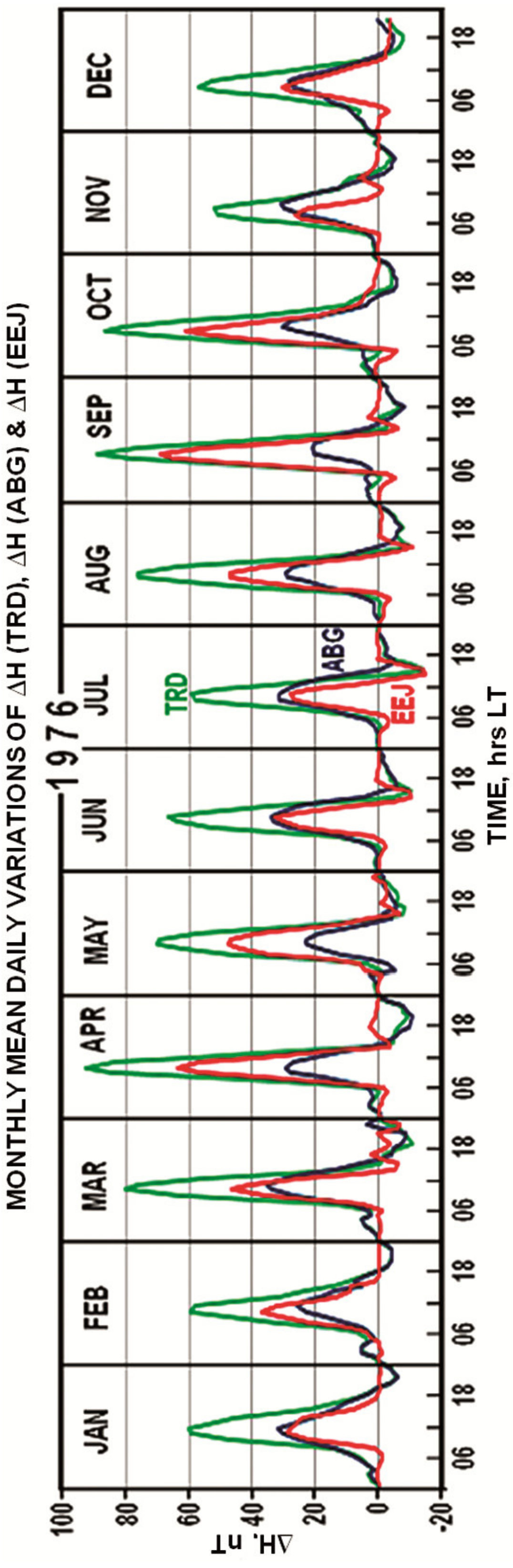

Fig. 9—Monthly mean daily variations of ΔH at Trivandrum, ΔH at Alibag and EEJ strength for each month of the year 1976

solar cycle dependence of the electrojet strength, derived from the difference of the ranges at TRD and ABG, is done for the first time.

Based on data from 1958 to 1965 at KDK and ABG, Rastogi[36] compared the solar cycle and seasonal variations of the range in H at the two stations and compared with the electron density variations at KDK and Ahmedabad (near to ABG). The seasonal variation of NmE showed equinoctial maxima at KDK but summer maximum at Ahmedabad. The daily range of the H depends both on the electric field and conductivity. The ionospheric drift measurements at Thumba (dependent on electric field) show equinoctial maxima and lowest values in June-July[20]. Therefore, near magnetic equator both conductivity (dependent on NmE) and electric field show equinoctial maxima so clear equinoctial maxima are seen in the range in H. At ABG, electron density, hence, conductivity peaks in summer; therefore, another maximum in June-July is noticed. Ionospheric drift measurements from Thumba and later from Tiruchirapalli, a station located near the edge of the equatorial electrojet in India showed, in addition to the lower drift values in summer, an eastward shift of the steady component of drift by about 20 ms^{-1} (Ref. 37). This appears to be the reason for more frequent appearance of the counter electrojet in summer.

5 Summary

Forty years of geomagnetic data, from 1958 to 1998, at Trivandrum near magnetic equator and Alibag, a low latitude station away from the magnetic equator are examined to study the daily ranges in H at the two stations and in the electrojet strength, as determined by the difference in the ranges at Trivandrum and Alibag.

The annual mean ranges in H show linear relations with sunspot number, Rz. However, the rate of increase is higher at Trivandrum than at Alibag. Seasonal variations show equinoctial maxima for TRD and EEJ during the months of April and October. The range of H at ABG shows, in addition to maxima during April and October, weak secondary maximum during June-July. The maximum of NmE in June-July at tropical latitudes appears to be the reason for this.

During the months of June-July, the range of H at ABG is larger than that of EEJ. The occurrence of the afternoon counter electrojet is highest during low sunspot years and seasonally during June solstices.

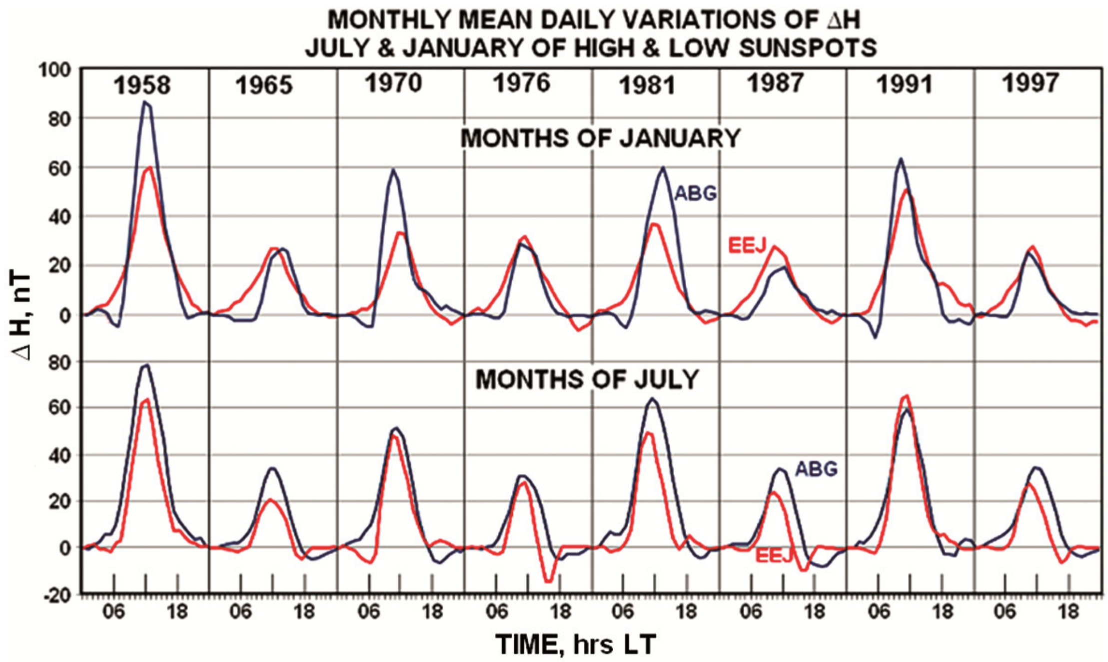

Fig. 10—Monthly mean daily variations of ΔH at Alibag and EEJ strength for selected high and low sunspot years during the months of January and July

Acknowledgement

Thanks are due to Director, Physical Research Laboratory, Ahmedabad for the facilities provided to the authors. Thanks are also due to the World Data Center for Geomagnetism, Kyoto, Japan for the geomagnetic data at Trivandrum and Alibag.

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