J. Ind. Geophys. Union (January 2016)
Special Volume-2/ 2016 pp: 120-126

Secular Variation Studies in the Indian Region – Revisited

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ABSTRACT
This paper provides a retrospective view of some studies on regional secular variation carried out at the Hyderabad Magnetic Observatory, taking into consideration presently available data and models along with an evaluation of the previous results in view of more recent ones. The long term features like quasi-periodic secular variation of horizontal and vertical components, as seen in the annual means of ABG(1850-1975) has been borne out by other studies reporting oscillatory movement based on IGRF models and smoothed spline fitting. Studies of repeat station data over India, as well, have confirmed features of secular variation of D and Z. Ground surveys conducted in the region of the dip equator, also provide confirmation of the rates of migration of the dip equator.

The updated plots of annual means from 1955 to 2010, confirm some important observations of the earlier studies: rapid migration of the dip equator in Indian region that is not reflected in nearby longitudes (East Africa and South-east Asia), and the estimated rates of migration. Other studies have corroborated inferences of quasi-periodic movement of the dip equator, and differences observed in secular change of Declination over Indian region. The predicted northward quasi-periodic oscillation of the dip equator, from 2005, however, has not occurred yet, as seen from the annual means, and from ground surveys.

Keywords: Calibration of observatory magnetometers, Equatorial vertical field measurements, Experiments on magnetometers

INTRODUCTION

This paper provides a retrospective evaluation of early results on secular variation in the Indian region. Three papers that were published during 1977-1992, (*Srivastava and Abbas, 1977, 1984: Srivastava, 1992*), using available information at that time, are discussed here. The results and inferences made are revisited, and examined in the light of the results of subsequent published work.

Recapitulating the results, Srivastava and Abbas (*1977*) used a long series of ABG annual means (Colaba and Alibag data series 1850-1975) to obtain smoothed secular variation trends for the components H, D, and Z by means of a smooth 5th degree polynomial fit to the data. Some of these results are reproduced in Figure 1. A smooth increase (1850-1890) and slight decrease up to 1920, is seen in H (Figure 1a), followed by more rapid increase from 1920 to 1960 and a decrease thereafter. Annual means of Z, show a smooth increase from 1850 to 1930, showing a slow decrease upto 1970 and a slight increase upto 1975 (Figure 1b). Secular change of Declination (D) annual means indicate a smooth increase (easterly) at ABG up to 1880, then a change to decreasing (westerly) declination up to 1960 (Figure 1c). Declination was zero at ABG in 1930. The agonic line passes through Central India, as evident in IGRF charts.The residuals from the smoothed fit to H and Z plots(Figure 1d), were seen to have an oscillatory quasi-periodic variation, 1850-1960 in both H and Z and that they are out of phase with each other. The authors, also inferred a corresponding movement of the dip equator, that is borne out by later studies, in the period 1960-2005. Secular variation rates of D, between 1900-1950, were high at ABG~3.6′/yr (Gulatee, 1954).However, on comparison of annual means at six observatories the authors found that after 1960, secular variation rates for D were found to be slightly less at ABG and HYB, which are near the Agonic line, compared to other observatories in peninsular India.

Using annual means for 1960-1975, of six magnetic observatories, some secular variation trends were obtained by Srivastava and Abbas (*1977*). These are replicated in the updated plots up to 2010, made in the next section(Figure 2). The notable observations were: that H component decreases at all observatories after 1965 (Figure 2a). There is a change in sign of variation of Z-component, but at different years, at each observatory between 1962-1968 (Figure 2c). Secular variation rates for D were found to be slightly less at ABG and HYB, which are near the Agonic line, compared to other observatories in peninsular India (Figure 2b). Table I lists the observatories examined in this study, along with their co-ordinates.

Srivastava (1992), obtained Sq (H),(Z) amplitudes over closely spaced stations, from a magnetometer array study in South India and observed that the line of maximum Sq(H), and of zero dip, are parallel to each other both from the array study and earlier ground survey (*IIG et al, 1972*). He also estimated an increasing gradient of secular change of Z, from 1 km/yr up to 7 km/yr, in 1980, in the Indian region, and predicted the trend of migration of the dip

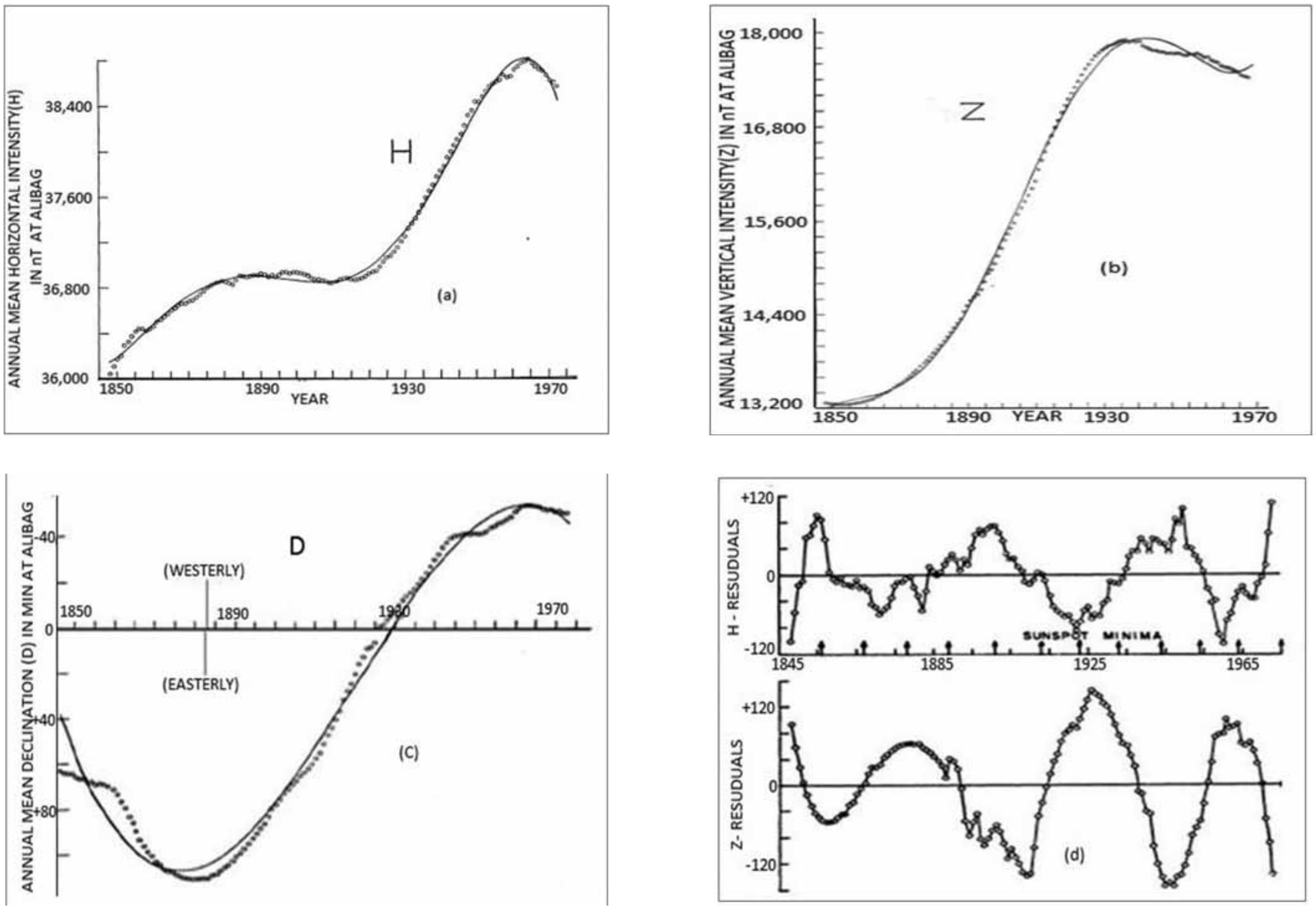

Figure 1. Composite figure showing secular variation in (a) H, (b) Z, (c) D components from annual means of Colaba-Alibag (1850-1975)together with the fit of a smooth polynomial and (d) residuals in H and Z, obtained by subtracting the smoothed trend, showing quasi-periodic variation (reproduced from Srivastava and Abbas, 1977).

equator, further south of the Indian peninsula up to 2005 and noted a corresponding northward movement of the dip equator at Huancayo observatory (285^{o} longitude) in comparison (*Golovkov et al., 1983*), in the American sector.

Srivastava and Abbas (*1984*) examined annual means from Indian observatories for signs of the geomagnetic jerk of 1969, (*LeMouel, et al, 1982*). This jerk was not seen in the annual means of declination at Indian observatories.

Subsequent work on secular variation in the Indian region have been presented by several authors, their inferences taking into account the availability/access to latest IGRF models and techniques. Their results refine global and regional features of secular variation, and estimation of migration of the dip equator and have largely corroborated the earlier findings. One of the earliest studies (*Arora et al, 1983*) focuses on the estimation of polynomial fit to a network of repeat station measurements and observatory data in India at 3 epochs,(1960-1975)and comparison of region secular variation patterns with IGRF (1965.0 – 1975.0).The rates of change have also been estimated. The most significant feature is the rapid change in rate of secular change in D, over the Indian peninsula. Studies on migration of the dip equator, estimated directly from ground surveys conducted approximately every 10 years (*IIG, et al,1971;Sanker Narayan and Ramanujachary 1971;Murty et al 1983; Rangarajan and Deka, 1991;Paramasivan et al, 1999; Deka et al 2005*), have delineated the position of the dip equator, along traverses in southern peninsular India and confirmed its southward migration until 2000. In the last survey in 2003, it was inferred that the equator was situated south of the landmass of the Indian peninsula. Deka et al, (*2005*), report that the movement of the dip equator at 77.5 °E longitude, along the centre of the Indian peninsula, over past hundred years, as derived from IGRF values, and the migration determined from ground surveys over 30 years (1971-2003), follow a similar trend. Oscillations of the position of the dip equator, have also been extracted from IGRF values (1910-1980) (*Rangarajan and Baretto, 2000*). The oscillatory southward movement (1900-1930)

Table 1. Co-ordinates of the magnetic observatories used in this analysis and availability of annual means.

STATION	Abbreviations	Geographic		Data Length (in Years)	Data Gaps
		Lat.	Long.		
TRIVANDRUM	TRD	8° 29' N	76° 57' E	1957-1999	
TIRUNELVELI	TIR	8° 42' N	77°48' E	2000-2010	
ETTAIYAPURAM	ETT	9° 10' N	78° 01' E	1980-2000	
KODAIKANAL	KOD	10° 14' N	77° 28' E	1955-2004	
ANNAMALAINAGAR	ANN	11° 22' N	79° 41' E	1957-1993	
PONDICHERRY	PON	11° 55' N	79° 55' E	1994-2010	
HYDERABAD	HYB	17° 25' N	78° 33' E	1965-2010	
ALIBAG	ABG	18° 37' N	72° 52' E	1955-2010	
SABHAWALA	SAB	30° 22' N	77° 48' E	1965-2010	
MUNTINLUPA	MUT	14° 22' N	121° 1' E	1955-2002	1989-1994,1997 &1999
ADDIS ABABA	AAE	9° 2' N	38° 46' E	1958-2010	

followed by northward movement (1930-1975) and again southward movement (1975-2005) clearly demonstrates a quasi-periodic feature.

PRESENT DATA SETS

In the present work, we have extended the datasets of annual means of six magnetic observatories, in India up to 2010. As in the work of Srivastava and Abbas (*1977*), we compare this regional trend against trends in Africa (AAE) and south-east Asia (MUT). Location, and details of all the observatories is given in Table I.

The annual means series for TRD, has been extended using the proximate observatory TIR, from 2000 and series for ANN is extended using annual means of PON. We compare this data series 1955-2010, against improved IGRF models and subsequent published work and evaluate the inferences made in the earlier papers, with knowledge presently available.

Plots of annual means (1955-2010) at all six Indian observatories and AAE(blue) and MUT(yellow) are presented in Figure 2a,b,c. Coloured lines show trends of annual means and dots of same colour show IGRF value at 5-year intervals at each observatory. Appropriate constant offsets have been added to mean value series of each observatory in order to bring all the plots into the same range. Also, the corresponding IGRF values at 5-year intervals have been shifted by known amounts to coincide/ align with the annual means shown as continuous lines for each observatory. In Figure 2a, the annual means of H-field at all six observatories show similar trends: slow decrease from 1965 to 1988 and increase thereafter. This decrease is in agreement with the plots of ABG in Figure 1a (*Srivastava and Abbas, 1977*).The rate of increase (1988-2010) is faster at the southern observatories ANN-PON, KOD, TRD-TIR compared to SAB, ABG and HYB. The plots of AAE(East Africa) and MUT(Philippines) in the same figure indicate similarity between AAE and the Indian region. In contrast secular variation at MUT is in opposite phase, showing increase up to 1989, and decrease thereafter.

Figure 2(b) shows plot of annual means of Declination along with IGRF values for the period (1955-2010). It is noted that there is a steady decrease in D (westward declination at Indian observatories) from 1965. SAB shows slightly different trend compared to others, with marked change between 1990-2000. This rapid change in D variation, on either side of the agonic line passing through central India, is also reflected in the IGRF models, for the Indian region (*http://www.ngdc.noaa.gov/IAGA/vmod/igrf_old_models.html*) and also pointed out from theisolines derived from repeat station data (*Arora et al, 1983*). Secular variation trends for D are similar at all peninsular observatories in Indian region. After 1960, there is slight divergence between trend at ABG and HYB as seen from IGRF values. At the three (TRD, ANN & KOD) southern observatories, similar trends are seen. The anomalous trends in rate of change of D, noted by Gulatee (*1954*) and Srivastava and Abbas (*1977*), are not seen in this data set. Secular variation at SAB is in the opposite trend showing gradual increase. In contrast, trends seen at AAE (East Africa) and MUT (East Asia) vary widely.

Figure 2(c) shows plots of annual means of Z variation at all six Indian observatories as well as those from AAE (Africa) and MUT (Asia). Z variations show a slight decrease from 1955 to 1975 and also at AAE & MUT. AAE shows a similar trend as ABG and HYB, the rate of increase is slightly less. MUT, on the other hand shows little variation up to 1981, and gradual increase thereafter. Rate of increase is more rapid from 1995 at all Indian observatories.

The Z annual mean values at 10 year intervals, for the four observatories in South India (TRD-TIR, ETT, KOD,

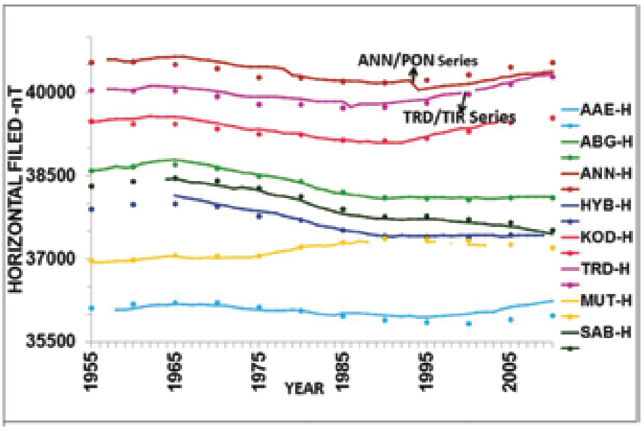

Figure 2a. Plots of annual means (1960-2010) at all 6 Indian observatories and AAE(blue) and MUT(yellow) of Horizontal intensity, along with IGRF values shown as dots..

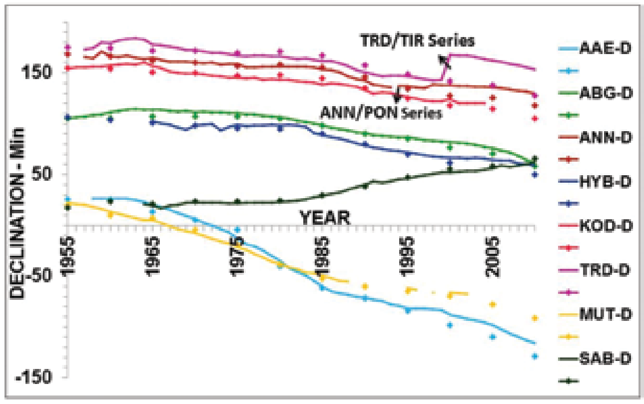

Figure 2b. Plots of annual means (1960-2010) at all 6 Indian observatories and AAE(blue) and MUT(yellow) of Declination, along with IGRF values shown as dots..

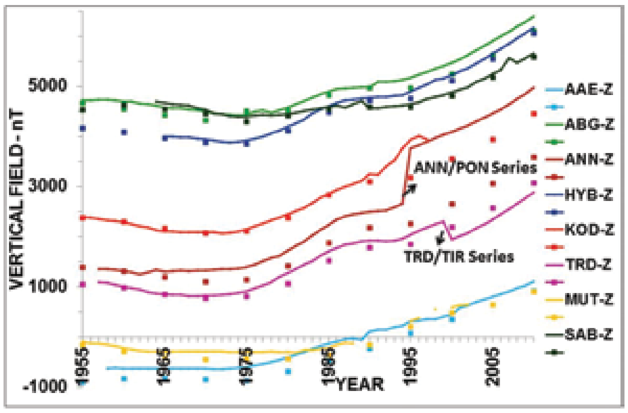

Figure 2c: Plots of annual means (1960-2010) at all 6 Indian observatories and AAE(blue) and MUT(yellow) of Vertical intensity, along with IGRF values shown as dots

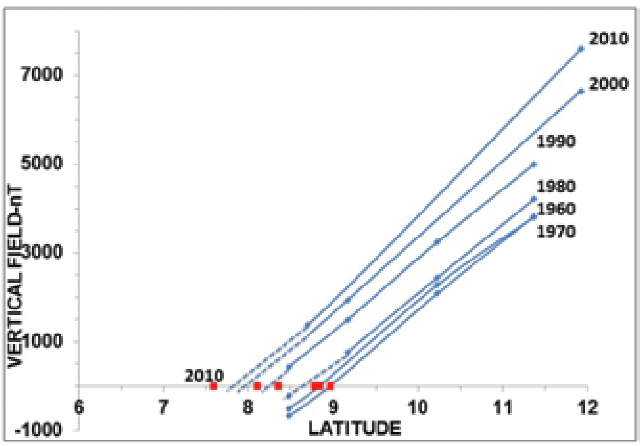

Figure 2 (d). Position of the dip equator (1960 -2010) as deduced from plots of annual means of Z,at observatories in the Indian region, at 10 year intervals. The location of the dip equator derived from IGRF of the same epoch is shown (red squares) at the latitude 77°E.

ANN-PON) are plotted against their respective latitudes, in Figure 2(d). The position of the dip equator, as obtained from observatory annual means is evident from these plots for epochs 1970.0 and 1980.0. Upto 1990, the dip equator, as delineated from observatory data and ground surveys, differed slightly from IGRF positions (*Deka et al, 2005*). After 1990, we can only extrapolate the location of the dip equator from observatory data, in the ocean south of the Indian peninsula. For the next 3 epochs, the position of the dip equator is found by extending the trend in decreasing Z, to find the latitude of the inferred location of the dip equator. With present data, we have projected the latitude at which Z would become zero, along the 77° longitude, based on the rate of increase of Z values at the four observatories in the Indian peninsula. The positions of the dip equator at 77° E longitude was obtained from IGRF and shown along the latitude axis, in red. The positions show a good fit with observatory data, except for the extrapolated values for 2010 and 2015. This plot shows the decadal change to be large between 1990-2010 compared to earlier period. From the annual mean values of Z from several low latitude observatories of the world for 1945 to1995, Rangarajan (*1994*) showed that at most of the observatories the secular trend in Z is consistent with the direction of the meandering dip equator.

DISCUSSION

Preliminary trends inferred up to 1975 (*Srivastava and Abbas, 1977*), and separately in repeat station data (1965-1975) by Arora et al, (*1983*), continue in the present data set, shown here (1955-2010). The regional differences noted between Indian region when compared with East Africa and Asia, also continue up to 2010. These results are also corroborated by values obtained from IGRF models over the period.

Rates of migration of dip equator

The differences in dip equator migration at different longitudes, was inferred by comparing annual means in the Indian region with observatories in Africa and East Asia by Srivastava (*1992*). The extended series (1955-2010) is presented here. Similar observations were extracted from IGRF values (1900.0-2000.0) and discussed in detail by Rangarajan & Baretto (*2000*). The extended series of annual means (1960-2010) plotted here, also reiterate the differences between Indian, African and East Asian sectors.

The long series of annual means of ABG (1850-1975) is a unique dataset and provides independent corroboration of secular variation models. The features noted by Srivastava and Abbas (*1977*), have thus been subsequently corroborated (*Baretto, 1987;Rangarajan and Baretto, 2000 and Deka et al, 2005*). Locally, from direct ground surveys, trace of the dip equator in India (76-78° E longitude) was plotted in 1971, 1983,1991 and 2003 (*IIG et al, 1972; Murty et al, 1984; Paramasivan et al 1999; Deka,et al 2005*) describing the migration up to 1991, after which the dip equator could not be located on the Indian peninsula.

Most significant is the quasi-periodic variation of Z, and migration of the dip equator, over a 80-year cycle. It was also inferred from these results that southward migration would reverse around 2005 (*Srivastava, 1992; Deka et al, 2005*). The dip equator migrated southwards up to 1925 and then reversed to a northward direction smoothly. After 1970, a southward migration is again noticed. Between 1945 and 1980, it is seen that the dip equator was confined to a narrow latitude belt between 8.5° and 9°N (*Deka et al, 2005*) and migrated southward rapidly (1990-2010) subsequently.

The quasi-periodic movement of the dip equator, postulated by Srivastava, (*1992*), predicts a northward movement after 2005. Present results from annual means plotted up to 2010 and values available up to 2014(quasi-definitive)and IGRF values up to 2015, show that southward migration of the dip equator continues and has not changed direction in 2005, as suggested earlier (*Srivastava, 1992; Deka et al, 2005*). The rate of southward migration has also increased after 1990. Differences are seen between the inferred location the dip equator for epochs between 1970-2010, and location derived from IGRF models of the same epochs. There is no evidence that northward migration of the dip equator has commenced.

Quasi-periodicity in secular variation

In Srivastava and Abbas (*1977*), annual means were compared against available values from the Survey of India charts of isolines (*Chatterjee, 1970; Gulatee, 1954*) and migration of the dip equator was further confirmed by a ground magnetic survey in 1971(*IIG et al, 1972*). The residuals derived from ABG data from 1910-1970 in that study, showed an oscillatory behavior of Z and also in H, but directly opposite in phase. From survey results collated over 60 years, it was inferred that the northward migration of the dip equator continued to occur during 1927-1967, and ground surveys confirmed its position near 9°N latitude in 1971. These observations together with the residuals obtained from the secular change at ABG, led to the inference that the migration is probably cyclic in nature and would complete its southward movement in further 40 years. Trends obtained from the long series of annual means at ABG, could only be compared against early IGRF models, available from 1900 (Rangarajan and Barreto, 2000), wherein an oscillatory movement of the dip equator (and inferred change in Z), was obtained for the Indian sector (longitude 70-80°E). This appears to have a period of nearly 80 years. When compared with the results of Srviastava and Abbas (*1977*), in Figure 1 above, some questions arise. The plot Figure 1(d), shows a maxima before 1845, and at 1880, 1925, and 1965. As presented in that paper, they indicate a periodicity (~40 years), but this has been subsequently attributed to 80yr Geissburg Cycle (*Bhardwaj & Subba Rao, 2013*). It must be acknowledged that the method of obtaining these residual curves using a polynomial fit to the 1850-1970 annual means series, is probably subjective. However, quasi-periodic structure of secular variation (~50 yr) has also been identified in the region (*Rotanova et al, 2003*).

Secular variation of D

The large changes in rate of secular variation in D, over the Indian region have been corroborated by later studies (*Arora et al, 1983; Bhardwaj & Subba Rao, 2013*). The rapid changes in D, taking place in the vicinity of the agonic line that passes through central India, has also been documented in IGRF maps. The more westerly change in declination has been documented earlier and compared with IGRF models (*Arora et al, 1981; Bhardwaj and Subba Rao, 2013*), wherein, ABG and HYB, along with SAB, in the Himalayan foothills show decreasing declination. A single trend of westward secular change is seen over the entire peninsula. The rate of change is about 0.25'/yr. The same decreasing trend is seen more sharply at AAE and MUT in our plot (Figure 2b), where the rates at AAE and MUT is about 0.35'/yr. Between 1980 and 2000, a slightly larger change in seen at ABG, compared to HYB. Similar trends are seen at the southern observatories ANN-PON, KOD, TRD-TIR. Rapid changes in D variation were reported (*Gulatee, 1954; Arora et al, 1983*) and is also evident in rates of secular change in IGRF models.

COMPARISON WITH GLOBAL SECULAR VARIATION

An attempt to identify the global geomagnetic jerk of 1969 (*Le Mouel, et al, 1982*) was made by Srivastava and Abbas, (*1984*). The signature of the geomagnetic jerk of 1969, could not be detected in regional secular variation trends in the Indian region. The residuals in first and second derivatives of secular variation, were large in this region (*McLeod, 1989*). However, wavelet analysis of the jerk, showed some regional differences in phase of the Jerk (*Alexandrescu et al, 1996*) that supported the original observations. Further global analysis of first and second derivatives of secular variation in the Indian and African regions delineated separate trends, one for Indian region, correlating well with the East African region, and that of West Africa with Europe (*Nandini Nagarajan, 1992*). Wavelet analysis of secular variation also indicated 60-yr periodicity, prominent over East Africa and Indian peninsular (*Rotanova et al, 2003*).

CONCLUSION

Cumulative results from successive IGRF estimates of migration of the dip equator, conclusively report that an oscillatory movement with periodicity of 80 years, is seen in the Indian region. This is partially corroborated by repeated ground surveys to determine the position of the dip equator, in India over the past 50 years. Early indications of this migratory, as well as oscillatory behaviour could be shown from the residual variation of annual means from the annual means of a single observatory (Colaba-Alibag). Further, observations made from analogue information, solely from reports of observatory data from other stations, also provided evidence that this migration is clearly seen in some longitude zones while absent at others. Observations of the secular change of declination made from repeat surveys and observatory means (1950-1975) indicating rapid changes over the Indian peninsula have been corroborated by subsequent IGRF models.

Regional estimates of secular variation from six magnetic observatories, in the Indian region, correspond well with global models. However, in respect of geomagnetic jerks, early indications of regional differences were also provided from this data series. These variations have been corroborated by subsequent analyses.

The trends found in a long, extremely valuable, series of annual means from a single station, as well as first results from 15 years of means from five other Indian observatories, have been corroborated by global models and subsequent analyses. The significant result of extending these series, in the present study, has been that the oscillatory migration of the dip equator, has not reversed in 2005, as hypothesised.

ACKNOWLEDGEMENTS

Authors thank LOC of IAGA XVI Workshop on Magnetic Observatory practice for support to attend the Workshop, and the invitation to contribute to the this special volume. We thank the reviewers for helpful comments that have expanded the discussion. Support of the Ministry of Earth Sciences(MoES/P.O.(Seismo)/1(124)/2010) is acknowledged (NN).

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