Earth Planets Space, **65**, 1515–1523, 2013

Secular trend of geomagnetic elements in the Indian region

S. K. Bhardwaj and P. B. V. Subba Rao

Indian Institute of Geomagnetism, New Panvel, Navi Mumbai 410 218, India

(Received May 13, 2013; Revised August 28, 2013; Accepted September 2, 2013; Online published December 6, 2013)

In the present study, secular trends and jerks in the geomagnetic elements D, H and Z are investigated at the six Indian magnetic observatories using annual and monthly mean values for all days, quiet days and night base (night time mean). The residuals of all-day annual and monthly means are computed by removing a polynomial fit from their best fitting curves. The residuals of D, H and Z curves do not show any parallelism with the 11-year sunspot cycle. At Alibag, the D residual shows a periodicity of 2 solar cycles, whereas the H and Z residuals indicate a quasi-periodicity of 3 solar cycles for the period 1921–2009. At the Indian stations, an in-phase solar cycle component is observed for 2 of the solar cycles in the D and Z residuals, while the H residual shows out-of-phase variations with the sunspot cycle for the period 1958–2009. Two geomagnetic jerks, 1970 and 1991, are well reflected in the monthly and annual mean values in the Indian region, as observed globally.

Key words: Secular variation, core-mantle, geomagnetic jerks, solar cycle, polynomial fit.

1. Introduction

Gilbert, in 1600 A.D., suggested a model Earth called Terrella in his book *De Magnete*. According to this model, the planet Earth is a huge magnet and is approximated to a magnetic dipole placed at its center. This geomagnetic field changes over a wide range of time scales from a fraction of a second to millions of years. The geomagnetic field consists of an internal and external field; the internal field is the main field on which external field variations such as Sq, storms and sub storms are superimposed. The main field variations (more than 90%) are generated by the Earth's liquid outer core. The core-mantle interactions lead to secular changes. The external source (less than 10%) is located in the Earth's ionized upper atmosphere and is due to highly-penetrating radiations from cosmic rays, solar, planetary or lunar origin. Among all these external sources, the Sun is the major energy source, causing upper atmosphere ionization that sets up currents responsible for short-period variations, such as Sq, storms and sub storms in the Earth's magnetic field.

The annual mean values of magnetic observations are used to determine the secular variations of the geomagnetic field components. These variations differ from place to place and vary with time. The secular variation covering a period of $\sim$100 to 1000 years in which the major part of the geomagnetic field does not undergo reversals comes under this type of study. Moos (1910) studied the secular variation of the geomagnetic field components at Bombay for the period 1871–1905 and, after reducing Bombay (Colaba) data to Alibag, Pramanik (1952) extended these secular variation curves up to 1949. Rao and Bansal (1969) fitted polynomials of a third order to the observed annual mean values of H, Z and D for Alibag from 1905–1965. Bhardwaj and Rangarajan (1997) further extended these curves up to 1990 for Alibag. In the present study, secular variations, long-period oscillations in the residuals, and secular jerks, are discussed using annual and monthly mean values of observations from six Indian magnetic observatories.

2. Data and Technique Used

The data used in this study are the annual and monthly mean values of the geomagnetic field components D, H and Z for all days, five international quiet days and night base (quiet days monthly mean values from 23–01 h LT) from six Indian observatories: Trivandrum (TRD) / Tirunelveli (TIR), Kodaikanal (KOD), Annamalainagar (ANN) / Pondicherry (PND), Hyderabad (HYB), Alibag (ABG) and Sabhawala (SAB). Table 1 shows the IAGA code, the geographic and geomagnetic coordinates of these stations, and the period of data used. The locations of these observatories, shown in Fig. 1(a), are located from the dip equator up to the Sq focus near Sabhawala (30.37°N Geographic Latitude). The position of the dip equator for the years 1975, 1985, 1995 and 2005 are shown in Fig. 1(b).

The data sets for Alibag are from 1921–2009, and, for other equatorial electrojet stations, from 1958–2009. As Annamalainagar and Trivandrum observatories are closed, the data for these stations have been reduced from Pondicherry and Tirunelveli by applying correction factors to all three elements D, H and Z. Data sets for Hyderabad and Sabhawala are from 1965–2009. Data for Kodaikanal station are from 1965–2005 for D and H, whereas data for Z are from 1965 to 1997 due to technical problems. It is to be pointed out that the declination (D) at Alibag was easterly up to 1926, and from 1927 has continued to be westerly and, at present, is again swinging towards the east.

The technique used in this study is propagating least squares as suggested by Gangi and Shapiro (1977). Us-

doi:10.5047/eps.2013.09.001

Table 1. List of stations along the Indian Sector, their Geographic and Geomagnetic coordinates, and the period of data used.

Observatory Name	IAGA Code	Geographic		Geomagnetic		Period of data used
		Latitude (°N)	Longitude (°E)	Latitude (°N)	Longitude (°E)	
Sabhawala	SAB	30.37	77.80	20.93	151.50	1965–2009
Alibag	ABG	18.63	72.86	9.74	145.55	1921–2009
Hyderabad	HYB	17.42	78.55	7.97	150.87	1965–2009
Annamalainagar / Pondicherry	ANN/ PND	11.37	79.68	1.85	151.39	1958–2009
Kodaikanal	KOD	10.23	77.46	0.92	149.11	1965–2005
Trivandrum / Tirunelveli	TRD/ TIR	8.48	76.95	−0.77	148.44	1958–2009

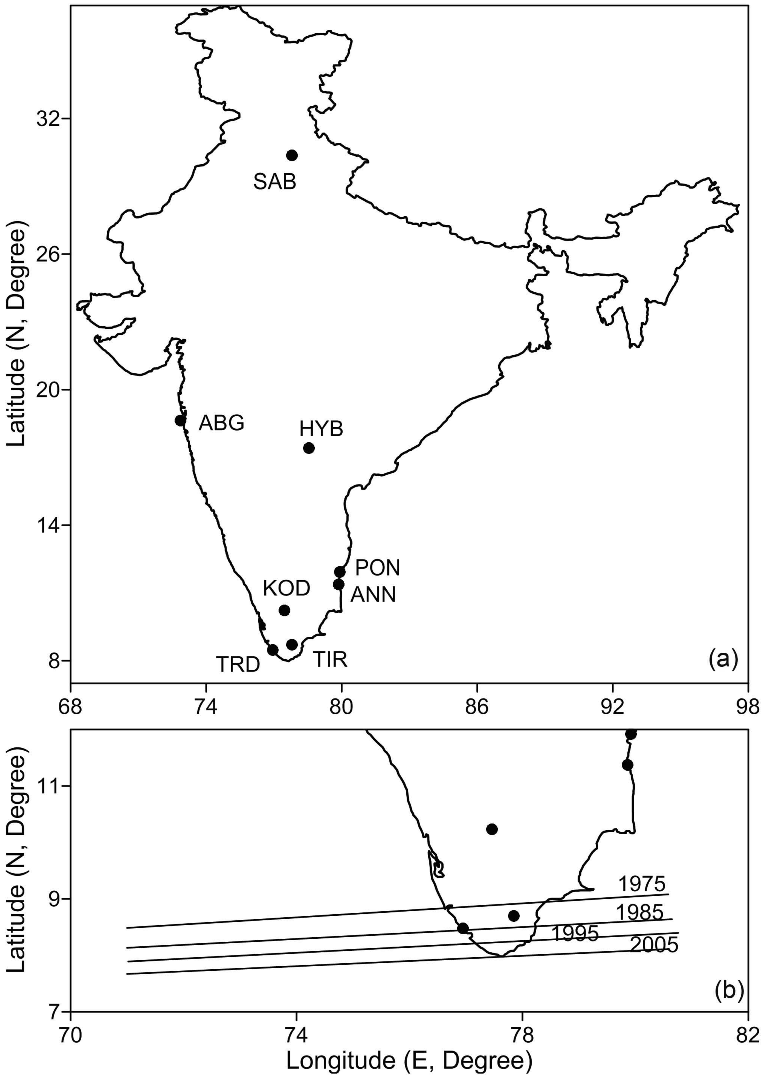


Fig. 1. (a) The location of the six Indian Magnetic observatories—Trivandrum (TRD)/Tirunelveli (TIR), Kodaikanal (KOD), Annamalainagar (ANN)/Pondicherry (PON), Hyderabad (HYB), Alibag (ABG) and Sabhawala (SAB). (b) shows the position of the Dip Equator for the years 1975, 1985, 1995 and 2005 and its migration towards the south. Note Pondicherry (PND) is shown as PON.

ing this technique, fifth-order polynomials were fitted for all days, quiet days and night base. The secular trend curves for annual and monthly mean values at all six observatories are not much different for all three categories, viz, all days, quiet days and night base. However, they differ in coefficients as shown in Tables 2 and 3 for quiet days and night base. In the present study, the annual mean quiet days plot for Alibag are shown in Fig. 2(a) and, for monthly mean all days, in Fig. 2(b). Plots for quiet days annual mean values at all six stations are shown in Figs. 3(a)–3(c) and, for night base, in Figs. 4(a)–4(c).

3. Results and Discussion

The results are based on the annual and monthly mean values of the geomagnetic field components D, H and Z and are discussed in terms of (a) trends in secular variations

Table 2.

(a) List of coefficients for D computed by quiet-day annual mean best-fitting curves at the Indian stations.

Station	a_0	a_1	a_2	a_3	a_4	a_5
TRD	181.4642	−0.1203	−0.0380	0.00039	—	—
KOD	159.3763	−2.9317	0.2439	−0.00941	0.00011	—
ANN	173.0193	−3.0471	0.3232	−0.01542	0.00029	−0.000002
HYB	106.1196	−3.8899	0.5905	−0.03442	0.00079	−0.000006
ABG	50.4585	−0.2133	0.1131	−0.01017	0.00026	−0.000002
SAB	18.1249	2.2947	−0.4009	0.02588	−0.00062	0.000005

(b) List of coefficients for H computed by quiet-day annual mean best-fitting curves at the Indian stations.

Station	a_0	a_1	a_2	a_3	a_4	a_5
TRD	40037.446	31.8294	−3.7060	0.1099	−0.00091	—
KOD	39636.265	−47.4673	4.6686	−0.3476	0.0110	−0.000113
ANN	40571.243	22.9623	−1.9759	0.0085	0.0012	−0.000014
HYB	40124.488	−1.33896	−3.0627	0.1091	−0.0010	—
ABG	38576.915	65.5623	−6.1481	0.1510	−0.0011	—
SAB	34194.990	19.5580	−4.9207	0.1717	−0.0018	—

(c) List of coefficients for Z computed by quiet-day annual mean best-fitting curves at the Indian stations.

Station	a_0	a_1	a_2	a_3	a_4	a_5
TRD	−342.1428	−39.6445	−2.3314	0.3945	−0.01144	0.000101
KOD	2209.6492	−68.1931	8.0936	−0.2235	0.00265	—
ANN	3809.6931	24.1544	−7.2175	0.5721	−0.01425	0.000117
HYB	15189.328	−113.277	12.1131	−0.3674	0.00389	—
ABG	17789.010	−19.6960	−3.5039	0.3542	−0.00943	0.000082
SAB	34782.070	−76.4116	5.6646	−0.1641	0.00189	—

Table 3.

(a) List of coefficients for D computed by quiet day's night-time annual mean best-fitting curves at the Indian stations.

Station	a_0	a_1	a_2	a_3	a_4	a_5
TRD	179.8490	0.0947	−0.0457	0.00047	—	—
KOD	159.3060	−2.9849	0.2480	−0.00952	0.00011	—
ANN	172.7217	−3.0832	0.3320	−0.01592	0.00030	−0.0000020
HYB	105.4217	−3.3481	0.5164	−0.03078	0.00072	−0.0000059
ABG	50.3889	−0.0324	0.1152	−0.01030	0.00026	−0.0000022
SAB	18.2142	2.2592	−0.3961	0.02563	−0.00061	0.0000051

(b) List of coefficients for H computed by quiet day's night-time annual mean best-fitting curves at the Indian stations.

Station	a_0	a_1	a_2	a_3	a_4	a_5
TRD	40005.441	33.8969	−3.8286	0.1124	−0.00093	—
KOD	39619.178	−48.5988	4.7564	−0.3509	0.01108	−0.000114
ANN	40540.598	27.5909	−2.4591	0.0297	0.00077	−0.000012
HYB	40117.033	−2.0848	−3.0216	0.1081	−0.00104	—
ABG	38561.087	66.6735	−6.2157	0.1525	−0.00117	—
SAB	34199.419	17.2593	−4.7598	0.1693	−0.00182	—

(c) List of coefficients for Z computed by quiet day's night-time annual mean best-fitting curves at the Indian stations.

Station	a_0	a_1	a_2	a_3	a_4	a_5
TRD	−348.670	−38.763	−2.3973	0.3968	−0.01147	0.000101
KOD	2128.734	−3.38921	−4.9038	0.8105	−0.03257	0.000428
ANN	3820.802	22.709	−7.0530	0.5644	−0.01410	0.000116
HYB	15190.476	−112.887	12.0755	−0.3658	0.00387	—
ABG	17796.631	−22.256	−3.1781	0.3374	−0.00905	0.000078
SAB	34782.838	−75.218	5.5345	−0.1597	0.00185	—

(b) long-period oscillations in the residuals, and (c) secular jerks.

3.1 Secular trends at Alibag (1921–2009)

Figure 2(a) shows the plots of annual mean values of D, H and Z for quiet days at Alibag together with best-fitting curves for the period from 1921 to 2009. The cumulative percentage of variance accounted for by polynomial fits in successive orders is given in Table 4. The 2nd-order polynomial is fitted for D as there is not much difference in the percentage of variance of 2–5 degree polynomials.

Table 4. Percentage of the variance in Alibag quiet-day annual means accounted for by polynomial fits.

Element	1st Degree	2nd Degree	3rd Degree	4th Degree	5th Degree
D	5.7	97.3	98.4	98.8	98.8
H	24.0	86.6	91.6	98.7	99.4
Z	44.3	72.7	94.4	96.7	96.9

The secular trend for D is a smooth parabola with a broad maximum around 1960–65. Negative values of D from 1921 to 1926 indicates that the declination was easterly up to 1926, and from 1927 it became westerly, which again swings towards easterly as D is approaching zero for the year 2009.

For the H-component, the percentage of variance accounted by a 5th-order polynomial is 99.4% and fitting well with the observed annual mean values in comparison with other low-order polynomials. The secular trend of H shows that this field has increased continuously since 1921, reaching a maximum by about 1965, and thereafter decreased at a rate of about 20 nT/year. This H-field has a quasi-periodicity of around 90–100 years and is consistent with earlier results.

The percentage of variance of the Z-component for the 5th-order polynomial is 96.9%. The secular trend of Z shows a near-sinusoidal variation with a periodicity of ∼80 years, known as the Gleissberg cycle (Gleissberg, 1965). The continuously increasing trend of the Z-field at present denotes another periodicity in the coming years.

Figure 2(b) shows the plots of D, H and Z for monthly mean values at Alibag for all days. There is no distinct difference between the monthly mean and the annual mean plots for all days and quiet days. Also, the cumulative percentage of variance accounted for by polynomial fits in successive orders is almost the same for the annual and monthly means of all days and quiet days.

3.2 Secular trends in the Indian chain of observatories

Three out of the six stations—TRD, KOD and ANN—are under the influence of the daytime equatorial electrojet. This causes an enhancement of the daily variation and short-period fluctuations in H, and though the electrojet does not contribute in any measurable way to the secular trends of H or D, it may introduce significant departures from the trend (Bhardwaj and Rangarajan, 1997). The diurnal variation in the vertical component close to the dip equator is expected to be small, but the analysis of south India magnetic array data suggests a significant internal contribution due to the channeling of induced currents through a sub-surface conductor between India and Sri Lanka (Rajaram *et al.*, 1979) and a regional south Indian offshore conductivity anomaly (Arora and Subba Rao, 2002). The three stations HYB, ABG, and SAB, are the low- and mid-latitude stations. The westerly declination (D-trend) is decreasing at all six Indian stations (the sign of SAB has been reversed to indicate westerly) and, at Alibag, it has again been swinging easterly from 2009, as shown in Fig. 3(a). The cumulative percentage of variance accounted for by the 5th-order polynomials varies between 97.0 to 99.6 for the D component, 98.7 to 99.6 for the H component, and 98.5 to 99.5 for the Z component, at all six Indian stations.

Secular trends for the horizontal component (H) at the six Indian stations for quiet day annual means are shown in Fig. 3(b). A distinct difference between equatorial and low-latitude stations is that the H-field increases rapidly after 1990 for equatorial stations and is linear for non-equatorial electrojet stations. The parallelisms in the secular trend of Hyderabad, Alibag and Sabhawala indicate that the feature has a broad regional coverage, whose southern latitudinal extent may be just above the edge of the equatorial electrojet belt. A quasi-periodicity of nearly 40–50 years is suggested close to the equator. In broader terms, we can say that all six stations show comparable trends without large local anomalies.

The secular trends of the vertical component (Z) for the six Indian stations for quiet day annual means is shown in Fig. 3(c). The Z-field decreased since 1958, reaching a minimum value around 1970, and then it increased again. The increase in Z from 1970 is more rapid at equatorial stations (denoting the southward migration of the dip equator) as compared with mid-latitude stations. The southward migration of the dip equator was suggested by Srivastava (1992) and confirmed by Rangarajan and Deka (1991). The maximum speed of the southward migration of the dip equator is estimated to be ∼5 km/year during 1980–1990 (Deka *et al.*, 2005). The southward migration of the dip equator is also shown in Fig. 1 for different years from 1975 to 2005. Srivastava and Abbas (1977) have found a quasi-periodicity of ∼80 years in the migration of the dip equator. In our analysis, the Z-field also completes a half-cycle in 40 years; hence, the period of the secular change of the position of the dip equator is of the order of ∼80 years, attributable to the Gleissberg cycle (Gleissberg, 1965).

Night base plots at three equatorial, and three non-equatorial, stations for the D, H and Z components, which are shown in Figs. 4(a)–4(c), are not much different compared with all days and quiet days plots. Hence, the equatorial electrojet current does not contribute to secular variations. Also, the cumulative percentage of variance of the 5th-order polynomials for D, H and Z is almost the same for all days, quiet days and night base at the six Indian stations.

3.3 Solar cycle component in the monthly means at Alibag

To observe the presence of a solar cycle component in the monthly means, residuals from the best fitting curves of D, H and Z are plotted as shown in Fig. 5. These residuals of D, H and Z for all days at Alibag, the monthly mean sunspot numbers from 1921–2009, covering 8 complete 11 year solar cycles are shown in the bottom panel. To see the presence of the Hale cycle (or double sunspot cycle) in the data, the monthly mean sunspot numbers are also plotted with a reversed sign in the alternate cycles. As the solar cycle component is more prominent in the all-day residu-

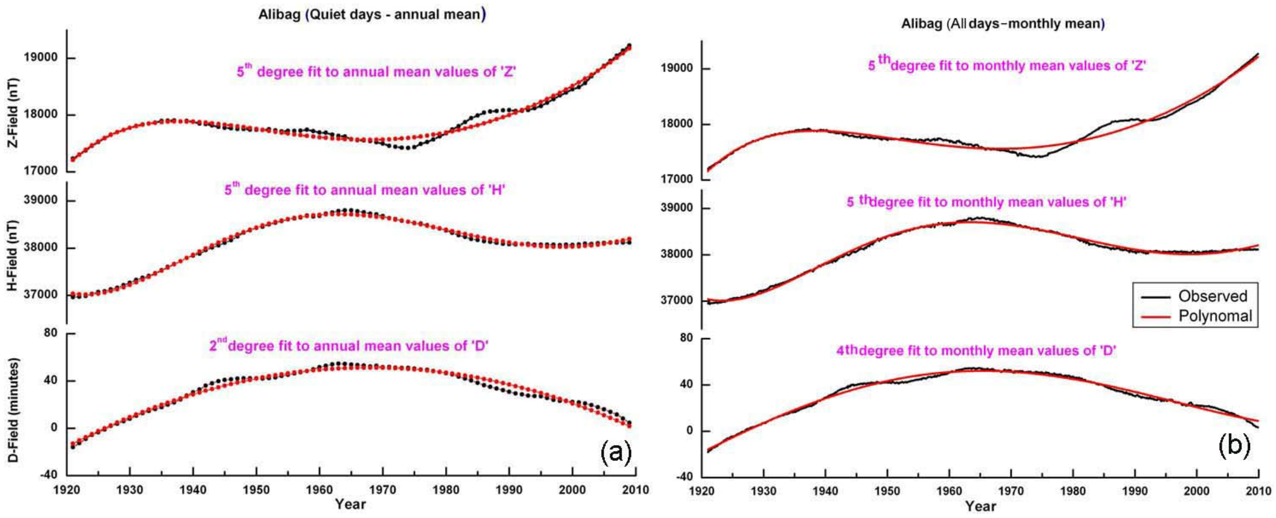


Fig. 2. (a) Observed annual mean values of D, H, and Z, for quiet days at Alibag from 1921 to 2009, together with their best-fitting curves. (b) Observed monthly mean values of D, H, and Z, for all days at Alibag from 1921 to 2009, together with their best-fitting curves.

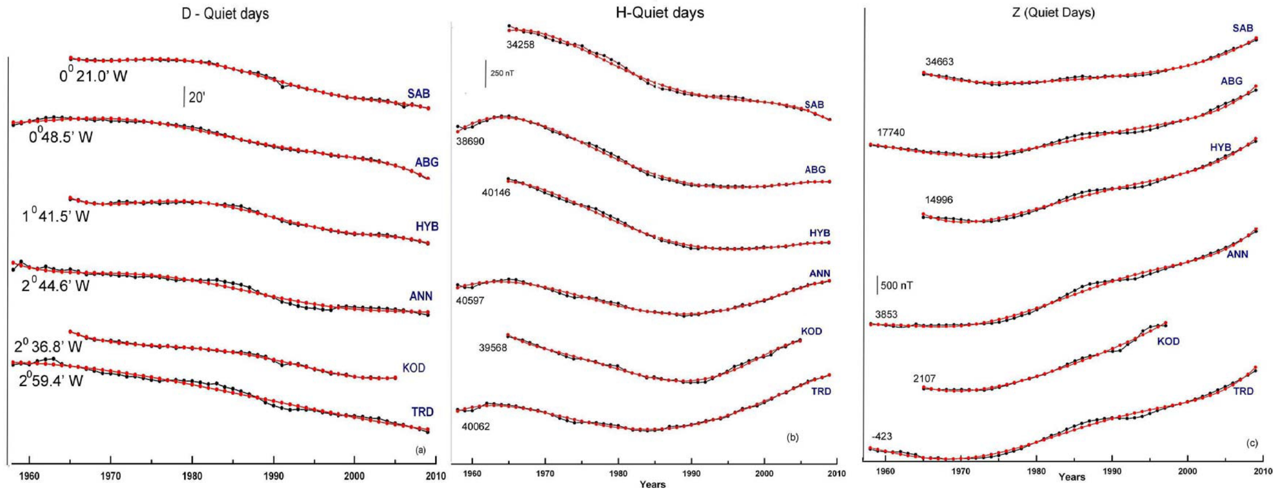


Fig. 3. Observed annual mean values of (a) declination (D), (b) horizontal component (H), and (c) vertical component (Z) for quiet days at the six Indian stations from 1958 to 2009, together with their best-fitting curves. Westerly-increasing declination is plotted downwards.

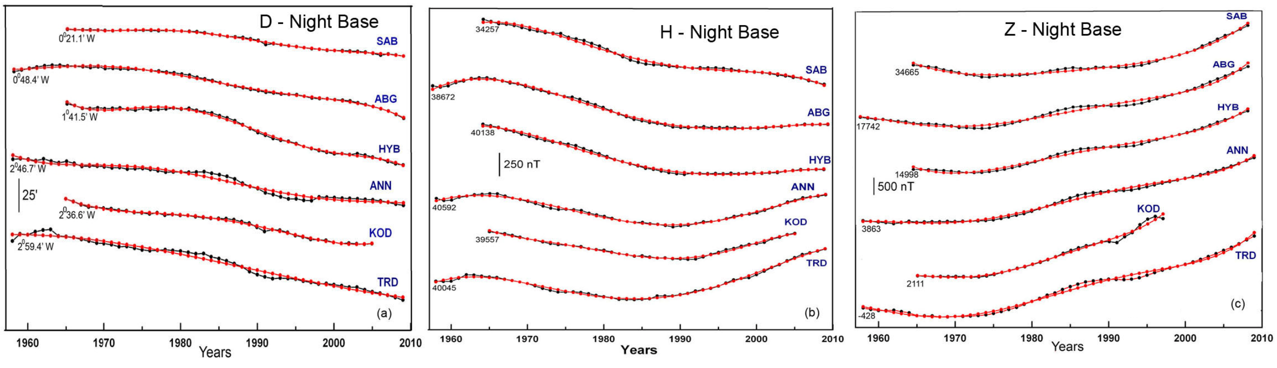


Fig. 4. Observed annual mean values of (a) declination (D), (b) horizontal component (H) and (c) vertical component (Z) for night base at the six Indian stations from 1958 to 2009, together with their best-fitting curves. Westerly-increasing declination is plotted downwards.

als rather than for the quiet day and night base, we have shown the residuals for all days in Fig. 5. The D residuals are computed from the 2nd-order best-fitting curves, while the residuals for H and Z are estimated from 3rd-order polynomials. The residual D, H and Z curves do not show any parallelism with the 11-year sunspot cycle. However, the D residual has a periodicity of nearly 2 solar cycles, whereas the H and Z residuals indicate a quasi-periodicity of 3 solar

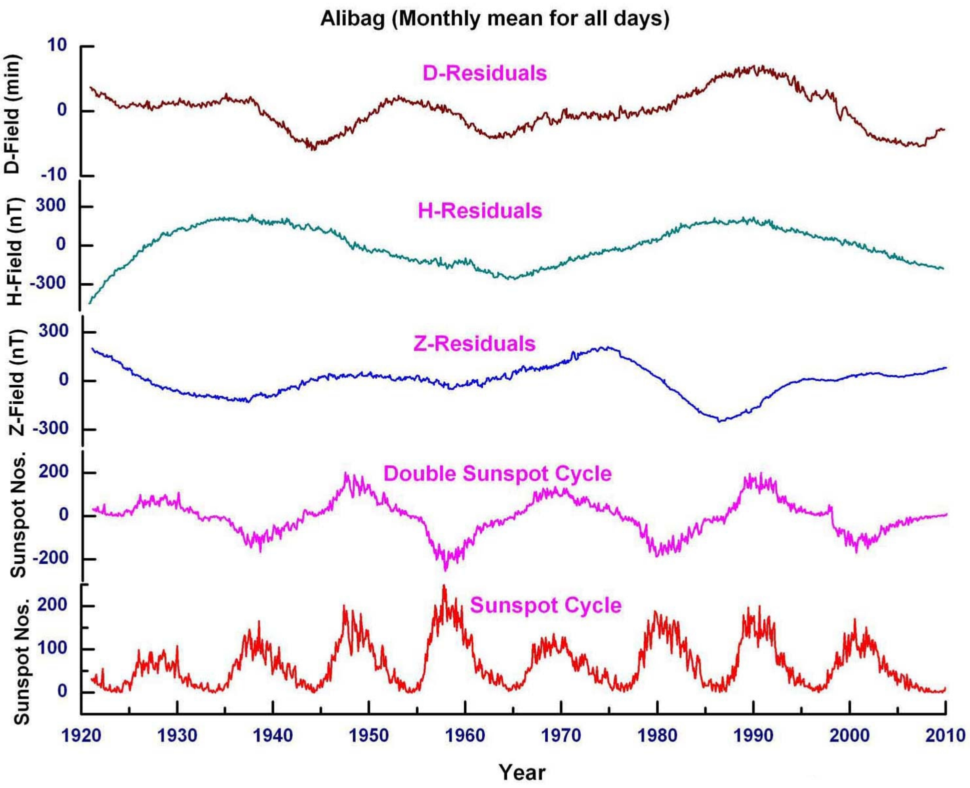


Fig. 5. Residuals of D, H, and Z, monthly mean values for all days from the smooth secular trend at Alibag and the annual mean sunspot numbers together with the Hale-cycle from 1921 to 2009.

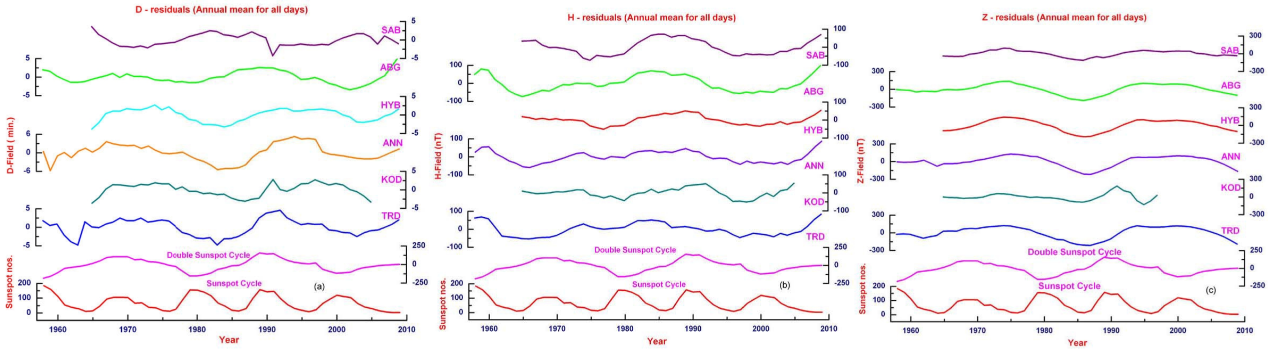


Fig. 6. Residuals of (a) declination (D), (b) horizontal component (H), and (c) vertical component (Z) annual mean values for all days at the six Indian stations, together with annual mean sunspot numbers and the Hale-cycle from 1958 to 2009.

cycles at Alibag. The H and Z residuals do not have identical periodicities. The 25–30-year oscillation (3 minima near 1930, 1955 and 1985) in the Z residuals do not match the H residuals, indicating a quasi-periodicity of about 50 years. Hence, these oscillations cannot be considered to be associated with sources of an external origin.

3.4 Solar cycle component in the annual means at the Indian observatories

To see the presence of a solar cycle, or Hale cycle, in the annual means at the Indian observatories, third-order residuals from the best fitting curves for all days annual means of D, H and Z together with the 11-year and 22-year sunspot cycles, for the period from 1958 to 2009, are plotted in Figs. 6(a)–6(c). The D residuals in Fig. 6(a) show a minimum at the equatorial stations in the initial part between 1958–65, and another minimum between 1980–85, and do not show any parallelism with the 11-year sunspot cycle. However, it shows a periodicity of nearly 2 solar cycles. The H residuals in Fig. 6(b) show an anti-correlation with sunspot cycles. This is because, when solar activity increases, the ring current increases which decreases the variation in the H component and vice-versa.

From Fig. 6(c), an in-phase solar-cycle component can be seen for 2 of the solar cycles in the Z residuals, with minima near 1963, 1986 and 2009, i.e. the Z residuals appear in phase with the double sunspot cycle at all the Indian stations (except KOD). The equatorial and lower-latitude group of stations do not indicate different patterns, so these variations are due to external sources. The minimum in Z in phase with the solar activity minimum is consistent with

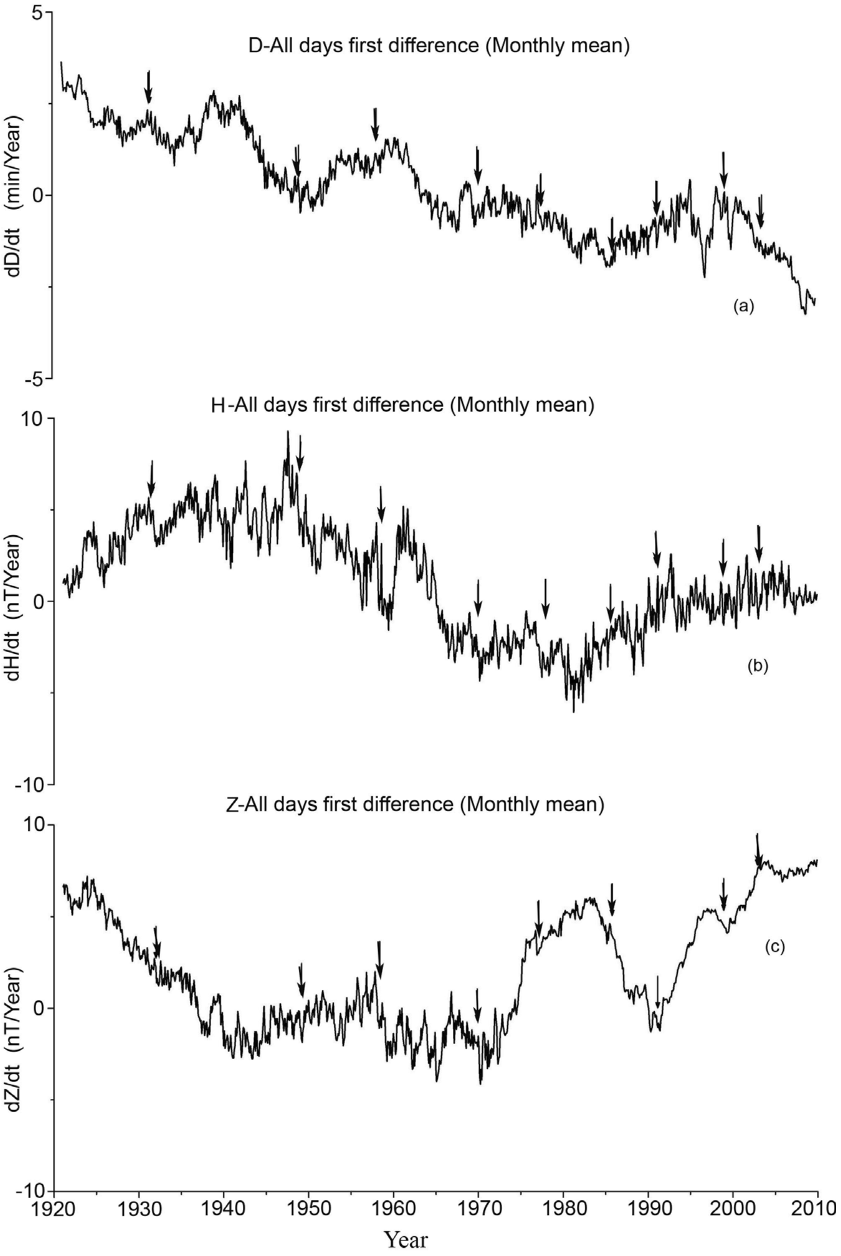


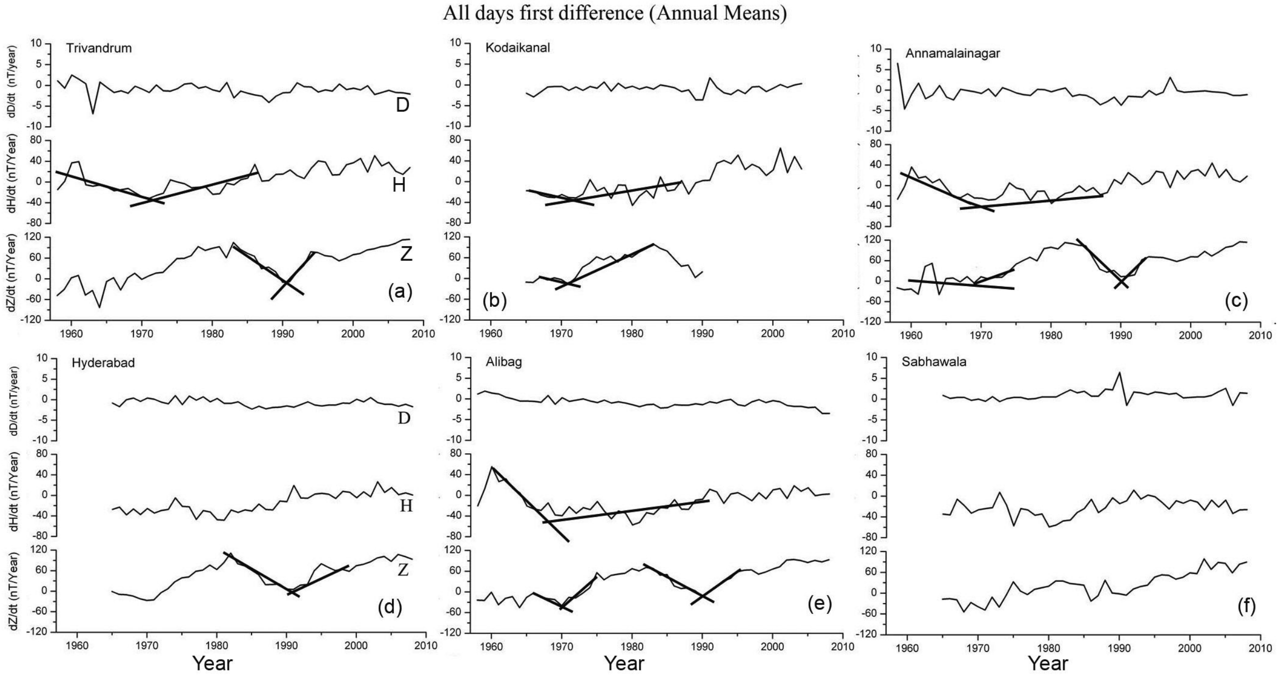
Fig. 7. Plot of the first difference of monthly mean values (from 1921 to 2009) of (a) declination (D), (b) horizontal component (H), and (c) vertical component (Z) for all days at Alibag.

the expectations of the signature of the equatorial ring current in the northern hemisphere, since this source (ring current) would create an increase in Z (a downward field) in the northern hemisphere and a decrease in Z (an upward field) in the southern hemisphere as the ring current (as well as the sunspot number) increases.

3.5 Secular impulse or Jerk

A sudden change in the slope of the magnetic secular variation is known as a secular impulse, or geomagnetic jerk, that arises from sources inside the Earth (Cafarella and Meloni, 1995; Macmillan, 1996; Le Huy *et al.*, 1998). Recently, these jerks have been suggested as geomagnetic rapid secular fluctuations (Olsen and Mandea, 2008; Mandea and Olsen, 2009; Qamili *et al.*, 2013) that have periods ranging from several months to a few years (Macmillan, 2007). These events are observed in magnetic data as sudden V-shaped changes in the slope of the secular variation (Mandea *et al.*, 2010). Geomagnetic jerks have been observed around 1901, 1913, 1925, 1932, 1949, 1958, 1969, 1978, 1986, 1991, 1999, and 2003, at a number of observatories around the world (e.g. Malin and Hodder, 1982; Courtillot and Le Mouël, 1984; Alexandrescu *et al.*, 1996; Mandea *et al.*, 2000; Mandea *et al.*, 2010).

Jerks can be seen by plotting first differences of observatory monthly and annual means. Two straight line segments with distinctly different slopes are indicative of a possible signature of a jerk. Figures 7(a)–7(c) show the plots of the first difference of the monthly mean values of D, H and Z for all days at Alibag for the period 1921–2009. Geomagnetic jerks observed during the different years mentioned above are shown by arrows. The 1970 and 1991 jerks are well reflected in all three components, the 1932 jerk is well



All days first difference (Annual Means)

Fig. 8. Plot of the first difference of annual mean values of declination (D), horizontal component (H), and vertical component (Z), for all days at (a) Trivandrum, (b) Kodaikanal, (c) Annamalainagar, (d) Hyderabad, (e) Albag, and (f) Sabhawala, from 1958 to 2009.

observed in the D and H components, the 1949 and 1986 jerks are seen in the D and Z components, and the 1958 and 1978 jerks in the H and Z components.

Mandea *et al.* (2000) reported jerks around 1970 and 1999 by using data from Chambon la Foret (~118 years) and Niemegk (~111 years) observatories' monthly mean values of the East magnetic component (Y). The jerk of ~1970 was recorded all over the globe in declination data. 1932, 1949 and 1970 jerks were reported by Alexandrescu *et al.* (1996) by using 97 European observatories, and Kerridge and Barraclough (1985) by using data of annual mean values from worldwide observatories. Gubbins and Tomlinson (1986) also noticed the signature of the 1969–70 jerk at Apia and Amberley magnetic observatories in New Zealand.

Plots of the first difference of annual mean values of D, H and Z for all days at the six Indian stations for the period 1958–2009, are shown in Figs. 8(a)–8(f). No sign of jerks can be seen in the declination at the six stations. At TRD, KOD, ANN and ABG, we found a jerk around 1969/70 in the H data. In the vertical component (Z), we found a geomagnetic jerk around 1991 at TRD, ANN, HYB and ABG. Macmillan (1996) also reported the signature of this geomagnetic jerk around 1991 in the Y component at 15 European observatories using the first difference of annual mean values. Jerks are observed around 1969/70 and 1991 at ANN and ABG in the Z data. The cause for these jerks in the secular variation could be the upper layers of the liquid core filtering through the conducting mantle material (Le Mouël *et al.*, 1982; Golovkov *et al.*, 1992).

4. Conclusions

- The secular change of D curves show a decreasing trend in the westward direction at all the Indian observatories, and, at Alibag, at present it again swings back towards the eastward direction.
- The secular trends of the H field show a distinct difference between the equatorial and non-equatorial stations.
- Increasing trends of the Z field at equatorial stations since 1970 indicates the southward migration of the dip equator, which has a periodicity of ~80 years—the so-called Gleissberg cycle.
- At the Indian chain of stations, D and Z residuals show a periodicity of ~2 solar cycles, while H residuals show out-of-phase variations with the sunspot cycle. At Alibag, the D residuals show a periodicity of ~2 solar cycles, whereas the H and Z residuals are found to be opposite in phase with a quasi-periodicity of 3 solar cycles for the period 1921–2009.
- As observed globally, geomagnetic jerks are observed in the Indian region. The 1970 and 1991 jerks are well reflected in the 3 components of the monthly mean values.

Acknowledgments. We are grateful to Prof. G. K. Rangarajan and Prof. B. R. Arora for their motivation and fruitful suggestions. We would like to thank Dr. B. Veenadhari, Observatory and Data chairperson, Indian Institute of Geomagnetism, Navi Mumbai, India, for providing us with the monthly means database and for helpful discussions. We would like to thank Prof. S. Gurubaran, Director-in-Charge, Indian Institute of Geomagnetism, Navi Mumbai, India, for his keen interest and encouragement for carrying out this work. The authors would also like to thank two anonymous reviewers for their constructive comments and sugges-

tions.

References

Alexandrescu, M., D. Gilbert, G. Hulot, J.-L. Le Mouël, and G. Saracco, Worldwide wavelet analysis of geomagnetic jerks, *J. Geophys. Res.*, **101**(B10), 21975–21994, 1996.

Arora, B. R. and P. B. V. Subba Rao, Integrated modeling of EM response functions from Peninsular India and Bay of Bengal, *Earth Planets Space*, **54**, 637–654, 2002.

Bhardwaj, S. K. and G. K. Rangarajan, Geomagnetic Secular variation at the Indian Observatories, *J. Geomag. Geoelectr.*, **49**, 1131–1144, 1997.

Cafarella, L. and A. Meloni, Evidence for a geomagnetic jerk in 1990 across Europe, *Ann. Geophys.*, **38**, 451–455, 1995.

Courtillot, V. and J.-L. Le Mouël, Geomagnetic secular variation impulses: a review of observational evidence and geophysical consequences, *Nature*, **311**, 709–716, 1984.

Deka, R. C., L. A. D'Cruz, V. J. Jacob, A. Iype, and P. Elango, Location of the dip equator over Peninsular India, **9**, 41–46, 2005.

Gangi, A. F. and J. N. Shapiro, A propagating algorithm for determining Nth order polynomial least square fits, *Geophys.*, **42**, 1265–1276, 1977.

Gilbert, W., *De Magnete (About the Magnet)*, translated 1893 from Latin to English by Paul Fleury Mottelay, Dover Books, paperback, 1600.

Gleissberg, W., The eighty-year cycle in auroral frequency numbers, *J. Brit. Astron. Assoc.*, **75**, 227, 1965.

Golovkov, V. P., G. M. Kozhoyeva, and A. O. Simongan, On the nature of the abrupt changes in the geomagnetic secular variation at the end of the 1970s, *Geomagn. Aeron.*, **32**, 872–875, 1992.

Gubbins, D. and T. Tomlinson, Secular variation from monthly mean from Apia and Amberley magnetic observatories, *Geophys. J. R. Astron. Soc.*, **86**, 603–616, 1986.

Kerridge, D. J. and D. R. Barraclough, Evidence for geomagnetic jerks from 1931 to 1971, *Phys. Earth Planet. Inter.*, **39**, 228–236, 1985.

Le Huy, M., M. Alexandrescu, G. Hulot, and J.-L. Le Mouël, On the characteristics of successive geomagnetic jerks, *Earth Planet Space.*, **50**, 723–732, 1998.

Le Mouël, J -L., J. Ducruix, and C. H. Duyen, The worldwide character of the 1969–70 impulse of the secular acceleration rate, *Phys. Earth Planet. Inter.*, **28**, 337–350, 1982.

Macmillan, S., A geomagnetic jerk for the early 1990's, *Earth Planet Sci. Lett.*, **137**, 189–192, 1996.

Macmillan, S., Geomagnetic jerks, in *Encyclopedia of Geomagnetism and Paleomagnetism*, edited by Gubbins, D. and E. Herrero-Bervera, pp. 319–320, Springer, Dordrecht, 2007.

Malin, S. R. C. and B. M. Hodder, Was the 1970 geomagnetic jerk of internal or external origin?, *Nature*, **296**, 726–728, 1982.

Mandea, M. and N, Olsen, Geomagnetic and archeomagnetic jerks: where do we stand?, *Eos Trans. AGU*, **90**, 208, doi:10.1029/2009EO240004, 2009.

Mandea, M., E. Bellanger, and J.-L. Le Mouël, A geomagnetic jerk for the end of the 20th century?, *Earth Planet Sci. Lett.*, **183**, 369–373, 2000.

Mandea, M., R. Holme, A. Pais, K. Pinheiro, A. Jackson, and G. Verbanac, Geomagnetic jerks: Rapid core field variations and core dynamics, *Space Sci. Rev.*, **155**, 147–175, 2010.

Moos, N. A. F., *Magnetic Observations Made at the Govt. Observatory, Bombay, for the Period 1846–1905 and Their Discussion, Part II*, pp. 291–782, Government Central Press, Bombay, 1910.

Olsen, N. and M. Mandea, Rapidly changing flows in the Earth's core, *Nat. Geosci.*, **1**, 390–394, 2008.

Pramanik, S. K., Secular variation of the magnetic field at Colaba and Alibag, *J. Geophys. Res.*, **57**, 339–355, 1952.

Qamili, E., A. De Santis, A. Isac, M. Mandea, B. Duka, and A. Simonyan, Geomagnetic jerks as chaotic fluctuations of the Earth's magnetic field, *Geochem. Geophys. Geosyst.*, **14**, 839–850, 2013.

Rajaram, M., B. P. Singh, N. Nityananda, and A K Agrawal, Effect of the presence of a conducting channel between India and Sri Lanka island on the features of the equatorial electrojet, *Geophys. J. R. Astron. Soc.*, **56**, 127–138, 1979.

Rangarajan, G. K. and R. C. Deka, The dip equator over peninsular India and its secular movement, *Proc. Indian Acad. Sci. (Earth Planet. Sci.)*, **100**, 361–368, 1991.

Rao, D. R. K. and R. K. Bansal, Secular variation of geomagnetic elements at Alibag, *Indian J. Meterol. Geophys.*, **20**, 141–144, 1969.

Srivastava, B. J., New results on the dip equator and the equatorial electrojet in India, *J. Atmos. Terr. Phys.*, **54**, 871–880, 1992.

Srivastava, B. J. and H. Abbas, Geomagnetic secular variation in Indian-Regional and local features, *J. Geomag. Geoelectr.*, **29**, 51–64, 1977.

S. K. Bhardwaj (e-mail: sandeep@iigs.iigm.res.in) and P. B. V. Subba Rao