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Geomagnetic Secular Variation at the Indian Observatories

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Annual mean values of geomagnetic field components *D*, *H* and *Z* for all days and quiet days at six observatories are analysed to investigate the secular variations and geomagnetic jerks in the Indian region. Secular trends show a region of demarkation between equatorial and low latitude stations. The residual *D*, *H* and *Z* curves, obtained by removing polynomial fits, do not show any parallelism with the 11-year sunspot cycle. However, the *D* residual has a periodicity of 2 solar cycles, whereas *H* and *Z* residuals indicate a quasi-periodicity of 3 solar cycles at Alibag. For the period 1958 to 1990, *D* and *Z* residuals show a periodicity of nearly 2 solar cycles, while *H* shows out-of-phase variations with the sunspot cycle for all the six stations. The secular jerk around 1969–70, noted at many observatories over the globe, is not seen in *D* but is noted in the *H* and *Z* components at some of the six Indian stations. A comparison between the observed annual means and IGRF models indicates very low secular variation anomaly in the Indian region.

1. Introduction

Annual mean values of observatory data are widely used to examine the secular variation of geomagnetic field components. In the use of annual mean values, the variations with periods shorter than one year, such as *Sq*, magnetic storms and substorms, are eliminated but longer-period oscillations associated with periodicities like 11 years, 22 years and more are retained. The exact mechanisms responsible for the secular variation are, as yet, not clear (McFadden and Merrill, 1995) but, in general, these variations are attributed to the relative motion between the liquid core and the mantle above with a time-scale of the order of decades.

In India, results of several investigations on secular variation have earlier been reported. Moos (1910) studied the secular variation of the field components at Bombay for the period 1871–1905, which was later extended by Pramanik (1952) up to 1949. Rao and Bansal (1969) fitted polynomials of third order to the observed annual mean values of *H*, *Z* and *D* for Alibag from 1905–1965. They showed *H*, *Z* an *D* residuals-departures of the observed values from the secular trend of the fitted curve-did not exhibit any parallelism with solar activity. Bhargava and Yacob (1969) found that the solar-cycle response in *H* was larger during odd cycles, indicating a probable 22-year variation. *H* and *Z* affected more than *D* by solar activity according to Alldredge (1976). In contrast, Yukutake (1965) suggested that the solar cycle effect on secular change was so small that it could safely be neglected. In addition to the exhaustive analysis of Colaba-Alibag data, Srivastava and Abbas (1977) examined data over a limited time span (1960–1974) from a chain of six Indian stations. They inferred a migration of the dip equator towards the south from 1968.

With the availability now of homogeneous geomagnetic data from several observatories in the Indian region for about 3 decades and with the data for Alibag covering nearly 7 solar cycles, the features of the secular variation in magnetic elements are reexamined to identify regional features of similarities and differences. The presence or absence of jerks in the secular variation is also studied. The residuals are analysed for the signature of external signals and the results discussed in the light of features reported earlier. A comparison is also made of the observed field values with IGRF model-based values for different epochs.

2. Data Analysis

Annual mean values of the geomagnetic field components D, H and Z for all days and quiet days have been used for the six Indian stations whose location and codes are depicted in Fig. 1. Though Colaba-Alibag data extend backwards in time to 1848 (as used by Srivastava and Abbas, 1977), only from 1921 were the mean hourly values in nT scaled from magnetograms (in UT) to generate a homogeneous time series. Note that the declination at Alibag was easterly up to 1926 and from 1927 has continued to be westerly.

Polynomials are fitted to the two sets of annual mean values of D, H and Z using the technique of propagating least squares suggested by Gangi and Shapiro (1977). For all the stations, the secular trend curves for the two categories are not very different. We, therefore, present the plots only for quiet days. Plots of the annual mean values of D, H and Z for quiet days at Alibag for the period 1921 to 1990 are given in Fig. 2 together with their best-fitting curves: a parabola for D, a quartic for H and a cubic for Z. The equations for the best-fitting curves at Alibag and the percentage variance accounted for by successive orders are given in Table 1.

In the quiet-day annual means, semi-annual and annual variations of geomagnetic activity are largely eliminated. In all-day values the effect of magnetic storms are likely to be still present.

The plots of annual mean values of D, H and Z for quiet days during 1958–1990 at the six Indian stations are shown in Figs. 3(a), 3(b) and 3(c), together with their best-fitting curves. The coefficients for the polynomials and the percentage variance accounted for by successive orders are given in Tables 2, 3 and 4.

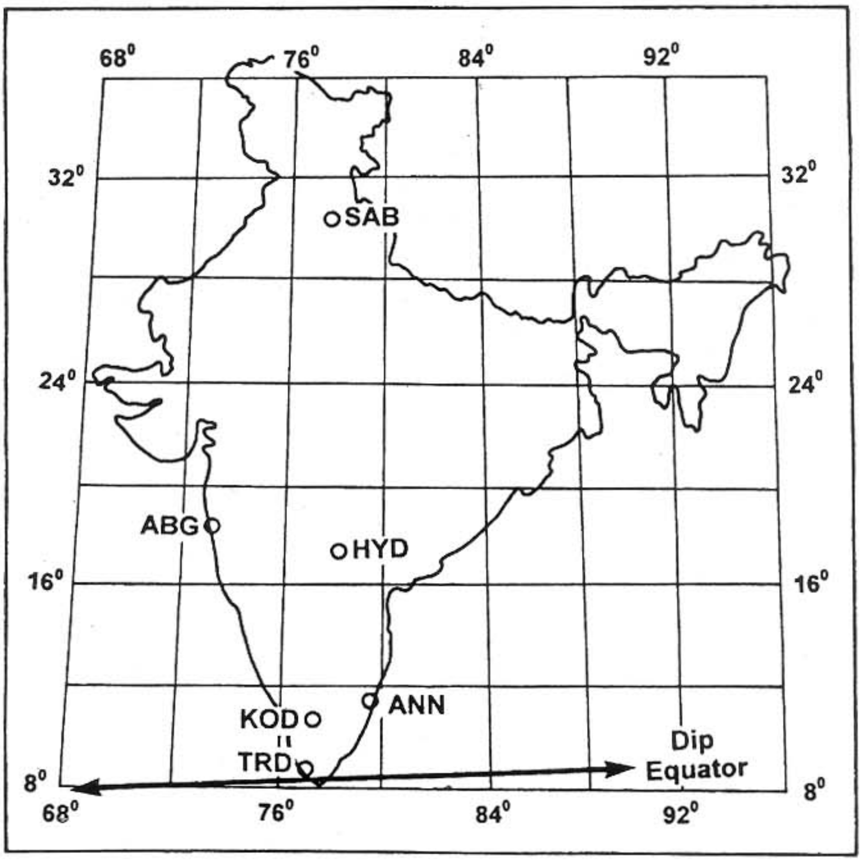


Fig. 1. The location of the six Indian observatories—Trivandrum (TRD), Kodaikanal (KOD), Annamalainagar (ANN) Hyderabad (HYD), Alibag (ABG) and Sabhawala (SAB) whose data have been used in this study.

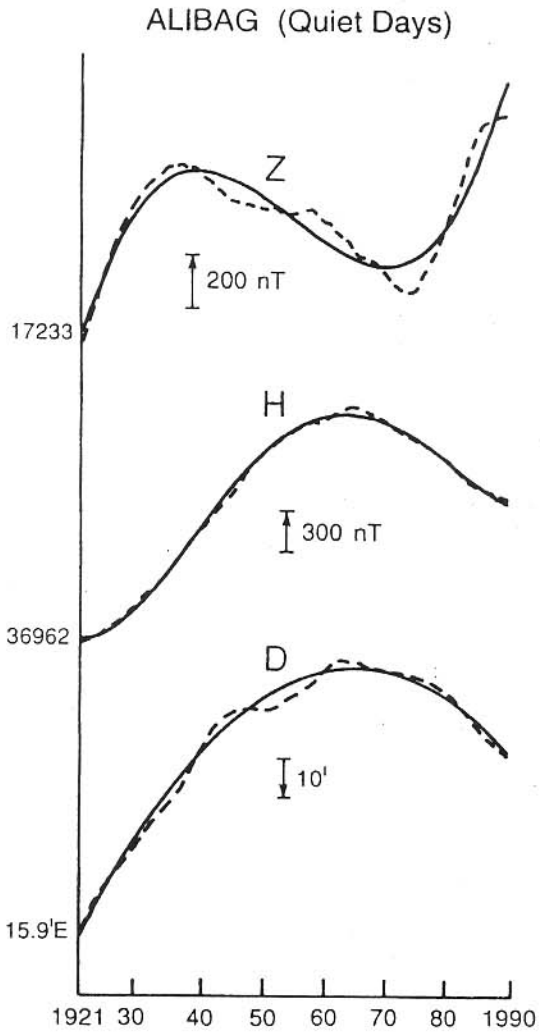


Fig. 2. Observed annual mean values of *D*, *H* and *Z* for quiet days at Alibag from 1921 to 1990, together with their best-fitting curves. The downward arrow denotes westerly-increasing declination.

3. Results and Discussion

The results of analysis carried out on the annual mean values are discussed in terms of (i) trends in secular variation, (ii) secular jerk, (iii) long-period oscillations in the residuals and (iv) comparison with IGRF models.

3.1 Secular change at Alibag (1921–1990)

Consistent with the results reported earlier, *H* attained a maximum by about 1965 and is decreasing presently at the rate of about 20 nT/year. The rate of ascent to the maximum was nearly linear, as pointed out by Bhargava and Yacob (1970), and faster than the post-maximum decrease. A long-period cyclicity is indicated with a minimum prior to 1921. The secular trend for *D* is a smooth parabola with the broad maximum near the same epoch as for *H*. *Z*, on the other hand, shows a near-sinusoidal secular trend with a ~80 year periodicity—the so-called Gleissberg cycle (Gleissberg, 1965). Bhargava and Yacob (1969) found evidence of this in *H* at Colaba-Alibag when data from 1860–1965 were utilized. There appears to be a phase opposition for this periodicity after 1945 between *H* and *Z*. The east-west component is not influenced by this periodicity, as seen in the secular curve for *D* at Alibag. This characteristic is brought out clearly by the extended data length, compared to the earlier analysis of Rao and Bansal (1969) or Srivastava and Abbas (1977).

Table 1. Percentage of the variance in Alibag quiet-day annual means accounted for by polynomial fits.

	1st Deg.	2nd Deg.	3rd Deg.	4th Deg.
D	55.3	99.2	99.2	99.3
H	55.3	96.4	98.1	99.8
Z	3.0	3.9	90.0	90.0

*Polynomial fits for Alibag quiet-day annual means.
D: $-19.14 + 3.134X - 0.03434X^2$.
H: $37002.3 - 10.35X + 4.456X^2 - 0.1043X^3 + 0.00065X^4$.
Z: $17193.1 + 80.04X - 2.815X^2 + 0.0269X^3$.
($X = 1, \ldots, 70$ correspond to the years 1921 to 1990).

Table 2. Percentage of the variance in "D" quiet-day annual means accounted for by polynomial fits.

Stations	1st Deg.	2nd Deg.	3rd Deg.	4th Deg.
TRD	93.8	94.4	94.5	98.6
KOD	94.8	95.0	95.0	98.5
ANN	89.6	92.3	96.1	98.6
HYB	57.4	80.2	97.0	97.0
ABG	73.6	98.6	98.6	98.6
SAB	71.3	96.4	98.5	99.1

*Polynomial fits for "D" for quiet-day annual means.
TRD: $176.8 + 2.834X - 0.46531X^2 + 0.021246X^3 - 0.0003183X^4$.
KOD: $155.0 + 2.153X - 0.37301X^2 + 0.016756X^3 - 0.0002431X^4$.
ANN: $166.3 + 0.618X - 0.18526X^2 + 0.010166X^3 - 0.0001758X^4$.
HYB: $102.5 - 1.356X + 0.13909X^2 - 0.004234X^3$.
ABG: $49.4 + 0.836X - 0.04304X^2$.
SAB: $21.3 + 0.195X - 0.03746X^2 + 0.002061X^3$.
($X = 1, \ldots, 33$ correspond to the years 1958 to 1990).

Referring to Table 1, the cumulative percentage variance accounted for by addition of each higher-order polynomial term indicates the closeness of the observed and fitted curves. It is clear that a cubic for H and a parabola for D almost completely reproduce the observed variation. The polynomial trend for Z leaves more than 10% of the variance unaccounted for, with no improvement even when a fourth degree equation is considered. This feature has been consistent even if the data from 1848 to 1975 are examined (Srivastava and Abbas, 1977) or from 1905 to 1965 (Rao and Bansal, 1969). The noise component could be due to internal induced variations at Alibag, a coastal station with significant land-sea conductivity contrast. Note that the technique of propagating least squares (Gangi and Shapiro, 1977) enables one to assess up to which degree of the polynomial is essential to derive the best-fitting curves, in contrast to the arbitrary termination at third degree (Rao and Bansal, 1969) or fifth degree for H and Z and cubic for D (Srivastava and Abbas, 1977).

3.2 *Secular trends in the Indian chain of observatories*

Three of the six stations, Trivandrum, Kodaikanal and Annamalainagar, are under the influence of the daytime equatorial electrojet, which causes enhancement of the daily variation and short-period fluctuations in H. While the electrojet will not contribute in any measurable way to the secular trends in H or D, it may introduce significant departures from the trend. The diurnal variation in the vertical component close to the dip equator is expected to be small, but analysis (Rajaram *et al.*, 1979) has shown

Table 3. Percentage of the variance in "H" quiet-day annual means accounted for by polynomial fits.

Stations	1st Deg.	2nd Deg.	3rd Deg.	4th Deg.
TRD	88.7	88.7	97.3	98.0
KOD	95.8	96.7	99.1	99.2
ANN	91.6	94.1	98.3	98.4
HYB	99.5	99.6	99.6	99.8
ABG	89.2	96.4	99.4	99.4
SAB	97.8	98.3	99.0	99.7

*Polynomial fits for "H" for quiet-day annual means.
TRD: $40061.5 + 19.512X - 2.16535X^2 + 0.043027X^3$.
KOD: $39534.5 + 16.115X - 2.10705X^2 + 0.037599X^3$.
ANN: $40575.1 + 22.492X - 2.18694X^2 + 0.038074X^3$.
HYB: $40177.3 - 27.223X - 0.09931X^2$.
ABG: $38614.5 + 47.138X - 3.98165X^2 + 0.062462X^3$.
SAB: $34220.1 + 3.836X - 2.60477X^2 + 0.055923X^3$.
($X = 1, \ldots, 33$ correspond to the years 1958 to 1990).

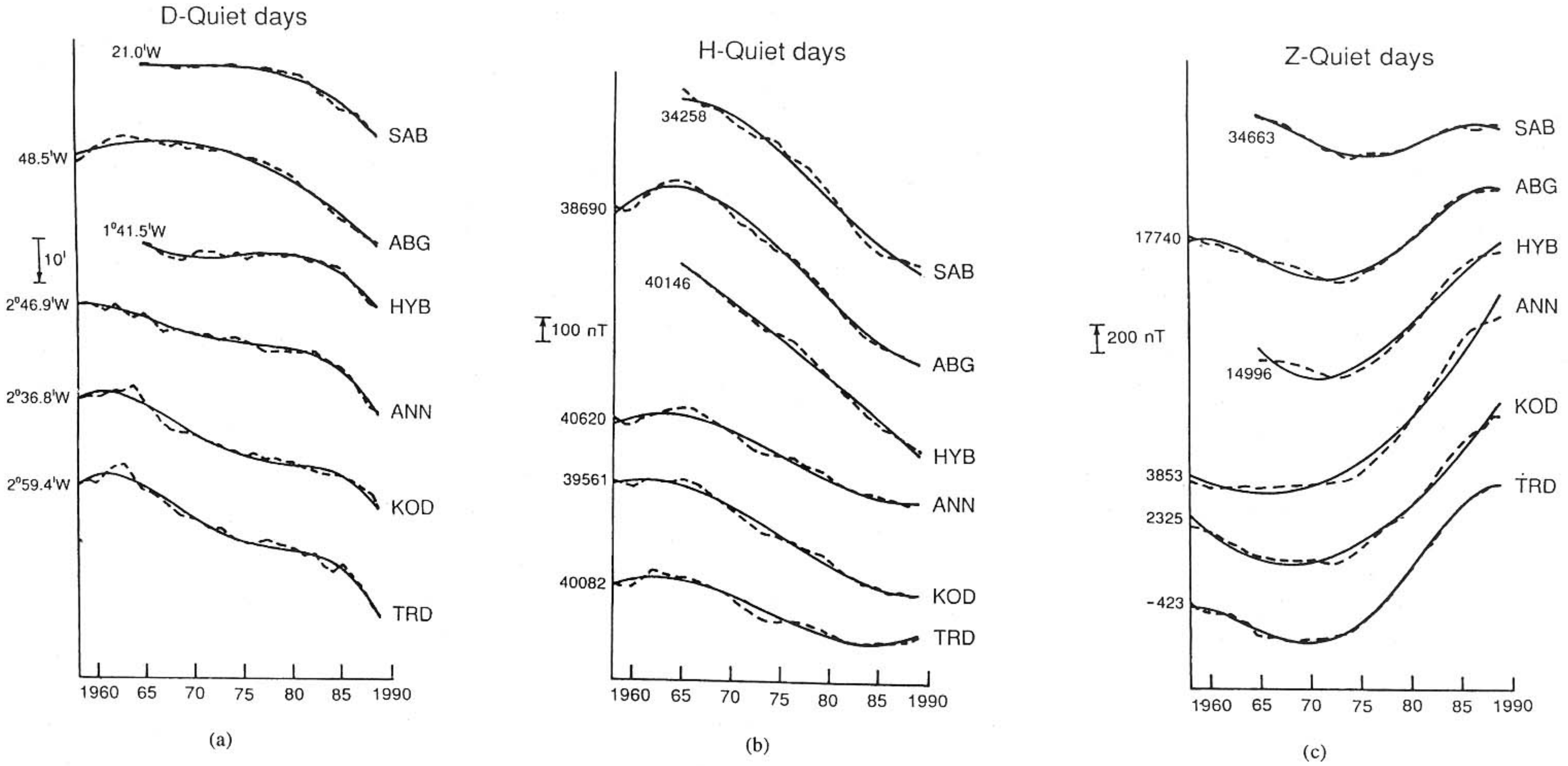
Table 4. Percentage of the variance in "Z" quiet-day annual means accounted for by polynomial fits.

Stations	1st Deg.	2nd Deg.	3rd Deg.	4th Deg.
TRD	65.5	97.1	97.8	99.8
KOD	62.9	98.4	98.7	99.8
ANN	78.4	98.1	98.1	99.4
HYB	80.1	95.7	98.1	99.9
ABG	37.9	92.3	92.6	98.8
SAB	0.4	82.6	90.2	96.6

*Polynomial fits for "Z" for quiet-day annual means.
TRD: $-462.8 + 21.673X - 9.2006X^2 + 0.595061X^3 - 0.009439X^4$.
KOD: $2464.9 - 76.876X + 3.9597X^2 - 0.028605X^3$.
ANN: $3934.4 - 39.767X + 2.3351X^2$.
HYB: $15176.6 - 96.366X + 8.5729X^2 - 0.149636X^3$.
ABG: $17658.1 + 48.188X - 11.4785X^2 + 0.627827X^3 - 0.009464X^4$.
SAB: $34694.1 - 13.257X - 5.2682X^2 + 0.486403X^3 - 0.013809X^4$.
($X = 1, \ldots, 33$ correspond to the years 1958 to 1990).

a significant internal contribution due to channeling of induced currents in the Palk Strait between India and Sri Lanka. Another notable feature of the region is the location of one of the foci of H and H maximum close to the Andaman Islands, just east of the Indian chain of magnetic stations, as can be seen in the iso-dynamic maps of F or H for any epoch derived from DGRF models (e.g., Baldwin and Langel, 1993).

A distinct difference between the three equatorial stations and the other three low latitude stations can be seen in the secular trend in H for the epoch 1958–1990 (Fig. 3(b)) (for Hyderabad and Sabhawala, the data coverage begins only in 1964–65). The decrease in the field after 1965 is more rapid and linear for stations at higher latitudes. A discernible difference in the epoch of maximum H is also seen between the two groups. Close to the equator, a cyclicity is suggested with a quasi-periodicity of nearly 40–50 years. The parallelisms in the secular trend of Alibag, Hyderabad, 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. In broader terms, all the six stations can be said to have comparable trends without large local anomalies.



(a) (b) (c)

Fig. 3. (a) Observed annual mean values of declination (*D*) for quiet days at the six Indian stations from 1958 to 1990, together with their best-fitting curves. Westerly-increasing declination is plotted downwards. (b) Observed annual mean values of the horizontal component (*H*) for quiet days at the six Indian stations from 1958 to 1990, together with their best-fitting curves. (c) Observed annual mean values of the vertical component (*Z*) for quiet days at the six Indian stations from 1958 to 1990, together with their best-fitting curves.

When the curves for D or Z are examine (Figs. 3(a) and 3(c)), once again we notice distinct differences between the electrojet and non-electrojet stations. The increase in Z since 1970, which is rather more rapid for the stations close to the equator, indicates the southward migration of the dip equator. This was suggested earlier by Srivastava (1992) who expected the dip equator to be over KanyaKumari (extreme south of the Indian landmass) by about 1992. The southward migration since 1971 has been confirmed both from observations and IGRF models by Rangarajan and Deka (1991). Secular trends in declination tend to be similar at the four southerly stations, whereas Sabhawala and Alibag feature only a broad minimum centred on 1975.

Srivastava and Abbas (1977) have highlighted some differences in the secular change in declination at Hyderabad and Alibag and attributed this to a combination of fossil magnetisation in the Decean traps beneath Alibag and deep-seated volcano-tectonic processes nearby as evidenced by seismic activity and hot springs in the vicinity. The present analysis with extended data indicates the persistence of the difference in D between Alibag and Hyderabad, but the secular trends H and Z are very similar.

The broad agreement in the secular trends over the Indian subcontinent indicates that the sources of secular variation are deep-seated, with depths comparable or greater than the lateral separation of Sabhawala and Trivandrum of more than 2400 km. The residuals, particularly between equatorial and low latitude stations, may also be attributed to the distinctive features in the core.

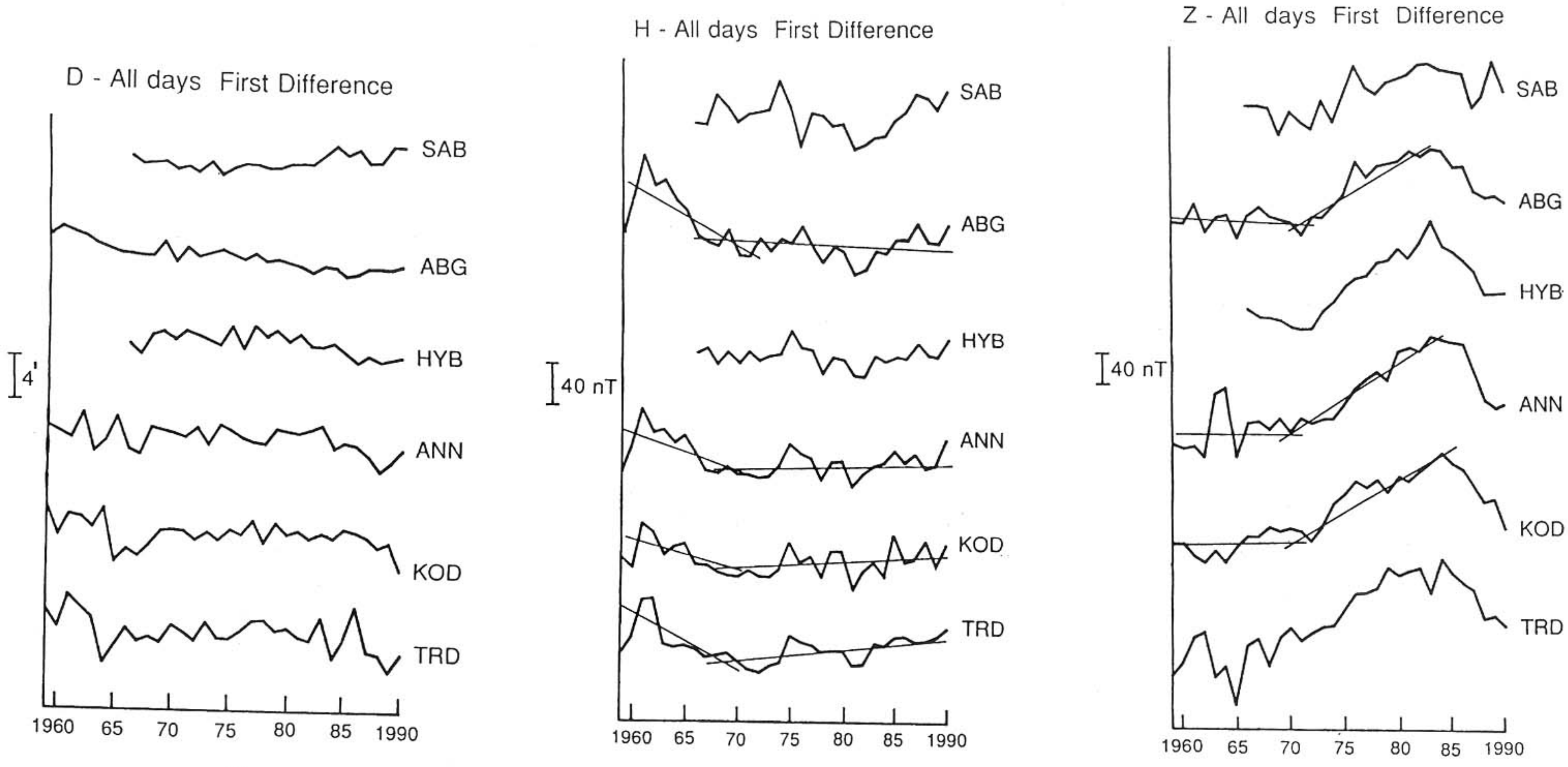
To quantify the local/regional anomalies in the secular variation over the Indian subcontinent, it will be necessary to take yearly observations at a denser grid of points, in the area between the fringe of the equatorial electrojet and Hyderabad/Alibag, take differences for successive years, and contour these after eliminating the large scale trends. The grid points should be operated as repeat stations with great care taken to remove external field effects and associated transient induced components from the observations. Such an exercise was undertaken by Spitta (1991) for the region surrounding Gottingen.

3.3 Secular jerk

When a sudden change in the slope of the smooth secular variation is seen, it is termed a secular impulse or a "jerk". A significant impulse was noticed in the declination at many observatories in Europe during 1969 (Le Mouël *et al.*, 1982). In the North American region, the H component was most affected, while Z was most effected in the Australasian and Siberian region (Whaler, 1987). A jerk around this period was also seen in Portugal (Pais and Miranda, 1995) and in Peru (Rangarajan *et al.*, 1996). Gubbins and Tomlinson (1986) detected the signature of the 1969–70 impulse in New Zealand too, but found that the epochs for the jerk in the Y component at Apia and Amberley differed by 2 years. Whether the causes for the impulsive changes are internal (Courtillot *et al.*, 1978) or external (Alldredge, 1979; Nevanlinna and Sucksdorff, 1981) is still debatable (Malin and Hodder, 1982).

Srivastava and Abbas (1984) examined the magnetic data for six Indian stations and found several significant changes, in 1963, 1970, 1974 and 1977, but attributed the impulses in H to external sources. According to Whaler (1987), the most striking visual effect is seen when the first differences of observatory annual means are plotted. Two straight-line segments with distinctly different slopes are indicative of a possible jerk. If the first derivative is fairly linear in time before and after the jerk, the cusp in the derivative is easy to detect (Gubbins and Tomlinson, 1986).

Plots of the first differences of annual means at the six Indian observatories are shown in Figs. 4(a), 4(b) and 4(c). No sign of a jerk is seen in the declination in the Indian region. In H and Z, however, discernible difference in slope could be noticed at some stations close to 1969–70. Sabhawala, farther away towards north, does not show the impulse. A suggestion for a second impulse close to 1980 is seen over the entire Indian network in H, and near 1985 in Z. Similar post-1969 jerks were indicated as a global feature by Langel *et al.* (1986) and also detected at Coimbra by Pais and Miranda (1995). Recently, Alexandrescu *et al.* (1996) suggested that the jerks in 1969 and 1978 are unguestionably of planetary extent. The jerk in Z seen here in 1985, on the other hand, appears to be local. From our analysis it appears that the secular jerk need not be a global phenomenon, but could be limited in extent. They are small in magnitude in the Indian region and lie in the same frequency region as the variation of external origin. If



(a) (b) (c)

Fig. 4. (a) Plot of first difference of annual mean values of declination (D) for all days at the six Indian stations from 1958 to 1990. (b) Plot of first difference of annual mean values of the horizontal component (H) for all days at the six Indian stations from 1958 to 1990. (c) Plot of first difference of annual mean values of the vertical component (Z) for all days at the six Indian stations from 1958 to 1990.

clearly identified to be of internal origin, the jerks can be used to investigate the generation/acceleration process in the Earth's liquid core and the distribution of electrical conductivity in the lower mantle (Le Mouël *et al.*, 1982; Golovkov *et al.*, 1992). The results presented here are consistent with the conclusions of McLeod (1985), who suggested that internal sources can give rise to changes in secular acceleration on short time scales of a year or two for some field components and some geographic locations.

3.4 Solar cycle component in the annual means

The detection of a quasi-periodic oscillation related to the solar activity or solar magnetic cycle in the presence of a large and occasional rapid change (as a secular jerk) in the magnetic field components requires careful analysis and scrutiny. Bhargava and Yacob (1969), Rivin (1974) and others have successfully attempted to elucidate the 11-year or 22-year signal in geomagnetic activity. Bhargava and Yacob (1969) found that the solar-cycle response was higher during the maximum of odd solar cycles, suggestive of a 22-year variation in the field. To study the long-term average effects of solar cycle activity on the magnetic field elements, Alldredge (1976) used annual means of *H* and *Z* as they were expected to reveal the effects of external sources more directly than *X*, *Y* or *D*.

The solar-cycle response, if present, is of magnitude much smaller than the secular trends or other oscillations with periods greater than 11 years. As suggested by Alldredge (1976), major trends must be removed and smoothing techniques adopted to leave a residual containing periods typical of the solar activity cycle. Several methods have been suggested (e.g., Rubin, 1988) and the final output appears to be dependent on the technique utilized. For example, the long series of *H* data from Alibag, when passed through an appropriate band pass filter, showed a diminishing amplitude of the solar cycle component

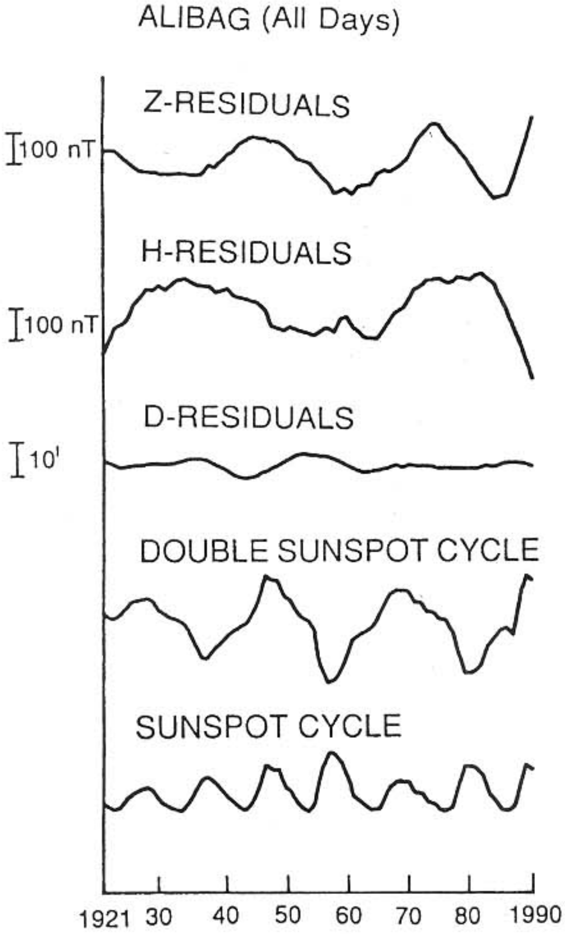


Fig. 5. Residuals of *D*, *H* and *Z* annual values for all days from the smooth secular trend at Alibag and the annual mean sunspot numbers together with Hale-cycle from 1921 to 1990.

between 1915 and 1940 (Bhargava and Yacob, 1970), whereas Alldredge's results for Alibag Z by a Fourier Analysis approach showed a significant presence throughout the interval 1900–1970 (see his figure 3(b)).

Keeping this in view, we consider only the actual residuals, measured as departure from the appropriate curves (cubic for H and Z and parabola for D) to see visually if there is any solar-activity-related component. As with the discussion on secular variation, we analyse the long series of Alibag data separately from the data for the Indian chain of observatories.

When we look for solar cycle component in the secular trends, it is likely to be more prominent in the residuals of all-day annual means rather than in quiet-day ones. The residuals from the best-fitting curves of D, H and Z for all-day annual means at Alibag and the annual mean sunspot numbers from 1921 to 1990, covering nearly 7 solar cycles, are shown in Fig. 5. To highlight the presence, if any, of the Hale cycle in the data, the annual mean sunspot numbers are also plotted with reversed sign in alternate cycles in Fig. 5. We emphasize that the residuals at Alibag derived from the polynomial fit for the longer series (1921–1990) are different from those shown in Fig. 6(b) for the restricted period of 1958–1990. The comparison of the two series for the common epoch would be indicative of some of the problems in using the rigged polynomials to model the long-term secular variation (as pointed out by our referee).

If the departures from the secular trend are largely due to the effect of the equatorial ring current, then there should be a phase opposition between H and Z at a station in the northern hemisphere as this source would decrease H and increase downward Z with enhanced solar activity (Alldredge, 1976). The fact that the D component in Fig. 5 hardly shows any oscillations, suggests that the residuals are indeed due to the effect of magnetic disturbances modifying the annual mean values. But when unfiltered raw residuals of H and Z are examined, there is no evidence whatsoever of a well-defined solar cycle signal. When this time series is processed to yield signals only in a limited band centred on 11 or 22-years, we may get a hidden solar-cycle component whose amplitude would only be a few nT at best, as shown by Bhargava and Yacob (1969). H and Z do not have identical periodicities. A 25–30 year oscillation (3 minima near 1930, 1955 and 1985) in Z residuals is not matched in H, which has a quasi-periodicity of about 50 years. Certainly these oscillations cannot be considered to be associated with sources of external origin.

The third-order residuals of D, H and Z for all-day annual means at the six Indian stations, together with the annual mean sunspot numbers for the period 1958 to 1990, are shown in Figs. 6(a), 6(b) and 6(c). Except for a significant minimum between 1960 and 1965 seen at the equatorial stations, annual mean declination residuals do not deviate appreciably from the secular trends, consistent with expectations of the minimal influence of equatorial ring current sources.

In the vertical component, an in-phase solar-cycle component can be seen for 2 of the solar cycles, with minima near 1964 and near 1985. Equatorial and lower latitude groups of stations do not indicate different patterns as was noticed for the secular trend curves depicted in Fig. 3(c). Sabhawala, farthest away from the dip equator, has the lowest amplitude. The minimum in Z, in phase with the solar activity minimum, is consistent with the expectated signature of the equatorial ring current in the northern hemisphere. Synchronously, we seen an anti-correlation between solar activity and the H and Z residuals, especially centred on the 1974–75 solar minimum. Larger residuals at Sabhawala suggests the absence of any latitude dependence in the magnitude of the oscillatory changes in the H component. This implies that there are other local features (including perhaps some errors due to baseline control) contributing to the observed departures from the smooth secular trend.

3.5 *Comparison of the observed annual mean values with IGRF models*

The International Geomagnetic Reference Field (IGRF) is a series of mathematical models of the main geomagnetic field and its secular variation (IAGA Commission 2 Working Group 4, 1969; Zmuda, 1971; Peddie, 1982, 1983; IAGA Division 1 Working Group 1, 1985, 1988; Barraclough, 1987; Langel, 1987; IAGA Working Group V-8, 1995; Barton, 1997). The reference field model gives a global representation of the geomagnetic field and could account for only very long wavelength anomalies. The comparison between observed and IGRF-derived field values helps to identify regional and local anomalies. Such a comparison of data from Teoloyucan observatory in central Mexico was carried out by

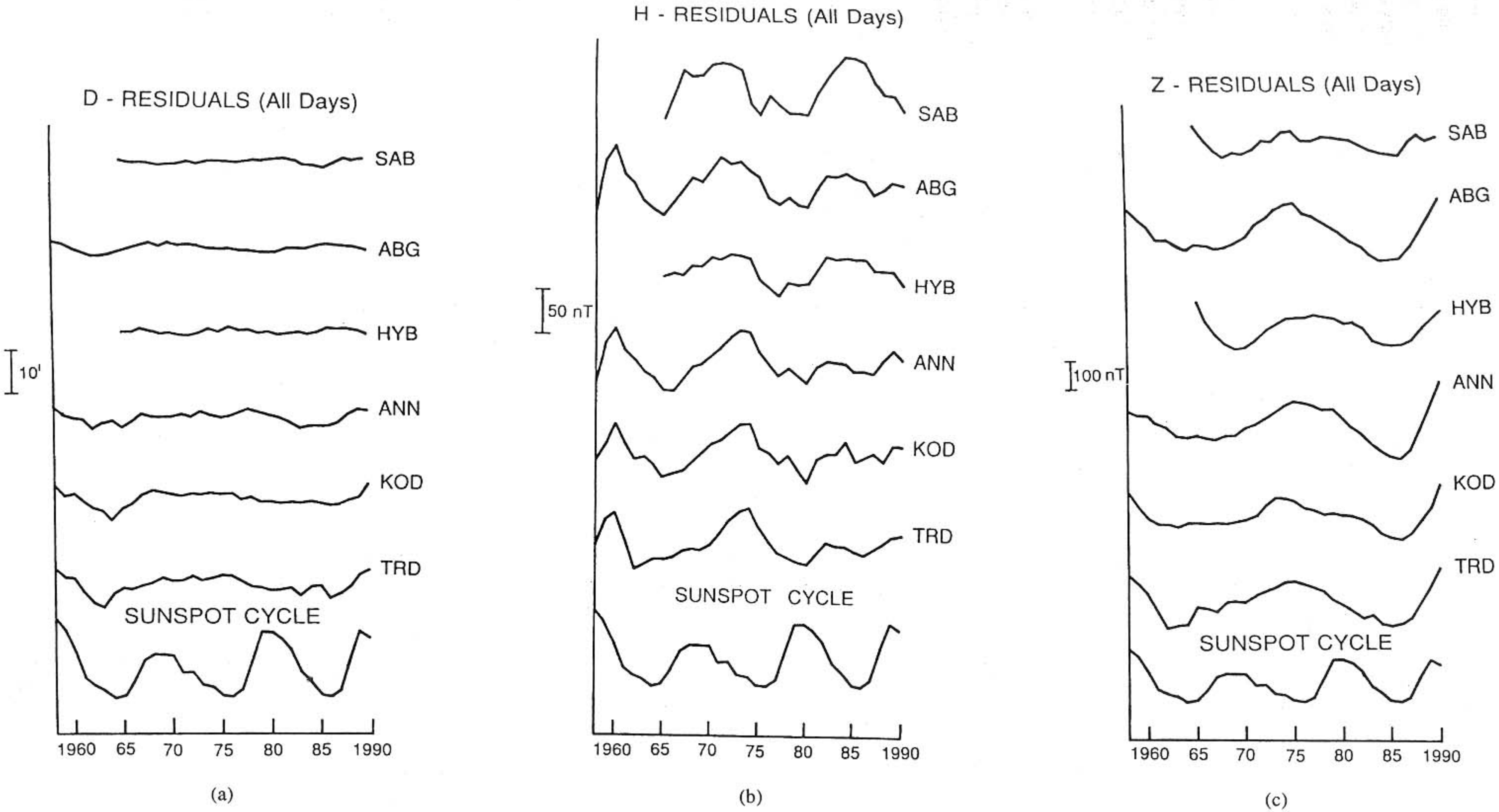


Fig. 6. (a) Residuals of declination (*D*) annual values for all days at the six Indian stations, together with annual mean sunspot numbers from 1958 to 1990. (b) Residuals of horizontal component (*H*) annual values for all days at the six Indian stations, together with annual mean sunspot numbers from 1958 to 1990. (c) Residuals of vertical component (*Z*) annual values for all days at the six Indian stations, together with annual mean sunspot numbers from 1958 to 1990.

Uruttia-Fucugauchi and Campos-Enriquez (1993). The good correlation between the two for the period from 1945 to 1990 was considered indicative of very low secular variation anomaly in the region of central Mexico.

Geomagnetic field values for the period 1955 to 1990 were calculated from the spherical harmonic coefficients of the IGRF. The differences between observed and model-based annual mean values of the three magnetic elements *D*, *H* and *Z* at 5-year epochs from 1955–1990 at all the six Indian stations, are shown in Fig. 7. Data from 1955 to 1957 for Trivandrum, Kodaikanal and Annamalainagar observatories were extrapolated backwards from the observed secular trend discussed earlier.

Among the DGRF models, the 1980 model may be considered the best one in view of the fact that MAGSAT satellite vector observations covering the entire globe were utilized systematically in its derivation. Departures between observed annual means and the model values for epoch 1980 can then be utilized as a standard for evaluation of anomalous local and regional contributions. For all the three components, Sabhawala in northern India has the least anomaly. From 1955 to 1990, a linear trend in the difference in *D* is seen at the stations close to the geomagnetic equator, while the anomaly in declination appears to be nearly constant farther away from the dip equator.

The time-dependent anomaly is most pronounced in Z. At Trivandrum, Annamalainagar and Kodaikanal, the initial datum may be unreliable since all were extrapolated from 1958 (see Alldredge, 1984, for example, for a discussion about such errors). The difference appears to be declining in the last decade (1980–1990). It appears that the regional and local nature of the secular variations differentiating between the equatorial and low latitude zones in the Indian subcontinent discussed earlier, are not adequately modelled by the IGRF. Interestingly, Sabhawala, farthest away from the dip equator, has the least *Z* departures with respect to the IGRF for all epochs. It may be noted that only the variation in the (observed-IGRF) differences is of interest. The size of the difference reflects mainly the crustal anomaly for the observatory.

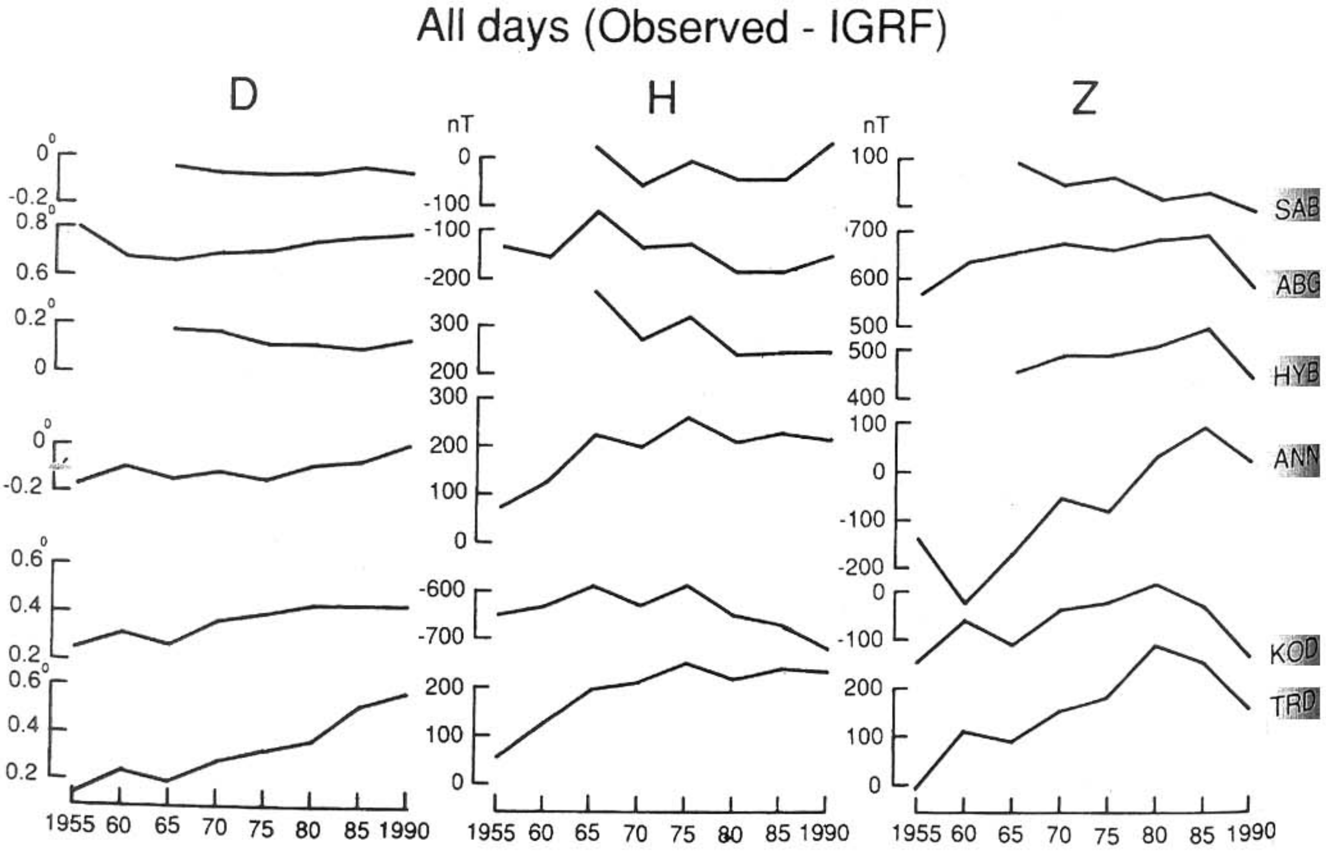


Fig. 7. Differences between observed and IGRF annual mean values of *D*, *H* and *Z* at the six Indian stations for the period 1955–1990, at 5 year intervals.

In the horizontal component, the secular trend in the observed field and IGRF model field are nearly the same after 1965. Between 1955 and 1960 there is an increase in the anomalous difference in *H* from 70 to 260 nT at Annamalainagar and 54 to 250 nT at Trivandrum, but this can again be an artifact of backward extrapolation. Also, first measurements at these two stations were made in 1958 when there was less expertise than in later years. We conclude that IGRF models, which are intended to provide only a broad regional representation of the main field and not local details, are adequate to provide grid values for India on a subcontinental scale.

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