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GEOMAGNETIC SECULAR VARIATION AT ADDIS ABABA OVER THE LAST FOUR DECADES: COMPARISON WITH 1945–2000 IGRF MODELS

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ABSTRACT: Addis Ababa Observatory (AAE) geomagnetic data analysed over the time-span 1958–1998 show that the annual mean values of the intensity have decreased since 1965 from 36186 nT to 35950 nT at a non-linear regression rate of 8–9 nT per year. Directional changes in the Earth's magnetic field that could be associated with southward and westward drifts of the dip equator are observed. On plotting the secular trends of the H, Z and D components, the variation in the H-component of Addis Ababa shows a near-sinusoidal cyclicity of about 40–50 years. The residual H, Z and D curves, obtained after removing polynomial fits, have been examined. The horizontal component H has been found to show pseudo-periodicity that would be considered to have parallelism with the 11-year sunspot cycle. Comparison of the observatory data with IGRF models for the period 1958–2000 show that the IGRF provides an excellent estimation of the geomagnetic Z and D components for the region, while it always underestimated the value of H. The mismatch in H may be due to the fact that the representative station being a dip equatorial station, it is under the influence of the equatorial electrojet and other solar activity effects. The comparison study in particular supports the existence of a relatively small magnetic anomaly in the region as implied by the IGRF data.

Key words/phrases: Equatorial electrojet, polynomial fitting, residual terms, secular variation

INTRODUCTION

Many attempts have been made to characterise the behaviour of the earth's magnetic field since the first quantitative records of the 16th Century. Information covering this behaviour can be found with the help of three types of data, namely historical, archaeomagnetic and paleomagnetic records. The first consists of direct geomagnetic field measurements and cover several centuries spanned by observatory measurements while the last two sources are through indirect measurements of the ancient field from the magnetised imprint left in human artefact or ancient rocks.

Direct ground magnetic observations have shown the earth's field to exhibit variations in intensity and direction whose periods range from milliseconds to decades. Those variations of short periods have been established to be caused by processes of external origin while the longer-period variations have been attributed to factors of internal origin (Doell and Cox, 1971; Bloxham and Gubbins, 1985; Courtillot and Le Mouel, 1976; 1988).

Concerning the variations of external origin, three major current systems have been accepted to be responsible for variations of the geomagnetic elements as recorded on the earth's surface. The solar daily variations of the quiet days S_q (associated with the solar daily variation of quiet days), the disturbance daily variations SD (related to the auroral electrojet and playing an important role in the annual line), and the storm time disturbance field D_{st} associated with ring currents. To separate the effects of these three current systems and associated fields, the monthly mean values of night hours only for quiet days at all hours and for disturbed days at all hours have been used (Rastogi and Patel, 1975; Campbell, 1980; 1981; Rastogi, 1993; Rastogi *et al.*, 1994).

External sources for the variation of the earth's magnetic field that are to be removed from magnetic data during secular variation studies may be found in electrical currents which may flow anywhere in the magnetosphere and ionosphere. The four principal external current systems of importance in such studies are (Roederer, 1970): magnetic boundary currents sustained by solar wind particles deflected on the boundary, the neutral sheet current dividing the magnetospheric tail in to two lobes of oppositely directed field, an east-west flow of currents around the earth centred on the magnetic equator (ring currents), and ionospheric currents flowing in the upper atmosphere. These external electrical currents are on the average throughout the year, symmetrical about the earth's geomagnetic equator (Roederer, 1970; Rastogi, 1993).

Secular variations, on the other hand, are long-term gradual changes in the earth's field and are of internal origin. These variations in the geomagnetic field arise primarily from changes in the irregular, or non-dipolar, part of the geomagnetic field. During the several centuries spanned by observatory measurements, for example, this non-dipole field has been observed to change slowly in shape and to drift westward at a rate of about 0.2° of latitude per year (Doell and Cox, 1971; Malin *et al.*, 1983; Bloxham and Gubbins, 1985; Gavoret *et al.*, 1986; Courtillot and Valet, 1995; Pais and Miranda, 1995).

A substantial part of the geomagnetic secular variation observed at a fixed locality is due to the westward drift of non-dipole features past the locality.

Hence, where the relief of the non-dipole field is small, the secular variation should also be small. The obvious way to determine whether there is a secular variation of the field would therefore be to map the behaviour of the non-dipole field for earlier times.

On most instances, it has been found adequate to use monthly and annual means to study variations of periods longer than the lower limit (2 yr. or 6.07 yr., Curie (1973)) to separate the causes of internal origin. In the use of annual mean values, the variations with periods shorter than one year, such as S_q, magnetic storms and substorms, are eliminated but longer period oscillations associated with periodicities like 11 years, 22 years and more are retained. Annual and monthly means and hourly values of measurements at ground observatories are typically used to model and map these variations (Peddie and Fabiano, 1976; Urrutia-Fucugauchi and Campos-Enriquez, 1993; Bhardwaj and Rangaranjan, 1997). Accordingly, all-day annual mean data have been used to study the geomagnetic secular variations, those variations which arise primarily from changes in the irregular or non-dipolar part of the geomagnetic field, over East Africa in this work.

Data analysis

Based on the many suggestions as to the period separating the variations of internal and external origin (Curie, 1976; Courtillot and Le Mouel, 1976; Gubbins and Tomlinson, 1986) it normally seems sufficient to use annual means in order to study variations with periods longer than a year. Therefore, annual mean values of the geomagnetic field components H, Z and D for all days of the year have mainly been used in this work. However, in order to test the validity of the method and for the purpose of comparison, data of quiet days comprising the five quietest-days of the month selected based on the K_p index were also used on some of the components.

In the analysis of the data, polynomials are fitted to the data of all-day annual mean values of H, Z and D using the available software utilising the technique of propagating least squares (Gangi and Shapiro, 1977). The fitting trend (a parabolic, cubic or curves of higher order) has been taken to account for the secular variation of internal origin. The close fitting of the fitted curves into the data (the all-day annual mean values), as given by the percentage of fit, have been taken as a measure of how good the fit are in accounting for the major part of the very regular secular variation. The residual variations that remain after the removal of the best fitting trends are expected to exhibit a world-wide character like the 11-year solar cycle or annual and semi-annual lines.

RESULTS AND DISCUSSION

The results of the analysis carried out on the annual mean values are discussed in terms of (i) trends in secular variation (ii) residual terms and (iii) comparison with IGRF models.

(i) Secular change at Addis Ababa (1958–1999)

Systematic observation of the earth's magnetic field at Addis Ababa has been carried out since the 1950's in the Addis Ababa Geomagnetic Observatory (AAE). The Geophysical Observatory of the Addis Ababa University operates the geomagnetic field observations. The geographic and geomagnetic co-ordinates of the station are, respectively, 9° 033′ N 38° 766′E and 5 ° 3′N and 109° 2′E and dip latitude of −0.5 °, clearly a dip equatorial station. Geomagnetic elements were measured uninterrupted using the Ruska Variometers and the station has recently joined the group of observatories in the INTERMAGNET programme with instrumentation for the digital recording of the geomagnetic elements and near real-time processing of data. As the only long period operating observatory in the region, these series of ground observation data have been analysed to obtain information on the secular variation of the earth's magnetic field over the East African region.

The analyses for the quiet day annual means of H, Z and D components have been found to show identical curves and trends as those of the all-day annual mean data. The plots of only the all-day annual means are presented and discussed.

In Figure 1 are shown the all-day annual mean values of the components H, Z and D of the earth's magnetic field at Addis Ababa over the period 1958-1999. In order to take secular variation into account, the technique of propagating least squares (Gangi and Shapiro, 1977) were used to fit polynomials to the three sets of data, and the fitted curves are also shown in the same figure. For the Z and D data, the quality of the simple numerical fit is striking: indicating that the fitted curves are sufficient to account for the major part of the slow variations that are known to be of internal origin.

Table 1 gives the percentage of variance in Addis Ababa all-day annual means accounted for polynomial fits. All the polynomial trends leave a very small percentage of variance unaccounted for. The closeness of the observed and fitted figures is indicated by the cumulative percentage variance accounted for by addition of each higher order polynomial term. Higher order polynomials of order of about five almost completely reproduce the observed variation.

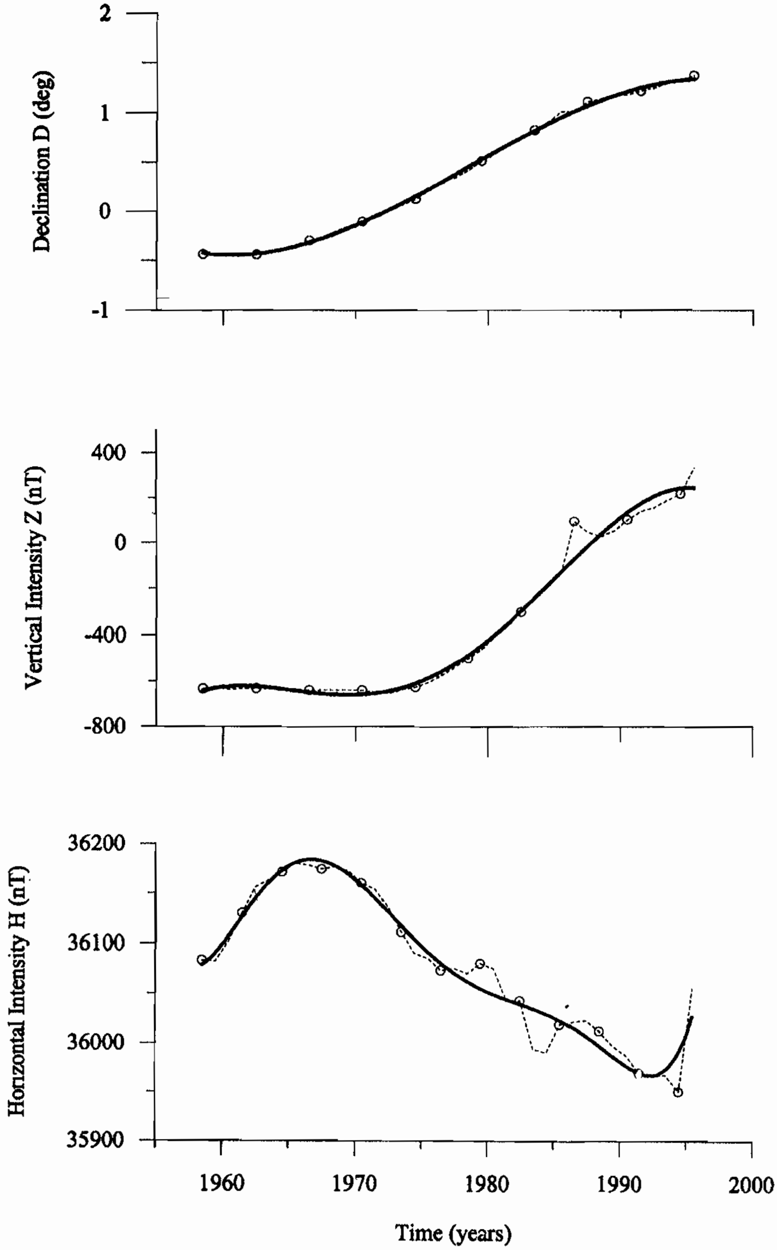

Fig. 1. Observed all-day annual mean values of H, Z and D for all days at Addis Ababa from 1958–1998 (dashed curves) together with their best fitting curves (solid lines).

Table 1. Percentage of variance in Addis Ababa for all-day annual means accounted by polynomial fits and the equation of best fitting curve.

	1st Deg.	2nd Deg.	3rd Deg.	4th Deg	5th Deg	6th Deg
H	70.99	75.79	91.96	92.71	93.14	95.43
Z	83.00	96.71	97.39	98.72	98.78	
D	97.93	98.23	99.88	99.89	99.9	

H: $36077-5.92X + 8.097X^2 - 1.10X^3 + 0.058X^4 - 0.0014X^5 + 1.226E\text{-}05X^6$.

Z: $-666.416 + 26.78X - 4.92X^2 + 0.274X^3 - 0.0038X^4$

D: $-0.4 - 0.029X + 0.005X^2 - 7.93E\text{-}05X^3$

(where, X= 1,2,3, … 40 corresponds to the years 1958–1999).

Referring to Figure 1, H shows a near-sinusoidal secular trend with a quasi-periodicity of about 40–50 years which is in agreement with the suggestion made on the expected cyclicity for stations close to the equator based on their studies on equatorial and low latitude stations by Bhardwaj and Rangarajan (1997). It attains a maximum by about 1965, consistent with results reported earlier for other stations, and has been decreasing at a rate of about 8–9 nT/year. This rate of decrease is less rapid as compared to those reported for low-latitude observatories, for example to those in the Indian sector. The rate of ascent in the field, prior to 1965, is more linear and faster than the post-maximum decrease.

The increase in Z since 1970, which is rather rapid for the equatorial station, indicates the southward migration of the dip equator, that has been confirmed to take place since 1971 (Rangarajan and Deka, 1991), and that of D to be due to the westward drift of the dip equator over the region.

The changes in direction of the earth's magnetic field over Addis Ababa for the period from 1958–1999 are also illustrated in Fig. 2 that shows the annual mean values of the inclination and declination taken from observatory data. The changes in both D and I are more or less similar throughout the period. The earlier period extending up to 1970 is characterised by relatively small directional changes followed by a steeper increase since. These are related to the southward drift of the dip equator and westerly declinations.

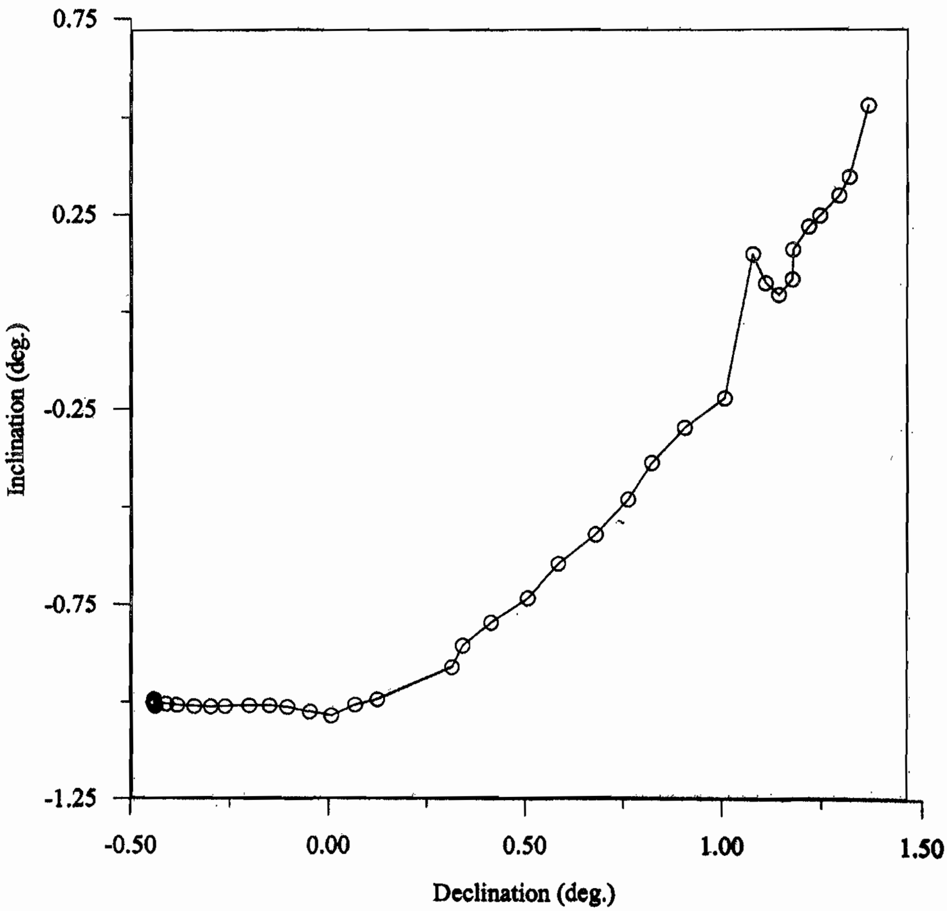

Fig. 2. Directional changes in the geomagnetic field in East Africa observed at the Addis Ababa observatory during the period 1958–1999.

An equatorial station like Addis Ababa is under the influence of the equatorial electrojet that causes enhancement of the daily variation and short-period fluctuations in H. Although the electrojet will not contribute in any measurable way to the relatively long-period variations that determine the secular trend, it may introduce departures from the trend that should be seen as residuals while the fitted curve is taken from the observatory data.

ii) Residual terms

These residuals, which are plotted in Figure 3 for the three components, are the differences between the annual means and the fitted secular variation curves. They are expected to show correlation of a global nature giving trends such as solar cycles and annual and semi-annual lines in the earth's magnetic field. Furthermore, residuals of all-day annual means considered in this work are expected to show any solar cycle component than the quiet mean annual means.

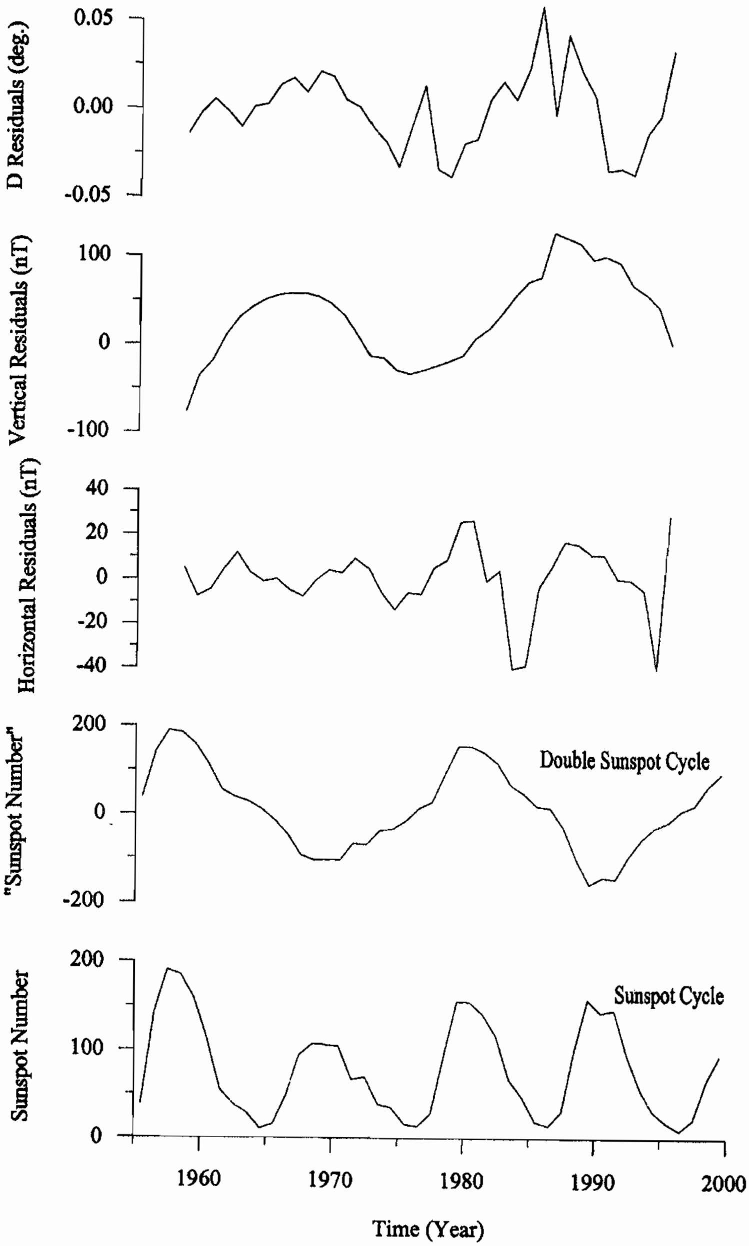

Fig. 3. H, Z and D annual residual values for all-days from the smooth secular trend at Addis Ababa and the mean sunspot numbers together with the Hale-Cycle from 1958–1999.

Visual inspection of the residual plots for H, Z and D, and solar cycle and double solar cycle plots for the corresponding years given in the same figure (Fig. 3) for any solar activity related component reveals no evidence of such a relationship. A closer examination of the curves shows that H attained four maxima in the period of about 40 years suggesting a quasi-periodicity of 10 years or more close to the solar cycle periodicity. The apparent lag in the H-residual peaks from the solar cycle maxima is because effects on the H-component observed field due to the westward flowing ring current, which generally increases as the sunspot numbers increase, lags behind the sunspot numbers by a year or two. The vertical component and the declination, on the other hand, show oscillations of about 25 years or more that are of longer period to be associated with sources of external origin and appear to show variations that are in phase opposition with the double solar cycle phenomena.

iii) Comparison with IGRF models

The International Geomagnetic Reference Field (IGRF) provides mathematical models for the earth's main magnetic field and its secular variation. It has been widely used to derive values of the geomagnetic components for places where limited direct ground observations are available. It would therefore be interesting to test how good the IGRF is representative to the magnetic field of a certain area by checking it against observatory values of magnetic components.

Comparisons of this type have been carried out for data from West Africa (Vassal, 1987), for data from Teoloyucan Observatory in Central Mexico (Uruttia-Fucugauchi and Campos-Enriquez, 1993), for data from Coimbra Observatory, Portugal (Pais and Miranda, 1995), and more recently for data from India (Bhardwaj and Rangarajan, 1997). A good/bad correlation between the IGRF values and observatory data were considered to be indicative of low/high secular variation anomaly in the respective regions under consideration.

IGRF magnetic field values calculated from the spherical harmonic coefficients for the period since 1958 (Papitashvili and Papitashvili, 1999; Mandea *et al.*, 2000) and values of these fields from Addis Ababa observatory for the horizontal component (H), the vertical component (Z), and declination (D) are shown in Figure 4.

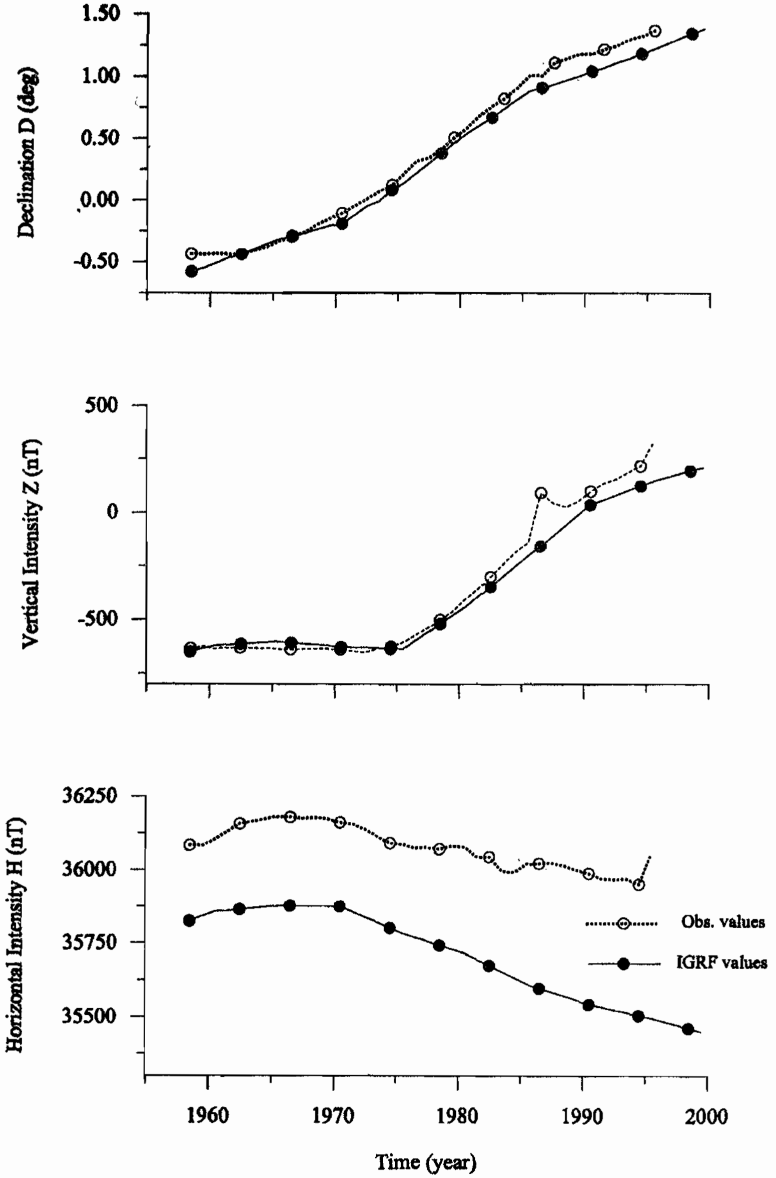

Fig. 4. Comparison of Horizontal Intensity (H), Vertical Intensity (Z) and declination (D) values according to the IGRF model and corresponding all-day annual means from Addis Ababa observatory for the period 1958–1999.

From the figure it is seen that the IGRF derived values for the Z and D components (dashed lines) are in a remarkable agreement with all-day annual mean data for Addis Ababa (solid lines). In the case of the horizontal field H, the IGRF values have always underestimated the value of this field over the region although the trends are similar. Variations of shorter duration in the observed H data are not reflected in the IGRF values. This is natural because the IGRF models are intended to provide a general regional representation of the main field and not local details, and further in all-day values we have considered here even the effects of magnetic storms are likely to be still present. This is explained through the fact that as the Addis Ababa station is a dip equatorial station under the influence of the equatorial electrojet currents and the component that reflects any shorter period variations in the region being the horizontal component, the response of this component to more local phenomena is expected. The less contribution of the region to the global spherical harmonic analysis due to scarcity of observatories or repeat station data is not reflected in the comparison studies.

SUMMARY

This work has briefly summarised the only available continuous observations of the geomagnetic field in the East African Region in terms all-day annual mean values of horizontal and vertical intensity, and declination.

In general, it is clear that parabolic and cubic (for Z and D), and higher order curves (for H) are excellent fits to the geomagnetic data and take into account the major part of the very regular secular variation of internal origin. The residual terms, obtained after the secular trends have been removed from the data, have been examined for relation to variations of intermediate period like solar cycle and double solar cycle variations.

Residuals in H show a near solar-cycle periodicity with the expected delay in ground measurable effects of a few years, while the Z and D components show quasi-periodicities of longer duration to be associated with variations of external origin.

The period under study is also shown to be a period in which directional changes in the earth's magnetic field are observed. These changes are characterised by a southward drift in the dip equator, as shown by the continuous increase in the vertical component/ inclination, and a westward drift in the dip equator associated with the westward drift of the Earth's non-dipole field which is the principal contributor to secular variation.

Although the contribution of the East African region in providing data for the derivation of the IGRF is limited to data from the AAE, the satisfactory fit between the IGRF magnetic field values and the observatory values indicate that the IGRF, which is mainly intended to provide a global representation of the earth's field, are also adequate to give a good representation of the earth's field in the region. The apparent good correlation between these two sets of data also shows that there are no significant secular variation anomalies in the region during the period under consideration.

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