Geofísica Internacional (2000), Vol. 39, Num. 4, pp. 323-336

Secular change in the location of the magnetic dip equator in the twentieth century

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Received: September 8, 1999; accepted: June 6, 2000.

RESUMEN

La situación geográfica del ecuador magnético (inclinación = 0°) en diferentes longitudes ha sido calculada, usando los coeficientes de armónicos esféricos definidos en Modelos de Campo Geomagnético de Referencia Internacional durante 21 épocas de 1900 a 2000. Se ha demostrado que la tendencia migratoria en el ecuador magnético es sumamente diferente en los sectores americano, africano e hindú. Grandes cambios se han visto de los 30°W a 40°W, mientras que prácticamente no existe movimiento por más de cien años en los 30° longitud este. Se ha visto que la longitud geográfica del ecuador magnético está mucho más lejana del ecuador geográfico en el sector americano, que demuestra una migración hacia el oeste del orden de ~0.2°/año, cuyo promedio es mejor que la deriva hacia el oeste del campo no-dipolar, tratada en publicaciones. Las distancias entre el eje magnético del dipolo inclinado, el eje terrestre y el eje de la Anomalía Geomagnética del Atlántico del Sur (SAGA), la migración local mínima de la longitud del ecuador magnético en el eje americano están linealmente relacionados. Además la deriva hacia el oeste en la línea límite sobre el ecuador geográfico en el sector americano es indicativo de las contribuciones desde las condiciones no-dipolar y está también relacionado linealmente con los tres parámetros. Como la ubicación observada del ecuador magnético en el sector americano se ajusta muy bien a los resultados del modelo, se sugiere que la identificación de la longitud geográfica del ecuador magnético en la zona americana basado sobre un levantamiento de una área pequeña puede proporcionar información útil sobre otros parámetros de la deriva hacia el occidente del campo geomagnético.

PALABRAS CLAVE: Ecuador magnético, variación secular, deriva al oeste, centro magnético, anomalía magnética del Atlántico del Sur.

ABSTRACT

Using the spherical harmonic coefficients defining the International Geomagnetic Reference Field Models for the 21 epochs 1900 to 2000, the geographic locations of the dip equator in different longitudes were computed. It is shown that the migratory trends in the dip equator are widely different in the American, African and Indian sectors.The largest change is seen over 30°W to 40°W while there is practically no secular movement over 100 years in the 30°E longitude. It is seen that the geographic longitude of the dip equator farthest away from the geographic equator in the American sector shows a westward migration at the rate of ~0.2°/year which compares favorably with the average westward drift of the non-dipolar field discussed in the literature. The distance between the magnetic center of the eccentric dipole and the Earth's center, the South Atlantic Geomagnetic Anomaly (SAGA) center and the migration of the local minimum of the dip equatorial longitude in the American center are all linearly related. In addition, the westward drift in the agonic line over the geographic equator in the American sector, indicative of the contributions from non-dipolar terms, is also linearly related to the three parameters. As the observed location of the dip equator in the American sector closely matches the model-based one, it is suggested that identification of the geographic longitude of the dip equator in the American zone based on a survey over a small area can provide useful information on several other parameters of the westward drift of the geomagnetic field.

KEY WORDS: Dip equator, secular variation, westward drift, magnetic center, South Atlantic magnetic anomaly.

INTRODUCTION

The dip equator, the line on the Earth's surface along which the geomagnetic vertical component (Z) and the inclination (I) are zero, does not coincide with the geographic equator. In the South American region, it has the farthest departure to the south from the geographic equator; in the African sector it runs in the vicinity of 10° N and in the Indian subcontinent and further to the east, it continues to be north of, and nearly parallel to the geographic equator. In the longitude sector between 60°W and 15° W, the dip equator swings rather dramatically from south to north, a feature not seen elsewhere. The electrodynamics of the daytime equatorial ionosphere and the consequent enhanced geomagnetic signature in the horizontal component due to the Equatorial Electrojet currents are intimately tied to the location of the dip equator (Rastogi, 1989).

As the geomagnetic field undergoes secular change, the geographic position of the dip equator in different regions also changes concurrently. Migration of the dip equator has been studied in detail in the past over restricted areas. Vassal (1990) found that in West Africa the movement was northward by about 10° between 1913 and 1986, but further east near 15° E longitude, there was practically no change during the 75- year period. He also noticed that the drift was faster after 1970 as compared to that in the interval 1950-1960. Over Brazil, the dip equator was found to move northward by nearly 8° between 1904 and 1960 and by only about 4° between 1960 and 1985. Further west, the displacement was less significant, just 1.4° northward (Barreto, 1987). In the Indian peninsular region, Rangarajan and Deka (1991) noticed that the migratory movement was southward since 1945 and it was more rapid after 1970 compared to the interval 1945-1970, when the dip equator was confined to a narrow zone between 8.5 and 9° N. Further to the east of India, in Vietnam, the southward migration at a comparable rate was identified by Thoa *et al.* (1990). At Addis Ababa in Ethiopia (~40° E), the annual mean value of the vertical component remained negative and nearly constant between 1960 and 1975 and has been increasing since then tending to a value close to 0 by 1989, corresponding to a northward progression of the dip equator in the vicinity of the station. Some of the reported results are based on observations of the field whereas others are based on the models of the main field of the Earth.

Thus, we notice that the dip equator is not meandering as a single entity. This may be largely due to the fact that the secular variation of the vertical component close to the equator has several known regional features such as the intense cell of secular variation in the North Atlantic which is shown to move north-west (Vassal, 1990). Also, on occasion, the secular change in some of the magnetic elements over some regions shows an abrupt discontinuity. A classical example of such an impulsive change was seen in 1969-1970 (Le Mouel *et al.*, 1982 and references therein). The two principal features of the secular variation of the geomagnetic field are the decay of the dipole component of the field by about 7% since 1845 and the westward drift, first recognized by Halley (1683,1692). Halley estimated a rate of 0.51°/year for the drift. These features have been under investigation in the last several decades (see Langel (1987) for details).

Mathematical representation of the Earth's main field and its secular change by Spherical Harmonic Analysis was initiated by Gauss (1839) and several different approaches using different magnetic elements have been attempted (Barraclough, 1978). In their seminal publications, Vestine *et al.* (1947a, 1947b) derived the harmonic coefficients up to degree and order 6 based on data from 2000 repeat stations and 100 observatories covering the interval 1905 to 1945. They interpreted the secular change in the main field in terms of the changes in conjectural electric current configurations inside the Earth.

To unify the plethora of models of the main field, the International Association of Geomagnetism and Aeronomy (IAGA) arrived at a process of consensus from among the competing models, using weighted averages of the harmonic coefficients so that the mean square deviation between observed and modelled data turns out to be the least. From 1965, these are called International Geomagnetic Reference Field (IGRF). These models are updated every five years.

IGRF, providing spherical harmonic coefficients up to degree and order 10 for the years between 1900 and 1995 and a model for secular variation up to the year 2000 are now available (Barton *et al*., 1997). While the first order coefficients (g_1^0, g_1^1 and h_1^1) of these models define the moment and position of the centred tilted dipole, the second order terms (g_2^o,g_2^1,g_2^2,h_2^1 and h_2^2) enable us to determine the parameters of the eccentric dipole i.e. the dipole approximation where the magnetic centre of the dipole is shifted away from the Earth's centre. Both the centred and eccentric dipoles have shown considerable change in position since 1600, as discussed in detail by Fraser-Smith (1987) who has given the governing equations to derive the different parameters.

In this paper, we identify the geographic latitude of the dip equator (I=0 and Z=0) in different longitude sectors, 5° apart, in the South American, African and Indian zones for each of the 21 epochs 1900 to 2000 and discuss their migratory changes in the last 100 years. We also determine the parameters defining the corresponding dipole and eccentric dipole for each epoch using the first eight Gauss coefficients and show how they change with time. The observed changes in the dip equator in the three continental areas and the relationship of the location of the dip equator in the American sector with the westward drift of the eccentric dipole and non dipole fields are discussed in detail.

DATA ANALYSIS

Working Group V-8 of IAGA dealing with the "Analysis of the Global and Regional Geomagnetic Field and its Secular Variation" has provided to the scientific community the definitive spherical harmonic coefficients (degree and order up to 10) constituting the International Geomagnetic Reference Field (IGRF) for each of the epochs 1900, 1905, 1910,.....,1995 and the model coefficients for secular variation for extrapolation to 2000. In addition, the necessary computer program to obtain the field values at any desired location (identified by its geographic latitude, longitude and altitude) for any chosen epoch is also given. The program is based on the routine of Malin and Barraclough (1981). With this, one can generate a grid of values for any magnetic element between any specified bands of longitude and latitude in steps pre-defined by the user (0.1° adopted here). From this grid, it is easy to interpolate for the geographic latitude corresponding to Z= 0 in any longitude sector as the values change from positive to negative with changing geographic latitudes. As the dip equator runs over only the landmass of South America, Central Africa and peninsular India, apart from a small section farther east of India, we confined our

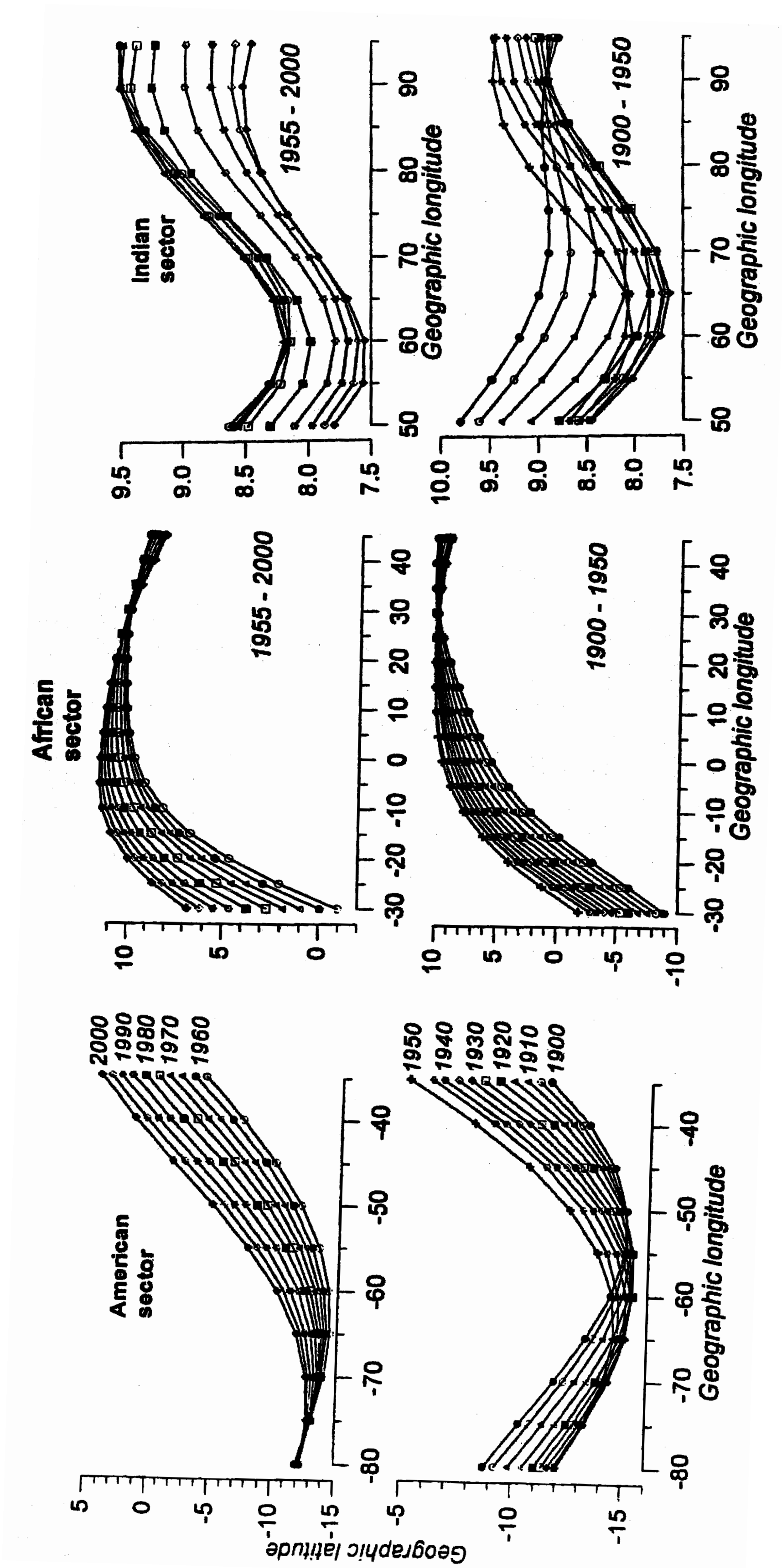

Fig. 1. Geographic latitude of the dip equator (corresponding to the vertical component Z=0) in different longitudes (5° apart) derived from the IGRF spherical harmonic coefficients for 21 epochs: 1900, 1905, 1910...... 2000. The longitudes are divided into three regions as American, African and Indian sectors for the purposes of discussion.

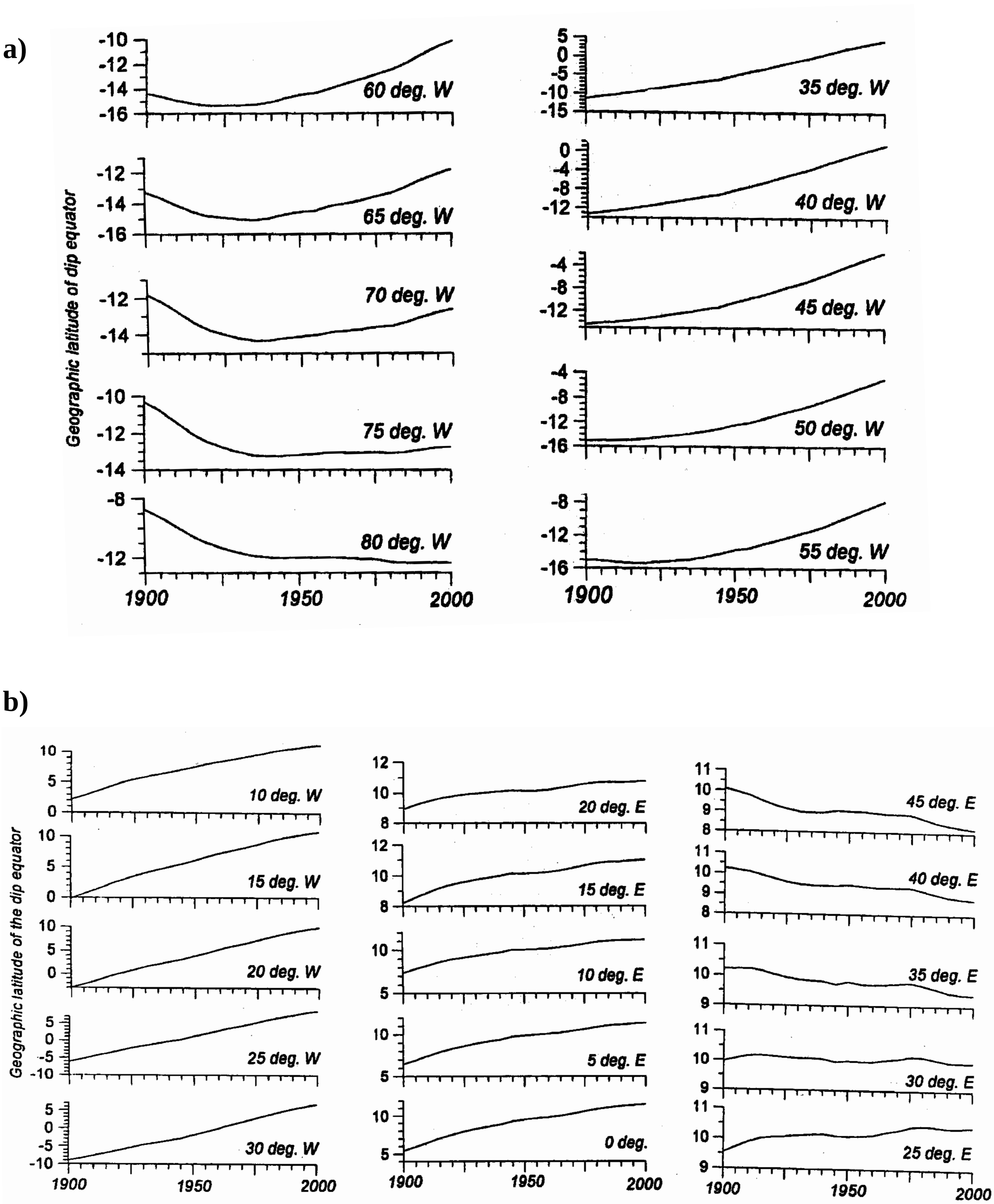

Fig. 2. The change in the geographic latitude of the dip equator with time in individual longitudes (5° apart) covering (a) the American sector, (b) the African sector.

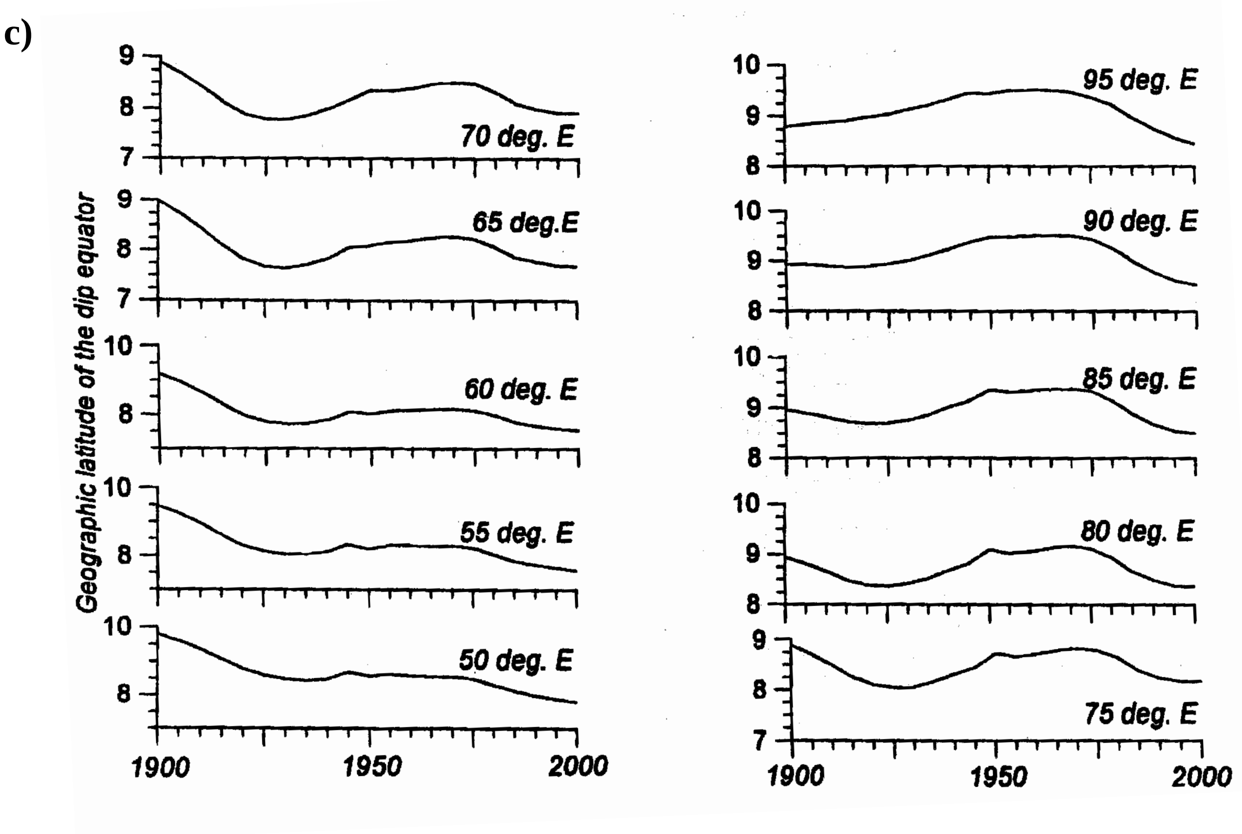

Fig. 2c. The Indian sector

attention to the longitudes between 80° W and 35° W (identified as the American sector), 30° W to 45°E (African sector) and 50°E to 95° E (Indian sector). For each of the 21 epochs between 1900 and 2000, we determine the geographic latitude corresponding to zero inclination (or Z=0) every 5 degree apart in longitude. The longitudinal profile of the geographic latitude of the dip equator for each epoch for the three sectors are shown in Figure 1. The migratory trends of the dip equator as indicated by the changing geographic latitude for each 5° longitude are depicted in Figure 2a, 2b and 2c for the American, African and Indian regions, respectively. To highlight the variable magnitude of the migration of the dip equator, the ranges of geographic latitude covered by the moving dip equator in different longitudes – taken as the difference of maximum and minimum values of the latitudes – are plotted in Figure 3. Third degree polynomials best fitting the curves for each epoch (Figure 1) are determined using orthogonal polynomials which ensured the adequacy of the terms, and these equations are then used to determine the extreme positions in terms of the displacement of the dip equator from the geographic equator. The corresponding geographic longitudes for each epoch for the three sectors are shown in Figure 4. While there is a clearly defined minimum in the curves for American sector and a fairly well determined maximum for the curves in the African sector, we get both a minimum and a maximum for the Indian sector due to the undulatory nature of the longitudinal profile of the geographic latitude. Hence for the Indian region, the first curve shows the longitude of the minimum (closest to the geographic equator), whereas the second curve shows the longitude of the maximum (farthest away from the geographic equator).

RESULTS AND DISCUSSION

The most important aspect noticed in Figure 1 is that the movement of the dip equator in the three sectors is distinctly different. While it is nearly parabolic in the American sector, all the curves tend to converge over 30°E longitude in the African sector, and the shape of the curves in the Indian sector tends to be sinusoidal. It provides clear evidence, yet again, that the dip equator does not swing as a single unit over a period of time but is intimately connected with the variable secular trends peculiar to each region. Another point worthy of note in Figure 1 is that, in the American sector, the minimum of the curves reflecting the farthest point away from the geographic equator in the southern hemisphere, hereafter called 'local minimum', is progressively shifting and there is a clear difference between

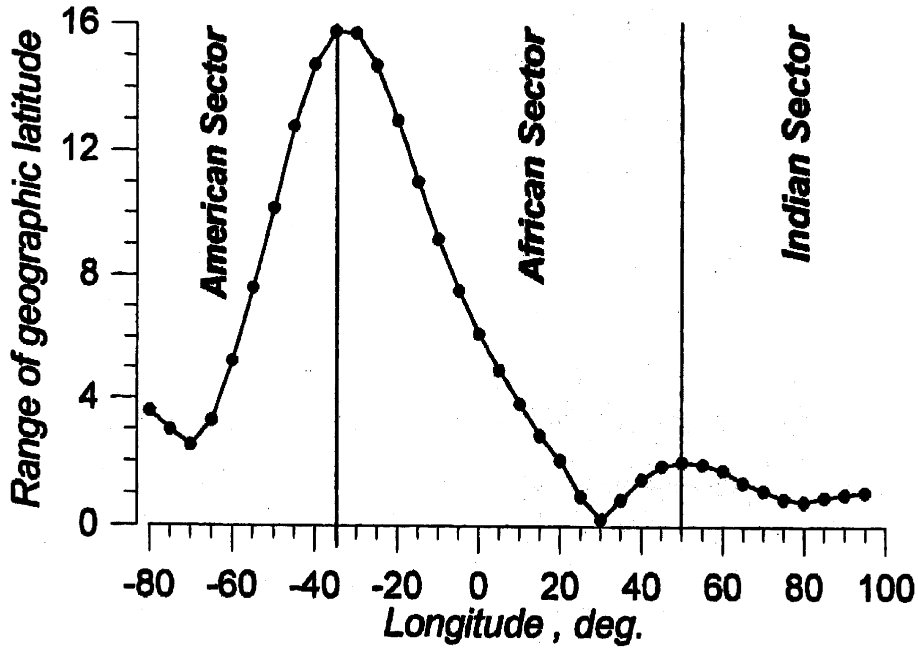

Fig. 3. Range of migration of the dip equator, in terms of the range of geographic latitude covered between 1900 and 2000, in different longitude sectors.

the two groups of 50 years. Such a difference, though present, is less pronounced in the African and Indian regions.

Figure 2a, 2b and 2c show the direction of movement of the line of zero dip in each longitude sector. Close to 75° W, the dip equator shifts south initially but after 1940 remains quite stable. This tendency is altered to a swing towards the north further east between 70°W and 55° W. An unmistakable northward change through the 100 years over the entire longitude zone between 50°W and 25°E is noteworthy. However, the most striking aspect of these profiles is the near-constant location of the dip equator (geog. lat.~10° N) centered on 30°E longitude for the entire 100-year period. This nodal point marks a clear separation of sectors to the west with a northward migration and to the east with a southward change. Earlier, Rangarajan (1994) found that this feature was seen when the spherical harmonic models were confined to the then available IGRF models between 1945 and 1990, but if one used all available spherical harmonic models beginning from 1600 (Barraclough, 1974), an unambiguous northward migratory trend was noticed even in this longitude sector. It thus appears that the nature of the secular variation of the geomagnetic field, of which this feature could well be a part, was different prior to and after 1900. This conclusion is consistent with the finding of Fraser-Smith (1987) who observed that the eccentric dipole was located south of the equatorial plane prior to 1900 and is presently at its greatest distance north of the plane.

Unlike the secular change of the dip equator seen in the American or African sectors, the migration in India is marked by two distinct categories. Up to 60°E, we notice a southward migration, albeit rather weak, but between 65°E and 95°E (last of the longitude zones covered in the present analysis), the movement is undulatory. A peculiar break in the smooth time profile is also noticed in the epoch 1945 or 1950. This cannot be attributed to any artifact of the models because such a feature is not seen in the other two regions considered, nor is it seen uniformly everywhere even in the Indian sector.

Urrutia-Fucugauchi and Campos-Enríquez (1993) reported that at Teoloyucan observatory, located to the north of the dip equator near 100°W, the dip angle increased steeply between 1923 and 1938 and much less later. This is in accord with the southward migration of the line of zero dip noticed at 80° W up to about 1940, which remained steady thereafter suggesting that the pattern of temporal change in the dip equator between 80°W and 100°W is similar to that shown for 80°W.

To quantify the magnitude of the migration over 100 years in different geographic locations, we have shown in Figure 3 the range, taken as the difference in the geographic latitudes of the dip equator between the farthest and least departure from the geographic equator for each 5° longitude. While the African and American sectors are marked by rather pronounced change in the magnitude of the range, the

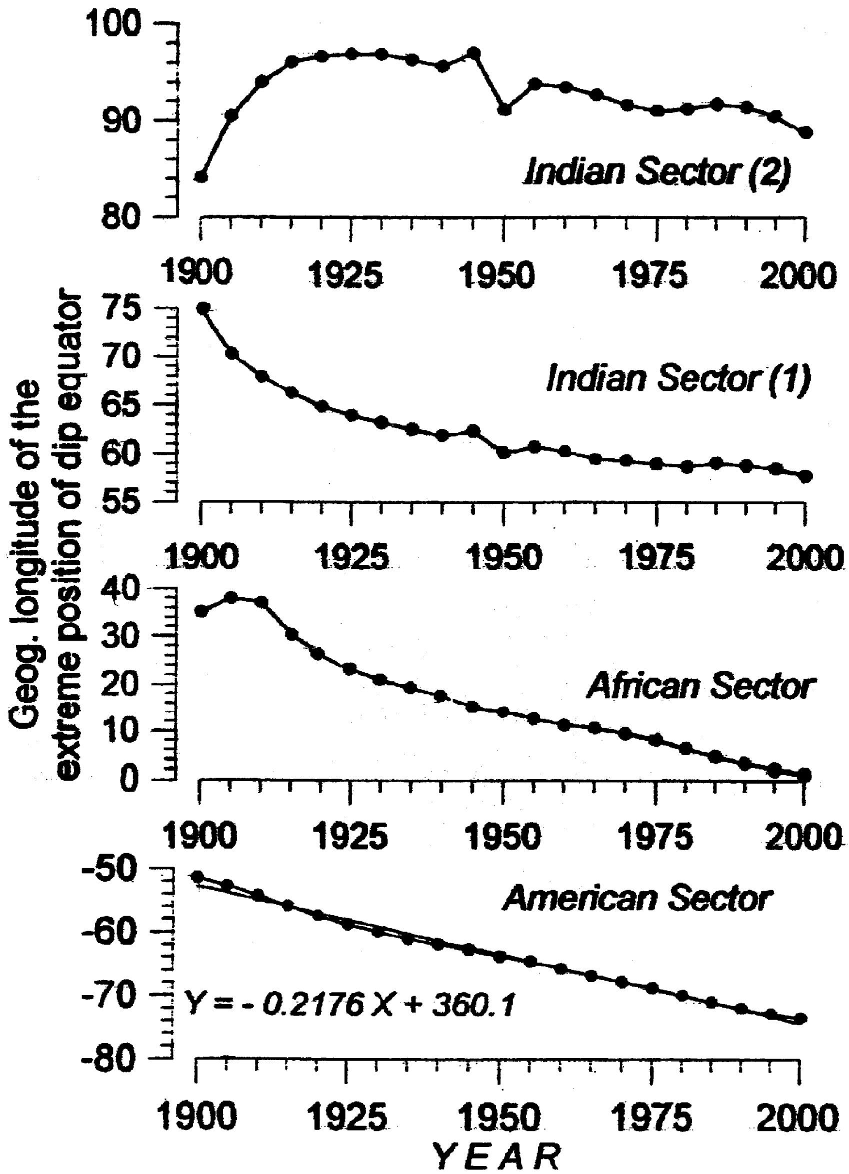

Fig. 4. Time variations in the longitude of the extreme position of the dip equator with respect to the geographic equator in each epoch derived from the third degree polynomial best fitting the curves shown in Fig. 1. For the American sector, it is a local minimum, for the African sector it is a local maximum and for the Indian sector (1) refers to the local minimum and (2) refers to the local maximum. For the American sector, the linear trend is approximated by the equation shown where Y is the longitude of the local minimum and X are years between 1900 and 2000.

movement in the present century is confined to a very small latitude zone beyond 30°E. From 70° W to 30°W, the range of migration increases from about 3° in latitude to a maximum of nearly 16° and the range steadily falls to its lowest value close to zero in the African sector. In his earlier study on the geographic location of the dip equator derived using all available spherical harmonic models from 1600, Rangarajan (1994) found that between 90°E and 210°E there was no noticeable migration of the equator for over four hundred years. Leaving out this sector from the present analysis will, therefore, not be of great consequence in the interpretation of the results. For the longitude zones included, the results may be viewed as more dependable because the estimation of the dip equator is now based on a very homogenous series of coefficients all truncated uniformly after degree and order 10, unlike the earlier work where different models used different truncation lengths.

The source of the secular variation in the geomagnetic field is at the core-mantle boundary (CMB), as convective motions of the conducting plasma in this layer tend to generate variations in the magnetic field at the Earth's surface. To identify the processes responsible for the generation of the secular variation and the geomagnetic field itself, Bloxham and Gubbins (1985) computed the model of the field expected at the CMB. From their analysis, they could notice rapidly drifting flux spots from around 90°E moving westward. In 1980, four such spots were marked; specifically, below the equator in central Africa, to the right of Cape Town in South Africa, over the equator in the ocean between South America and Western Africa and near the tip of the South American continent. At least one of these rapidly drifting flux spots near the equator should be considered responsible for the observed difference in the range of migratory movement of the dip equator. Bloxham and Gubbins (1985) also detected localized field oscillations with large amplitude under Indonesia near the magnetic equator, but these oscillations do not propagate nor drift westward. The restricted range of movement in the eastern part of the Indian sector may well be related to this feature of secular variation in the CMB. Interestingly, they also find some regions with 'static flux bundles', identified with permanent regions of intense flux under arctic Canada, Siberia and in the Persian Gulf, where the field was virtually stationary for 250 years. Once again we find that the location of zero migration (30°E) and negligible change of the dip equator in its vicinity tie up nicely with their suggestion.

All the curves in Figure 2 are marked only with either a linear or curvelinear trend without any indication of the presence of any short period fluctuation in the migratory movement. Filipov and Rotonova (1989) detected a clear 20-yr signal in the secular variation of the geomagnetic field between 1903 and 1975 at low and middle latitudes. The spatial distribution of the structures of the 60-, 30- and 20-yr. oscillations are found to be similar and they conclude that the variations are generated by the same sources. Their diagram depicts focii near Mexico, in Central Africa and below the Indian peninsula and to the west of it. None of the three quasi-periodic fluctuations could be detected in the migratory change of the dip equator, except perhaps for a longer period oscillation (> 100 years) confined to the longitudes between 65°E and 90°E. This could be due to the fact that the focii are located farther away from the dip equator and do not influence the vertical component or the inclination close to the equator. Similar longer-period variations in the range 17-30 yrs, 50-60 yrs and ~67 yrs of the dipole field in the spherical harmonic terms were noticed by Greiner-Mai (1989). He indicated that the variation near 20 to 30 years could be connected with the core drift velocity, that near 67 years to the mantle rotation velocity and that the periods between 50 and 60 years could be due to the variation in the axial part of the dipole field. Once again, there is no indication of any of these fluctuations in the curves shown in Figure 2. It may be appropriate to point out that Malin and Bullard (1981) did not detect any longer period variation such as the ~60-yr cycle in the declination observations of London covering 400 years. LeMouel *et al.* (1981) discuss the oscillations in westward drift with periodicity of about a decade, but we cannot identify this in the present analysis as this falls on the Nyquist period with the sampling interval of 5 years between two epochs of the IGRF.

The extreme positions of the dip equator with respect to the geographic equator in the three sectors are next determined by equating the derivative of the third degree polynomials best fitting the curves for each epoch (shown in Figure 1) and determining the root of the equation that lies within the longitude sector. The geographic longitude of the extreme location of the dip equator for every 5 years in the three sectors are shown in Figure 4. For the Indian sector, both the minimum and maximum values are found to be within the region and these are shown as (1) and (2) in the figure. The progressive shift of the minimum in American sector seen in Figure 1 is quantified as an almost perfect linear change in Figure 4. The movement of the local minimum is westward at a rate of nearly 0.2°/year. This matches quite closely the value of the westward drift based on harmonic terms n=2 to 4 plotted by Langel (1987; see his Figure 59). Concurrently, the local maximum in the African sector also is shifting westwards, particularly after 1925, but in the initial part of this century, there is ambiguity about the direction of change. During this interval, the decrease is from 23° E to 1° E at a rate of 0.291°/year, slightly more than what is observed for the American sector. In India, the linearity is not observed in the longitudinal location of either the local minimum or maximum. This sector is marked with a rapid change in the initial 50 years and a significantly slower rate of shift in the latter part. A peculiar discontinuity is noticed with epochs 1945 and 1950 tending to be outside the otherwise smooth time profile. It may be recalled that a similar discontinuity was noticed in the time profile of the location of the dip equator in some longitudes in the Indian sector (Figure 2c). Kalinin and Rozanova (1994) attempted to isolate the 11-yr variation in the eccentric dipole parameters and found that the nature of changes in the ED parameters were very different after 1942, for reasons yet unknown. As was shown earlier (Rangarajan, 1994), the first 8 terms of the spherical harmonic models may adequately describe the dip equatorial location, this jump noticed in the Indian sector and the changes after 1942 observed by Kalinin and Rozanova (1994) may be linked in some fashion and needs to be investigated.

The rate of 0.2°/year of the westward migration of the local minimum in South America between 1900 and 2000 matches almost perfectly with the general estimates of the westward drift of the non-dipole field given in literature (see Langel, 1987; Table 39). Langel concluded that 'it seems established that the phenomenon of westward drift is real and many features of the non-dipole field do drift in a predominantly westward direction... Also there are substantial regions where little or no westward drift is evident'.

Barraclough (1974) carried out a spherical harmonic analysis of the geomagnetic field for 8 epochs between 1600 and 1910 and found that the zero declination (Agonic) line moved systematically westward over the American region. Similar drift was seen in Europe but none was noticed in eastern Pacific, Canada, western Asia, Australia or Antarctica. Yukutake and Tachinaka (1969) suggested that the field has both drifting and non-drifting parts. There is also the possibility that the drift is not always smooth but could be episodic as pointed out by Newitt and Dawson (1984) who found that the declination maxima drifted significantly prior to 1915 but not afterwards.

Based on the foregoing discussions, it appears that the special features in the South American region, like the westward drift of the Agonic line, the center of South Atlantic Geomagnetic Anomaly (SAGA) which marks a significant low in the total field and the westward movement of the longitude of the local minimum shown in Figure 4, are all related to the general drift of the non-dipole field. However, Rangarajan (1994) had inferred that the first 8 harmonic coefficients which determine the eccentric dipole parameters are also sufficient to delineate the dip equator correctly. Hence, we next attempt to first get the parameters of the dipole and eccentric dipole for the 21 different epochs and examine how they are related to the reported movement of the local minimum in the curves for American sector shown in Figure 1.

Figure 5a shows the dipole and eccentric dipole colatitudes and longitudes between 1900 and 2000. In Figure 5b are shown the shift of the 'magnetic center' relative to the Earth's center. The derivations of these parameters are described in detail by Fraser-Smith (1987) who examined the changes in the centered and eccentric geomagnetic dipoles between 1600 and 1985. However, for his analysis, he could use definitive IGRF only from 1945. The changing latitude or longitude of the dipole pole or the eccentric dipole pole between 1900 and 2000 is not linear and, hence, none of the four parameters will be linearly related to the rate of migration of the dip equator in the American sector. On the other hand, we note that the distance of the magnetic center from the Earth's center has been linearly increasing from a value of about 300 km to more than 500 km in the present century. The components deltaX, deltaY and deltaZ also show fairly linear trends, with X increasing towards 180° E longitude, Y increasing towards 90° E longitude and Z increasing towards north. In other words, throughout this century the eccentric dipole is north of the equatorial plane and presently is at its farthest position away from the Earth's center, as was indicated earlier by Fraser-Smith (1987).

We next examine the relation between the geographic longitude of the farthest point of the dip equator in the American sector and (i) the distance of the magnetic center and (ii) the geographic longitude of the SAGA center for 21 different epochs in this century. The SAGA center is determined by identifying the latitude and longitude of the lowest value of the total field (F) from the IGRF model for each epoch. In contrast to the precise determination of the dip equator, the minimum is somewhat diffuse (i.e. the same value occurs over a fairly wide region) and an element of subjectivity in the choice of the center is, therefore, inevitable. In spite of this, Figure 6a shows the near-perfect linear relation between the longitude of the SAGA center and the location of the dip equator, while Figure 6b shows a similar kind of functional relation with the distance of the magnetic center. However, the linearity for the latter case is better preserved, with a slightly less-steep slope after 1920, whereas the initial five points tend to fall on another straight line indicative of a possible discontinuity. The shift of the SAGA center in longitude is not very uniform with a jump between 1910 and 1915 and again somewhat similar enhancement in the shift after 1955 and 1970. It is tempting to ascribe these episodic changes to the impulses in secular variation that has been discussed in relation to the now famous 1969 secular jerk (Le Mouel *et al.,* 1982). It may be seen that the rate of shift of the local minimum in the dip equator's longitudinal profile is faster compared to the westward shift in the SAGA center, the ratio being close to 1.3. The linear relation between the location of the dip equator in the American sector and the distance of the magnetic center may be considered as yet another confirmation that the dip equator may be determined if we have reliable spherical harmonic coefficients up to degree and order two only. Also, it appears certain that the westward movement of the local minimum in the American sector is more intimately tied to the dipole terms rather than the general westward drift associated with non-dipole terms.

To examine whether there exists similar relationship of the movement of the dip equator, the eccentric dipole center location and the SAGA center longitude with the non-dipole terms, we compare these with the westward drift in the Agonic line in the American sector. For this purpose we again use the 21 IGRF models to identify the geographic longitude on the geographic equator where the value of declination turns out to be zero. This could be precisely estimated, unlike the SAGA center, for all the 21 epochs.

Figure 7 shows how the longitude systematically changed, though not precisely linearly, by about 22° during 100 years (in close agreement again with the average westward drift of 0.2°/year). It also depicts the functional relation between the geographic longitude of zero declination over the equator in the American sector and the longitude of the local minimum of the dip equator over south America, the longitude of the SAGA center and the distance of the magnetic center from the Earth's center. In all the graphs, one can notice two distinct linear relationships, one for the epoch 1900–1945 and another for 1950–2000. It is confirmed

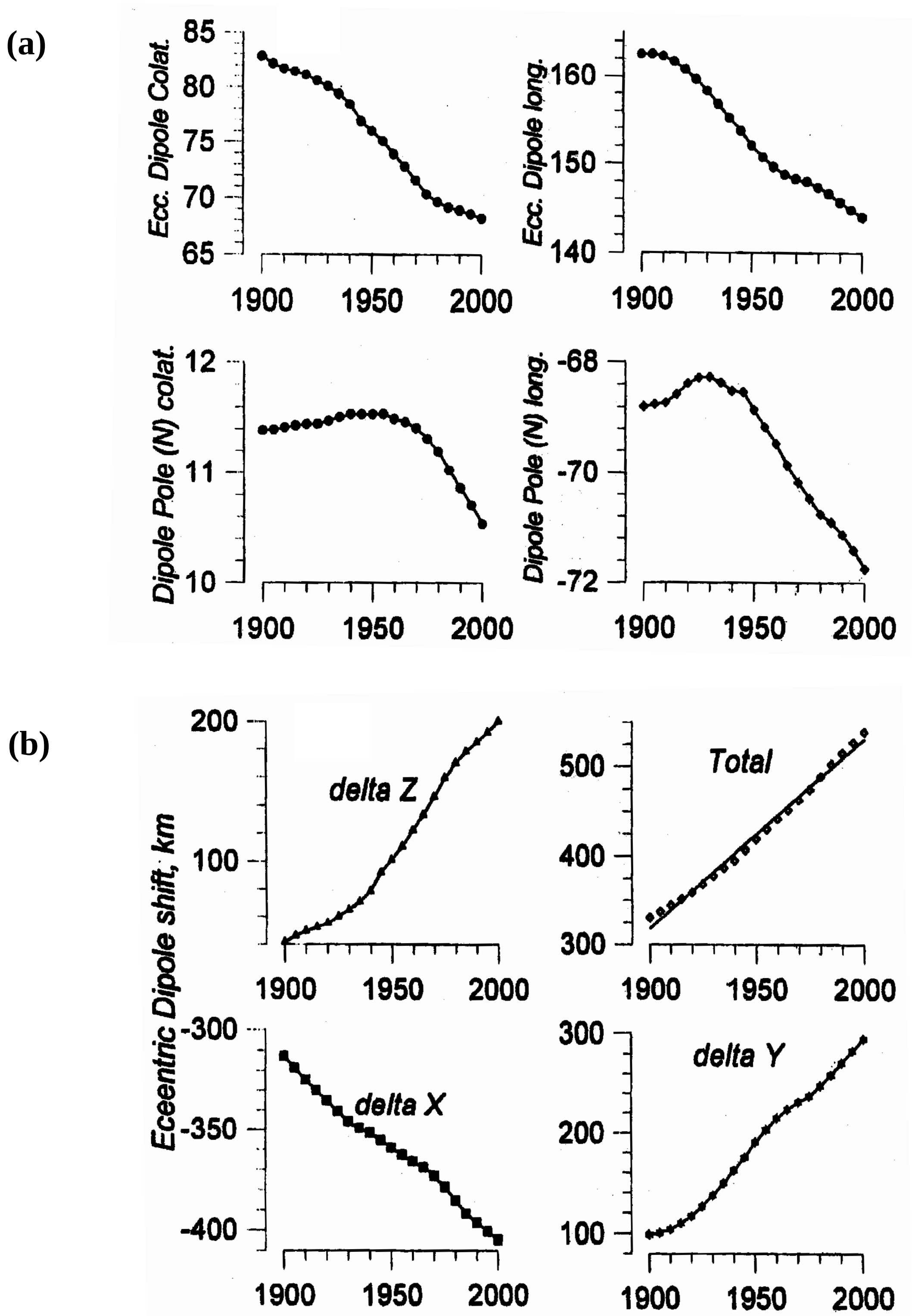

Fig. 5. (a) Colatitude and longitude of the North Dipole location and Eccentric Dipole pole location derived from the spherical harmonic coefficients representing IGRF for each epoch between 1900 and 2000, (b) Change in the position of the magnetic center of the Eccentric Dipole with time. 'Total' indicates the distance between the Earth's centre and the magnetic centre. DeltaX, deltaY and deltaZ are the components of the total distance in a co-ordinate system where Z points to geographic north, X to 0° E longitude and Y to 90°E longitude.

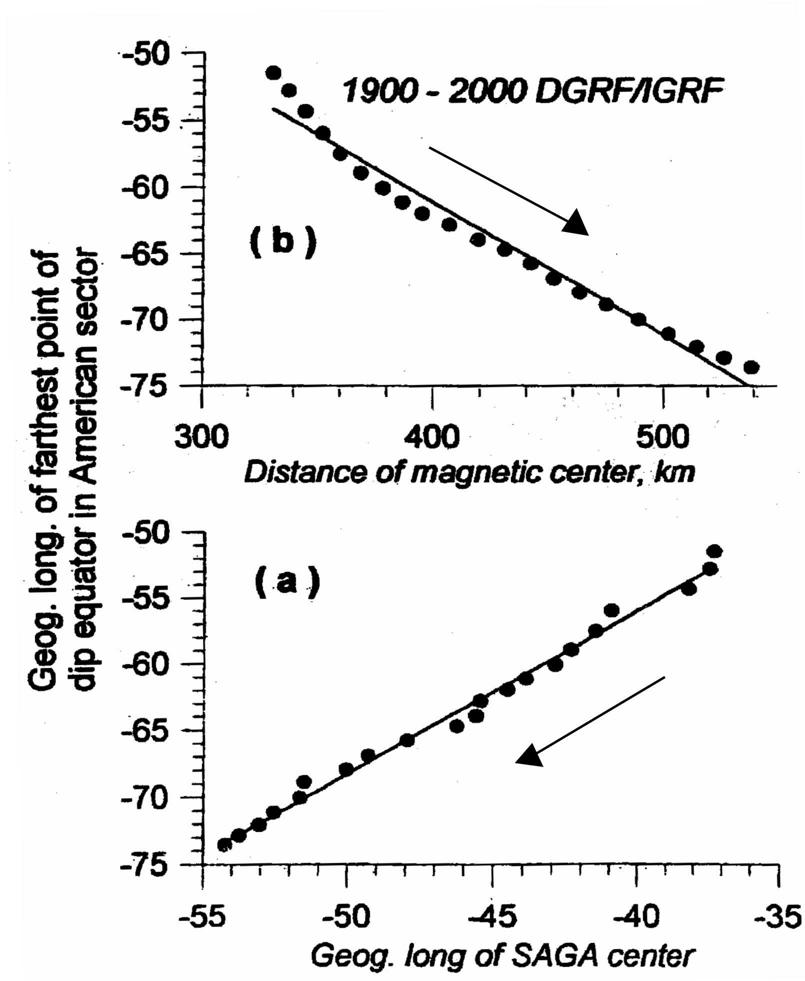

Fig. 6. Scatter plots of the geographic longitude of the farthest point away from the geographic equator in the American sector and (i) the geographic longitude of the center of the South Atlantic Geomagnetic Anomaly (SAGA) (ii) the distance of the magnetic center from the center of the Earth. The arrows indicate the direction of change from 1900 to 2000.

that a close link exists between the three different parameters and the westward shift of the non-dipole terms as identified by change in zero Declination position over the geographic equator, and it may be inferred that the movement of the dip equator in the American sector in the present century is controlled both by the eccentric dipole and non-dipole terms rather than by the latter only. Unlike the SAGA center movement which is slower towards the west compared to the change in the location of the Agonic line, the local minimum in the dip equator in the American sector matches the westward drift of zero declination almost exactly (both changing by about 22° in 100 years), again in close correspondence with the average value listed by Langel (1987).

Finally, it is interesting to note that the geographic location of the dip equator based on field observations over Brazil and its westward migration for two epochs – 1960.0 and 1965.0 – for some selected longitude sectors (Gama,

Table 1

Geographic latitude of the dip equator in three longitudes derived from IGRF (present work) and as computed from field observations by Gama (1969) for the two epochs 1960.0 and 1965.0

Longitude	1960.0		1965.0	
	Gama	IGRF	Gama	IGRF
	(Geographic latitude of dip equator)			
40° W	-6.38°	-6.34°	-5.34°	-5.36°
50° W	-11.37°	-11.32°	-10.70°	-10.63°
60° W	-13.83°	-13.89°	-13.54°	-13.56°

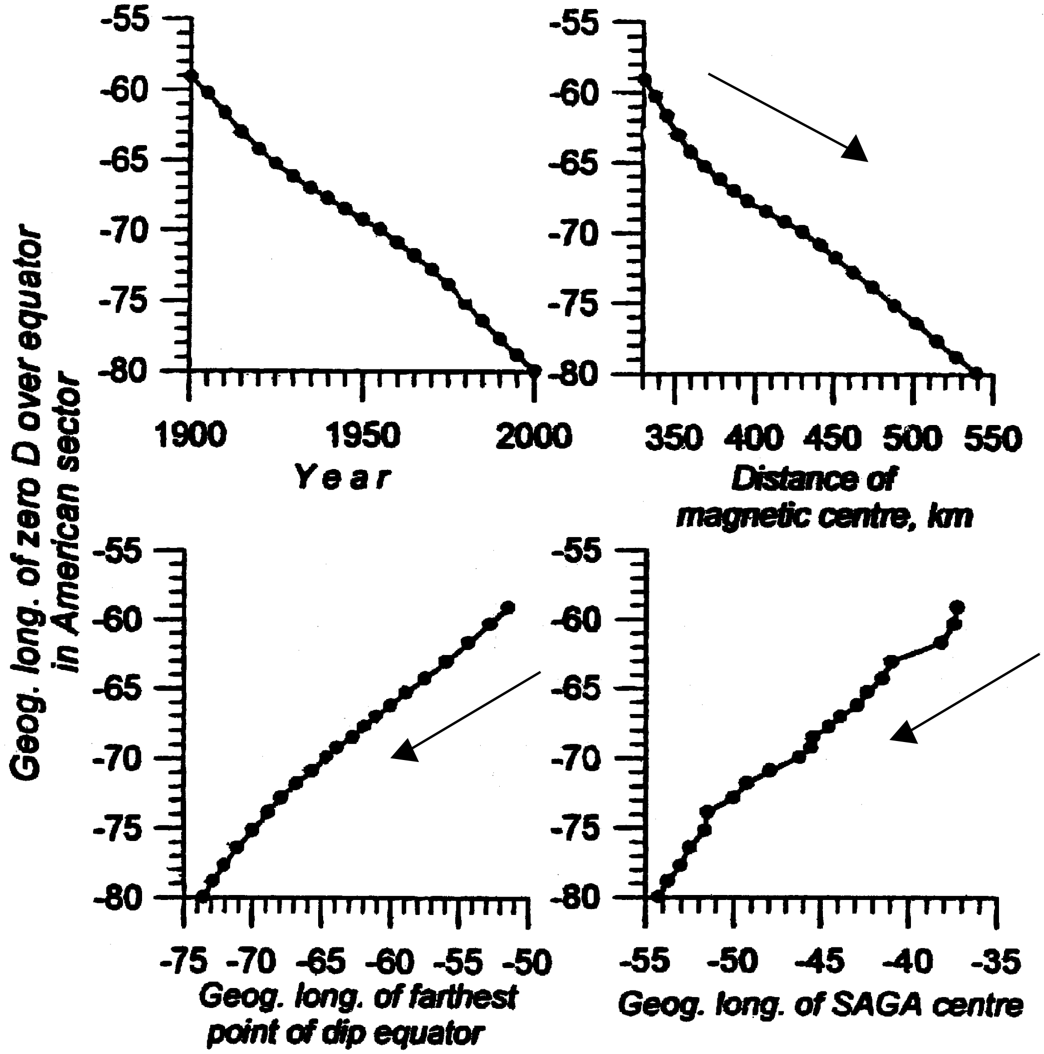

Fig. 7. Westward drift in longitude of the zero Declination location over the geographic equator (top left) and scatter plots showing the relation between the geographic longitude of the location of zero declination over the geographic equator in the American sector and (i) geographic longitude of the local minimum in the American sector (ii) geographic longitude of the SAGA center and (iii) distance of the magnetic center from the center of the Earth. The arrows indicate the direction of change from 1900 to 2000.

1969) match very closely with the IGRF-based values computed here. Table 1 shows the comparison between the two to highlight the fact that we may, with a great degree of confidence, use the model-based location of the dip equator in the American sector for all relevant studies.

CONCLUSIONS

Based on the homogenous series of spherical harmonic coefficients of degree and order 10 representing International Geomagnetic Reference Field (IGRF) for 21 epochs between 1900 and 2000, we compute the geographic location of the dip equator in three continental sectors - America, Africa and India - and examine how the line of zero dip has moved in the twentieth century. We find significant differences in the migratory trends in the three sectors with the largest swing between 20°W and 50°W and practically no change throughout the 100 years, further to the east centred on 30°E. Between 30°E and up to 60°W (covering a longitude span of 270°), the migration of the dip equator is significantly less compared to that noticed close to 30°W. We find that while the movement of the centered dipole in terms of its pole position is not significantly connected with the secular change in the dip equatorial location, the changing distance of the magnetic center of the eccentric dipole is linearly related to the movement of the farthest point of the dip equator away from the geographic equator in the American sector. The rate of change in the longitude of the local minimum in the time profile of the dip equator in different epochs (~0.22°/year) closely matches the average westward drift reported in the literature.

Though the westward drift of the Earth's magnetic field is largely attributed to the non-dipolar terms, we find that the terms of degree and order 2 of the IGRF models defining the eccentric dipole delineate the westward movement in the dip equator at least in the American sector. Apart from the geographic location of the farthest point of the dip equator from the geographic equator in the American sector, the center of the South Atlantic Magnetic Anomaly (SAGA center) which is identified with the abnormal low in the total magnetic field, also moves westward, though relatively slowly, in consonance with the shift in the magnetic center. From about 1925, a tendency for the local maximum in the location of the line of zero dip to move systematically westward is noticeable even in the African sector, whereas it is conspicuously non-linear in the Indian longitude zone. From a comparison of the westward movement of the agonic line over the past 100 years with the shift in the distance of the magnetic center, the geographic longitude of the SAGA center and the geographic longitude of the farthest point of the dip equator from the geographic equator, we establish once again linear relationships indicative of the link between the migration of the dip equator in the American sector and the non-dipolar terms in the spherical harmonic expansion of the geomagnetic field in different epochs.

We suggest that by carrying out a simple field survey for identifying the geographic location of the dip equator over a very restricted longitude zone in south America, as indicated by the linear equation shown in Figure 4, we can estimate several other parameters, such as: (i) the location of the center of the South Atlantic Geomagnetic Anomaly (SAGA); (ii) the location of the Agonic line over the geographic equator in America and (iii) the distance between the magnetic center of the eccentric dipole and the Earth's center as well as all the three components of this vector.

ACKNOWLEDGEMENTS

GKR expresses his sincere thanks to CNPq, Brazil for the award of a Fellowship to work at the Observatory Nacional, Rio de Janeiro. The authors express their grateful thanks to the Director, Observatory Nacional for the facilities offered to carry out this research. They also thank IAGA Working Group V-8 for making available the IGRF coefficients for 1900 to 2000. Useful comments by two anonymous referees are grateful acknowledged.

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