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The Induced Effects of Geomagnetic Variations in the Equatorial Region

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Abstract. The present paper concerns possible contributions from induced currents in geomagnetic field variations in the equatorial region for day-time substorms and solar-quiet day (*Sq*) variations. The analysis uses ground magnetic records from a close chain of observatories lying between ±5° of dip equator in the Ethiopian region. This valuable data pertains to an array study carried out in Eastern Ethiopia by the late Dr. H. Porath. The Kertz operator has been used to separate the external and internal parts of total magnetic field components. It is found that induced currents are associated with both classes of events. An average induced effect as measured from ratio of internal to external component (H_i/H_e) is seen to be more pronounced for sub-storm event ($H_i/H_e \simeq 0.35$) than for Sq variations ($H_i/H_e \simeq 0.28$). However, the half-width of the equatorial current system (electrojet) is found to be same for both types of variations. This is in contrast to the observation made by Mason (1963) who suggested that there is an apparent decrease of equatorial width for short periods. Another important result noticed is that induced effects due to the electrojet can be seen in a more pronounced way if separation proceeds by total magnetic field (S_R^T) component rather than using only the electrojet part (S_R^E). Our results suggest that currents induced by the equatorial electrojet are strongly dependent on local geological setting and this may be the reason that in some geographical locations internal currents have been identified and in others they are found to be practically absent.

Key words: Induced effect – Geomagnetic variations – Ethiopian region – Kertz operator

Introduction

The equatorial electrojet provides a strong non-uniform source field for studying the phenomena of electromagnetic induction in earth. It is essentially a day-time phenomenon of intensified ionospheric currents over and around the dip equator and leaves its signature most distinctly as an abnormally large variation in the horizontal component (*H*). Other enhancements are also observed near the dip-equator during day-time hours as short-period fluctuations: such as sudden impulses (SIs), storm sudden commencements (SSCs) etc. It is further noticed that in general the equatorial enhancement for short-period events is more than the enhancement for daily variations (Mason 1963; Rastogi 1964). One most intriguing aspect of the equatorial electrojet, which has not yet been resolved, is the internal induced effect associated with it. Chapman (1951) first took up studies of the daily geomagnetic variations near the dip-equator to investigate the internal part due to the electrojet by assuming that the Earth was a perfect conductor below a given depth ($\simeq 250$ km). For this, he concluded that the induced current has the same magnitude as the external current but flows at a depth of about 600 km below the Earth's surface and that the observed magnetic variations at equatorial stations do include contributions from internal induced currents. However, data collected from ground observatories and from space-borne experiments have given different results in different regions. In some regions, signatures of anomalous induced currents are seen, whereas in others, they are found to be very weak or even absent. Crochet, Poman and Hanuise (1976), using radar studies of horizontal phase velocities of electrons in Central Africa and Eastern Africa, have concluded that the equatorial electrojet does induce anomalous internal currents in Eastern Africa but not in Central Africa. A similar induced effect has also been reported by Balsley (1970) from his studies in the Peru region. In summarizing these differences, Crochet et al. (1976) conclude that the presence of large conductivity variations is the cause of these discrepancies.

The presence of anomalous currents induced by the electrojet has also been reported by Oni and Alabi (1972) in the Nigerian region and by Forbush and Casavarde (1961) in the Peruvian region from analysis of ground magnetic variations. From a comparison of rocket data and ground magnetic data, Davis et al. (1967) have shown the induced component to be 0.28 of the inducing current component. However, a series of papers by Fambitakoye (1972, 1973), Mayaud (1974) and Fambitakoye and Mayaud (1973, 1976) based on a magnetic survey conducted in Chad suggest that equatorial magnetic variations have a very little or insignificant induced component. Some recent studies (Yacob and Bhargava 1973; Cain and Sweeney 1972; Yacob

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1977; Rajaram et al. 1978) again give a definite indication of the presence of internal contributions in the electrojet field. Recently, Duhau and Romanelli (1979) using the latitudinal profile of height integrated current density determined from rocket measurements and their correlation with ground magnetic data, has also shown the presence of internal induced currents in the equatorial Peruvian region. The aim of present paper is to further ascertain the possible contribution of induced currents in *Sq*-variations. The study also aims to investigate the nature of currents induced during geomagnetic sub-storms during day-time in the equatorial regions, because current systems of substorms and *Sq*-variations have different morphological features.

Data and Analysis

The magnetic array data from the Ethiopian region have been used here. This array study was carried out in Eastern Ethiopia by the late Dr. H. Porath, University of Texas at Dallas during the period from November 1970 to May 1971. The stations were mainly situated along the western edge of the Afar depression and the main Ethiopian rift with a further line of stations across the centre of the Afar depression. A part of the array data containing various geomagnetic events was available in digitised form on magnetic tape at Dallas and had been acquired by Professor R.G. Rastogi. Using these values on tape, we first computed the daily *Sq*-range for two normal quiet days, 1 and 2 March 1971 for selected Ethiopian stations. The stations were so chosen that they fall within a very narrow range of longitudes. The measured *Sq*-range contains contributions from both planetary (S_R^P) and electrojet (S_R^E) current systems. The contribution of the planetary part (S_R^P) is estimated by taking daily ranges at stations on the same longitude on either side of electrojet. Table 1 gives the geographic coordinates and dip-latitudes of all observatories used here.

For evaluating normalised planetary ranges (S_R^P) as a function of dip-latitude, we use the formula $F(H)=\frac{ab}{a^2+t^2}$ given by Forbush and Casavarde (1961). Here t is dip-latitude in degrees, $F(H)$ is the total *Sq*-range of the H-component and a and b are constants. These constants are derived by fitting the following linear equation:

$$\frac{1}{F(H)}=\frac{t^2}{ab}+\frac{a}{b} \qquad (1)$$

to *Sq*-ranges for stations on the two sides of the dip-equator and "outside" the equatorial region (listed in Table 1). The best values of b and a are found to be 1180 nT and 22°, respectively, for 1 March 1971, and as 1020 nT and 21°, respectively, 2 March. The b and a so

Table 1. The Geographic coordinates and dip-latitude of the observatories used in the present study

Sr. No.	Station Name	Code	Geographic coordinates		Dip Latitude	Station used for	
			Lat.	Long.		*Sq.*	Sub-Storm
1.	Lourenco Marque	LMQ	−25.92	32.58	−35.32	Y	Y
2.	Tananarive	TAN	−18.92	47.55	−28.32	Y	Y
3.	Nairobi	NAR	− 1.28	36.83	−10.68	Y	Y
4.	5 YAV	YAV	4.90	38.12	− 4.50	Y	Y
5.	12 LAP	LAP	6.57	37.87	− 2.83	Y	Y
6.	23 AWA	AWA	7.05	38.47	− 2.35	Y	Y
7.	4 KOL	KOL	7.33	38.03	− 2.07	Y	N
8.	28 LAN	LAN	7.63	38.70	− 1.77	Y	Y
9.	29 ASE	ASE	7.97	39.12	− 1.43	Y	N
10.	25 WON	WON	8.47	39.22	− 0.93	Y	N
11.	27 DBZ	DBZ	8.75	38.92	− 0.65	Y	Y
12.	26 MUF	MUF	9.33	38.17	− 0.07	Y	N
13.	24 DBH	DBH	9.67	39.50	0.27	N	Y
14.	14 MAJ	MAJ	10.55	39.83	1.15	Y	Y
15.	17 DEG	DEG	11.12	39.88	1.72	Y	N
16.	18 BAT	BAT	11.20	40.02	1.80	Y	N
17.	8 BOM	BOM	11.22	39.63	1.82	Y	N
18.	15 ELO	ELO	11.27	40.33	1.87	Y	N
19.	21 WOL	WOL	11.82	39.58	2.42	Y	N
20.	3 ALA	ALA	12.40	39.55	3.00	Y	Y
21.	1 MAK	MAK	13.50	39.48	4.10	Y	Y
22.	Tamanrasset	TAM	22.80	5.53	13.40	Y	Y
23.	Misallat	MIS	29.52	30.90	20.12	Y	N
24.	Pendilli	PEN	38.03	23.52	28.63	N	Y
25.	Kandilli	ISK	41.07	29.07	31.67	Y	Y
26.	Surlari	SUR	44.68	26.25	35.28	N	Y

YES = Y NO = N

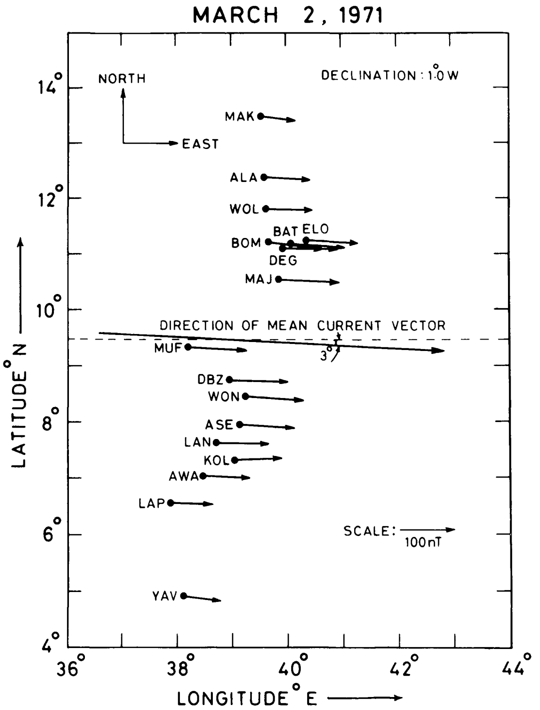

Fig. 1. The current vectors computed at each Ethiopian station for *Sq*-ranges of 2 March 1971 along with the deviation of mean current vector from geomagnetic east (*stippled line*). These vectors are obtained by rotating horizontal vectors through 90° clockwise

determined for each day are then used to calculate the S_R^P for H at each of the equatorial stations. This part is then subtracted from total *Sq*-ranges to get electrojet ranges (S_R^E). The planetary part for Z is computed using the formula

$$F(Z) = -0.43 * \frac{bt}{(a^2+t^2)}. \tag{2}$$

Having obtained $S_R^E(H)$ and $S_R^E(Z)$ the external and internal components of H and Z are computed by the technique defined by Siebert and Kertz (1957) through the use of Kertz operator. The application of this operator requires that field to be separated must be two dimensional in nature. In our analysis we neglected ΔD and considered only ΔH and ΔZ. Our results would be correct if $\Delta D = 0$ or the same at all stations. In order to confirm this, we have computed the magnitude and direction of horizontal vectors by measuring the changes in *Sq*-ranges of horizontal components (ΔH and ΔD) at each Ethiopian stations. These *Sq* ranges are measured at the time of maximum deflection in H and D near local noon from the mid-night value. The direction of the current vector is obtained by rotating this vector through 90° clockwise. The magnitude and direction of current vectors thus obtained are shown in Fig. 1. It is seen that the deviation of mean directions of current vectors from geomagnetic east is about 3°. Since the deviation is very small, it may be assumed that the electrojet current flows approximately from west to east and separation can be made using the 2-*D* formulation of Kertz.

The external and internal components are obtained using the following equation (Siebert and Kertz 1957)

$$\begin{aligned} H_e &= (H+kZ)/2 \quad & Z_e &= (Z-kH)/2 \\ H_i &= (H-kZ)/2 \quad & Z_i &= (Z+kH)/2 \end{aligned} \tag{3}$$

where H_e, H_i and Z_e, Z_i are external and internal parts of H and Z-components. In the above equation k is the Kertz operator and is defined as

$$k_f = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{f(t)}{t_0 - t} dt$$

where $f(t)$ is a continuous function of t (dip latitude). For numerical evaluation of the integral, $f(t)$ is approximated by having N discrete values $f_1, f_2, \ldots, f_n$ at corresponding points of $t_1, t_2, \ldots, t_n$. It may be noted that the numerical evaluation of above integral requires some care near the singularity $t = t_0$. This is overcome following suggestions given by Hartmann (1963) and Schmucker (1970). They show that evaluation of the integral transform has a simple form when we evaluate these at the centre ($\bar{t}_m$) of each interval. By setting $t_o = \bar{t}_m$ they have shown that the above equation reduces to the following simple form:

$$k_f = \frac{1}{\pi} \left[f_m - f_{m+1} + \sum_{\substack{n=1 \\ n \neq m}}^{N-1} \{\lambda n [\bar{f}_n + f_n'(\bar{t}_m - \bar{t}_n)] + f_n - f_{n+1}\} \right]$$

with

$$\lambda_n = \ln|(\bar{t}_m - \bar{t}_n)/(\bar{t}_m - \bar{t}_{n+1})|,$$

$$\bar{t}_m = \tfrac{1}{2}(t_{m+1} + t_m), \quad \bar{t}_n = \tfrac{1}{2}(t_{n+1} + t_n)$$

and

$$f_n' = (f_{n+1} - f_n)/(t_{n+1} - t_n).$$

The above formula has been used to compute numerical value of k_f operator at each point. The operator k_f has been applied to S_R^T components and to S_R^E components separately.

In evaluating $S_R^P(Z)$ we have used the suggestions given by Chapman and others from spherical harmonic analysis of the normal '*Sq*' variation that internal component is about 40% of the external field. This gives the external and internal parts as (Forbush and Casaverde 1961)

$$\begin{aligned} H_e^P &= 0.714 H^P \quad & Z_e^P &= 1.666 Z^P \\ H_i^P &= 0.286 H^P \quad & Z_i^P &= -0.666 Z^P. \end{aligned} \tag{4}$$

In the prescription adopted above, it was tacitly assumed that $S_R^P(Z)$ has a value expected over a stratified conductor having no lateral conductivity contrasts. In doing so, what we have done indirectly is that the anomalies in Z arising out of perturbations in the internal current system of planetary origin have also been lumped with the anomalies in Z associated with the electrojet part. This makes the separation of S_R^E into its internal and external components formal. To circumvent this limitation, we separated external and in-

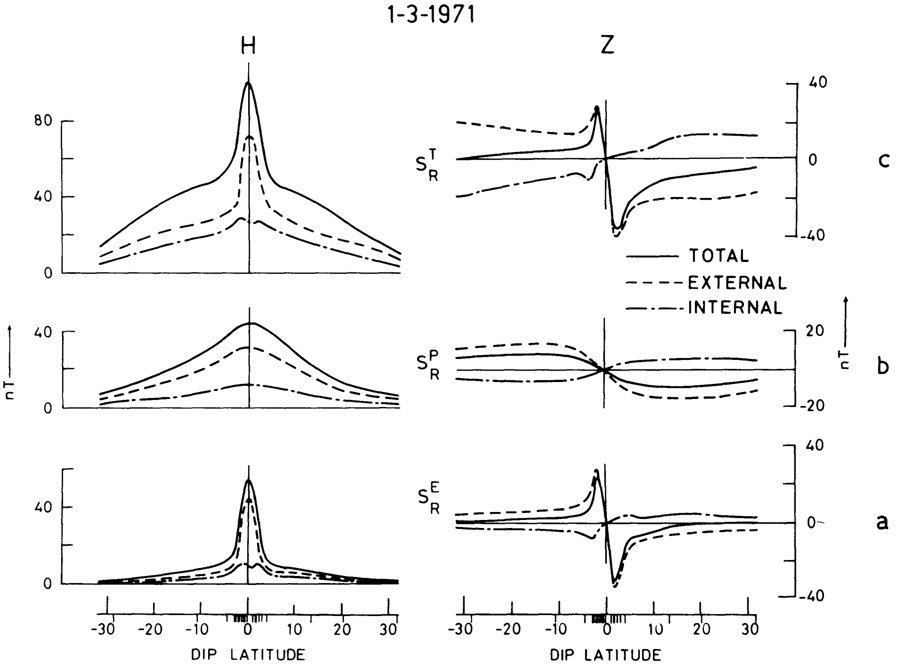

Fig. 2a–c. The magnetic field variations of external and internal parts together with total magnetic field components (H, Z) as a function of dip-latitude are shown for Sq-ranges of 1 March 1971 for three cases: **a** separation of S_R^E into external and internal components, **b** adopted separation of planetary ranges from global analyses, **c** separation of total range S_R^T. The values on the y-axis are in nT and downward vertical lines shown on x-axis indicate the positions of stations

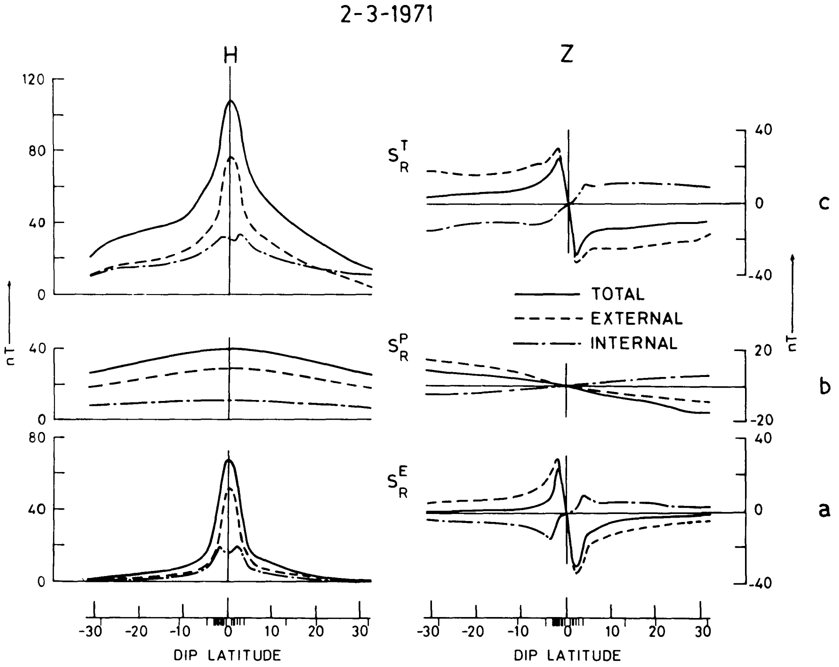

Fig. 3. The same as in Fig. 2 for Sq-ranges of 2 March 1971

ternal parts from total Sq-ranges of H and Z also without any previous separation into planetary and electrojet parts. The latitudinal dependence of external and internal parts of H and Z for the electrojet, planetary and total field are shown in Fig. 2 for 1 March 1971 and in Fig. 3 for 2 March 1971.

A similar procedure has also been adopted to analyse the substorm event recorded from 0936 UT to 1030 UT on 9 April 1971. First the maximum amplitude of this event is measured at all equatorial and non-equatorial stations for both H and Z components. The range in this case was taken as the change in H and Z when H attained its maximum value. The changes were measured by taking the base value as the value at the start of the event. In this case too we separated first the planetary (S_R^P) and electrojet (S_R^E) parts, following Eqs. 1 and 2. The best values of k and h are found to be 900 and 18. The separation of the external and internal components of the electrojet and the total field is done using Eq. 3 and that of the planetary part using Eq. 4. Figure 4 shows the variation of external and internal parts of H and Z as a function of dip-latitude for the electrojet, planetary and total field respectively. In this case also we have taken for the planetary part the i/e ratio just as for the Sq periods. This is at best a crude approximation.

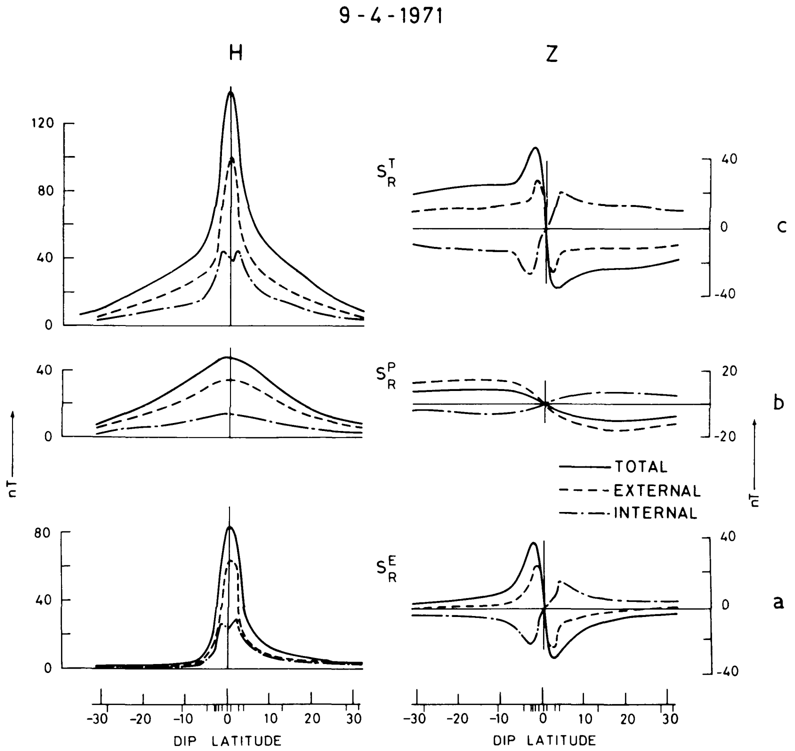

Fig. 4. The same as in Fig. 2 for sub-storm event recorded for about one hour from 0936 UT to 1030 UT on 9 April 1971

Results and Discussion

It is clear from Figs. 2 and 3 that induced currents are associated with the equatorial electrojet. The internal component (H_i) of H variations follows the shape of the external inducing field (H_e) except at a few end points. We notice a hump around the dip-equator in the internal component (H_i) of H variations only. This may be attributed to perturbations in flow of internal currents near these stations, arising from an anomalous electrical conductivity distribution beneath the Afar depression (a tectonically active zone). It is further noticed that the increase in magnitude of the external inducing field (H_e^J) for the electrojet part (S_R^E) on 1-2 March 1971 (from 43γ in Fig. 2a to 53γ in Fig. 3a around the dip-equator) shows an increase in magnitude of the internal field (from 12γ to 15γ for H_i^J) whereas for the planetary part (S_R^P) a decrease in magnitude of an external inducing field (from 32γ to 29γ for H_e^P) causes a decrease in magnitude of the internal field from 12.5γ to 11γ for H_i^P). These results further suggest that the anomalous internal component is very much controlled by the intensity of the external inducing field on each day. An average induced effect as measured from the ratio of an internal to external component (H_i/H_e) is around 0.28 for the electrojet field (S_R^E) whereas it is 0.40 for the planetary field (S_R^P), which is rather natural to expect. The half-width of the equatorial electrojet, as evident from the nature of the external component of H and Z variations, is about 400–500 km.

The induced effects are also seen to be present for sub-storm events (Fig. 4) and these are more pronounced than the currents induced by solar daily variations. The H_i/H_e ratio for sub-storms is about $\simeq 0.45$ but its half-width is approximately the same as that for electrojet current system. A large value of induced effects i/e for short periods is again to be expected and this is discussed later in more detail. An apparent decrease of equatorial width for shorter periods is not evident from our results which is contrary to what was observed by Mason (1963). In Table 2 we summarise the ratio of internal to external components (H_i/H_e) for the electrojet, planetary and total field of *Sq* and sub-storm variations.

Table 2. The ratios of an internal (H_i) and external (H_e) parts of total horizontal magnetic field (H) component for both sub-storm and solar quiet-day (*Sq*) variations

Event	Date	Ratio of H_i/H_e	
		Electrojet field (S_R^E)	Total field (S_R^T)
Sq	1.3.71	0.28	0.38
Sq	2.3.71	0.28	0.40
Sub-storm	9.4.71	0.35	0.45

Another interesting point noticed is that the sum of external parts of both planetary (S_R^P) and electrojet (S_R^E) fields is different from the values obtained for the external component using the total magnetic field component H directly. It is found that sum of external parts as obtained in the first case is larger $(H_e^J + H_e^P > H_e^T)$. As one would expect in this case, the sum of the internal parts is smaller than the value obtained directly using the total field $(H_i^J + H_i^P < H_i^T)$.

Until recently, the induced effects associated with the equatorial electrojet have been interpreted in terms of image currents at a certain depth ranging from 500 to 600 km below the Earth's surface on the assumption that Earth is perfectly conducting below a depth ranging from 200 to 250 km. On this basis estimates of induced currents were found to be around 0.16–0.20 of the external current systems. Davis, Burrows and Stolarik (1967) have also noticed the induced effects from the results of rocket observations and ground observations as 0.28 of an external current system, which is in agreement with the results obtained by us. However, the contribution and penetration depth of currents induced by an external varying field depend not only upon an average conductivity (σ) of sub-surface geological features but also on frequency (ω) and source field wavelength (L) of the inducing field. For relatively longer period variations such as Sq-variations, induced currents penetrate to considerable depths within the Earth whereas for short-period variations (30 min), the depth of penetration reduces to a greater extent. The dependence of above parameters on induction effects over land areas has been studied in details by Price (1967) by a simple mathematical model. He has noted that the contribution of internal part depends on the relative magnitudes of $4\pi\sigma\omega$ and γ^2 where γ is equal to $\frac{2\pi}{L}$ and $\sqrt{2\pi\sigma\omega}$ is reciprocal skin depth. If $4\pi\sigma\omega$ is much smaller than γ^2, then induced effects are negligible or insignificant. The induction effects start to become significant when the ratio $\alpha = 4\pi\sigma\omega/\gamma^2$ reaches a value of $\simeq 0.25$ or more. These effects are quite prominent when α is equal to one or more. The Ethiopian region is known to have an abnormally high electrical conductivity distribution beneath the Afar depression and along the main Central Ethiopian rift. (See: Berktold et al., abstract published in programme of "Workshop on electromagnetic induction in the earth" held in Ottawa, Canada, 1974 and Bennett et al., abstract published in programme of "Fourth workshop on Electromagnetic induction in the Earth and Moon" held in Murnau, Federal Republic of Germany, 1978). The presence of such a high conductivity in this zone will result in a significant value of α for longer-period variations (for Sq-variations) which has made it possible to detect an internal contribution due to the electrojet. For shorter periods, the value of α will be much larger due to an enhanced conductivity (σ) at shallower depths possibly because of anomalously high temperature (Berktold et al. 1975; Haak 1977) along the main Ethiopian rift and a larger value of ω. Thus the induced effects will be more pronounced for short period than for long period variations. Some earlier studies have noticed different signatures of induced effects in different regions. This may be due to the varying conductivity (σ) of geological sub-surface features from region to region. Fambitakoye and Mayaud (1976) did not observe any significant induced effects in Central Africa possibly because of the existence of resistive layers in that region.

Conclusion

It is evident from our results that induced effects are present in the Ethiopian region for the electrojet (S_R^E) components in geomagnetic variations. The effects are more pronounced for sub-storm events compared to solar-daily variations. In agreement with the model described by Price (1967), we notice larger contributions from internal components for rapid variations. It is also found that induced effects can be better studied by studying the total observed fields directly using Kertz's equation rather than by making a separation into S_R^P and S_R^E.

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