Equatorial electrojet in the south Atlantic anomaly region

R G RASTOGI¹, H CHANDRA^{1,*}, N B TRIVEDI² and V DOUMBIA³

¹*Physical Research Laboratory, Ahmedabad 380 009, India.*

²*INPE, CP 515, Sao Jose dos Campos, SP, Brazil*

³*Universite de Cocody, Abidjan, Ivory Coast.*

**e-mail: hchandra@prl.res.in*

Features of the equatorial electrojet are studied at Sao Luiz (2.6°S, 44.2°W, inclination -0.25°) in eastern Brazil and Sikasso (11.3°N, 5.7°W, inclination 0.1°) in the western African sector. The stations are situated on either side of the lowest magnetic field intensity in the region of rapid changes in the declination. The daily variations of ΔX at the two stations are almost similar with the peak around noon with maximum values during equinoxes and minimum values during J-solstices. Daily variations of ΔY differ with the maximum deviation of about -35 nT around noon at Sao Luiz and much smaller value of about -10 nT around 14 h LT for Sikasso. The direction of the H vector varies from 15° W of north at 08 h to more than 30° W of north at 17 h for Sao Luiz and from 14° E of north to 25° W of north at 18 h for Sikasso. The plot of the deviations in ΔX and ΔY at different hours for the two stations shows the points along narrow ellipses with major axis aligned along 22° W of north for Sao Luiz and along 3° W of north for Sikasso as compared to declination of 20° W for Sao Luiz and 6° W for Sikasso. The deviations in ΔX at the two stations are fairly well correlated.

1. Introduction

The abnormally large solar daily range of the horizontal component of the geomagnetic field, H , at Huancayo and other equatorial stations was explained by Chapman (1951) as due to a thin sheet of enhanced electric current in the E-region of ionosphere. This intense daytime eastward current within $\pm 3^\circ$ dip latitude was named as 'equatorial electrojet' (EEJ). Enhanced current was later explained as an abnormally large electrical conductivity (Hirono 1952; Baker and Martyn 1953). The eastward electric field and the northward magnetic field cause a vertical Hall current in the dynamo region over the dip equator. This is inhibited because of the non-conducting atmosphere below and above the region at 90 and 140 km. Thus vertical polarization field is set up,

which significantly enhances the conductivity along the east–west. Polarization field is not sustained beyond 3° dip latitude as the electrons/ions can move vertically along the inclined magnetic field lines.

Equatorial electrojet has been extensively studied from ground, rocket and satellite based magnetometers, spaced receiver drift, VHF backscatter radar and theoretical studies (Reviews by Forbes and Lindzen 1976; Forbes 1981; Rastogi 1989; Reddy 1989). Features of EEJ have been described for longitude regions of 75° W (Forbush and Casaverde 1961), 15° – 19° E (Fambitakoye and Mayaud 1976a, 1976b), 75° E (Arora *et al* 1993; Rastogi 1999) and 5° W (Doumouya *et al* 1998).

A chain of 3-axis digital fluxgate magnetometers at a number of equatorial stations around the world is maintained by Prof. K Yumoto of Kyushu

Keywords. Equatorial electrojet; Brazilian anomaly in equatorial electrojet; asymmetries in equatorial electrojet.

University, Japan. Rastogi *et al* (2008) described the features of EEJ along 60°W longitude sector using the data from six observatories in central Brazil. Rastogi and Trivedi (2009) and Rastogi *et al* (2010) described the features of equatorial electrojet in the east Brazilian sector.

It is to be noted that the deviation of the H field from the geographic north along the dip equator is largest in this sector. We have examined the equatorial electrojet at Sao Luiz (2.6°S, 44.2°W, inclination 0.25°S, declination 20.3°W) in eastern Brazil and at Sikasso (11.3°N, 5.7°W, inclination 0.1°N, declination 6.4°W) in the western African sector. The geographic coordinates and geomagnetic parameters of the two stations are listed in table 1. Both the stations are close to the dip equator but declination changes rapidly in the region. Figure 1 shows the map of the location of the two stations. The contours of the total magnetic field intensity (F) and the Y component of the geomagnetic field are also shown in the figure. The stations are situated on both sides of the anomaly. Sao Luiz is located close to the low of Y (−9368 nT) and

Sikasso is located little away on other side of the low with Y value of around −3595 nT. In terms of the total intensity, SLZ is located little north of the lowest magnetic field intensity called south Atlantic minimum field anomaly region with total intensity of 26783 nT while SIK is northeast of the low with total intensity of 32,400 nT.

2. Data and analysis

The geomagnetic field measurements by the 3-axis fluxgate magnetometers were the component pointing to magnetic north (B_H), magnetic east (B_Y) and vertically downward (Z). The deviations at each hour from the midnight value (00 h local time; 45°WMT) have been converted into the geographic northward (X) and geographic eastward (Y) components using the relations described by Rastogi *et al* (2008).

$$\Delta X = \Delta B_H \cos(D) + \Delta B_Y \sin(D), \quad (1)$$

$$\Delta Y = \Delta B_H \sin(D) + \Delta B_Y \cos(D), \quad (2)$$

where D is the declination.

The analyses used all available data for individual stations for the period January 1993–December 1994. The data were carefully screened and compared with quick look maps available at the website of Kyushu University. Only the days with complete 24 hourly values were used. To have a good statistics of data, only the days with A_p value of less than 20 were selected.

Rastogi *et al* (2010) made quantitative estimate of the standard error in mean $\sigma/\sqrt{n}$ and of the standard deviation (σ) of ΔX , ΔY and ΔZ at each hour for the month of April 1993 for SLZ. The standard error in mean in ΔX varied from around 8 nT

Table 1. Geographic and geomagnetic parameters of stations: March 1993.

Station code	SIK	SLZ
Geog. lat. deg.	11.3	−2.60
Geog. long. deg.	−5.7	−44.20
Declination deg.	−6.4	−20.34
Inclination deg.	0.1	−0.25
X nT	32200	25114
Y nT	−3595	−9368
Z nT	80	−118
H nT	32400	26783
F nT	32400	26783

Figure 1. Map showing the location of SLZ and SIK. Contour plots of the total intensity and the eastward component of the geomagnetic field, Y , are also shown in the map.

at noon to 5 nT in the evening–midnight hours. The value of the standard error in mean in ΔX was least in the midnight–morning hours (1–2 nT). The standard deviation was 40 nT around noon and remained fairly high in the evening–midnight hours with values around 30 nT. The standard error in mean in ΔY was maximum around noon with a value of about 5 nT. The standard deviation was also maximum around noon with a value of 23 nT and decreased to 7–8 nT in the evening–midnight hours. The high values of the standard deviations at noon are partly because of the day-to-day variability in the electrojet. Based on the mean values and standard errors in mean of ΔX and ΔY at SLZ, the errors in the direction of H vector were computed. Error was very small (about a degree) between 09 and 15 h. The error is very high between sunset and sunrise hours due to low values of the deviations in ΔX and ΔY .

3. Results

The yearly mean daily variations of ΔX and ΔY at SIK and SLZ for the years 1993–1994 are shown in figure 2(a). The error in mean is not plotted in the figure as it is very small due to the database of 2 years with values ranging from less than 1 nT (midnight to morning) to 2 nT (near noon) for ΔX and from less than an nT to 1 nT for ΔY . The daily variations of ΔX at the two stations are almost similar with the peak value of 93 nT at SIK little higher than 87 nT at SLZ. This is consistent considering the declination angles at the two locations. The ΔX values at SIK are expected to be about 5% higher than at SLZ. The values of ΔH obtained from ΔX and ΔY at the peak are 93 nT for both the stations. The peak occurs almost around noon (local time) at both the stations. The daily variations of ΔY , however differ significantly

Figure 2. (a) Annual average daily variations of the northward component ΔX and eastward component ΔY of the geomagnetic field at SIK and SLZ for the year 1993–1994. (b) Annual average daily variations of the angle θ , the direction of H vector, perpendicular to the horizontal current at SIK and SLZ for the year 1993–1994. (c) Plots of the annual average hourly values of ΔX plotted against ΔY at SIK and SLZ for the year 1993–1994.

at the two stations. The maximum deviation of ΔY occurs around noon at SLZ with a value of about -35 nT. The deviations are much smaller for SIK with maximum value of about -10 nT around 14 h LT. The ranges of ΔY at the two locations are again consistent with the declination angles at the two locations (ΔY at SLZ about 3 times that of ΔY at SIK). However, the positive deviation in the forenoon and the negative deviation in the afternoon are distinct features at SIK.

The daily variations of the angle θ ($\arctan \Delta Y / \Delta X$), the direction of the H vector (perpendicular to the direction of the current vector) for the two stations are shown in figure 2(b). The H vector for SLZ is aligned around 15° W of north at 08 h in the morning and increases slowly to more than 30° W of north around 17 h. Its value is around 30° – 75° E of north in the morning (05–07 h) and late evening hours (21–00 h). For SIK, it is about 14° E of north at 08 h and changes slowly to about 25° W of north at 18 h. The values are up to 60° E of north in the morning hours. However, the large values of the angle θ close to morning or late evening or night hours are due to the fact that the deviations ΔX and ΔY are very small and therefore, the error in estimating current direction is large (Rastogi *et al* 2010). The error in mean in angle θ for the data sample of 2 years is 1° near noon to about 10° in

the night hours. Comparing with the results for stations in east Brazil, the changes in the direction of H vector during daytime at SIK are very large. The direction of the H vector at the two stations is also shown in figure 2(c) where the deviations ΔX and ΔY are plotted at different hours for the two stations. The declination angles at the two stations are also shown in the figure (20° W of north for SLZ and 6° W of north for SIK). The points lie along an ellipse with major axis aligned along 22° W of north for SLZ and along 3° W of north for SIK. The ellipse is narrower for SLZ than for SIK. Also while for SLZ most of the points show negative values of ΔY , for SIK the ΔY values are positive in the forenoon and negative in the afternoon hours. There is a difference of about 2° towards west between the direction of H vector and declination angle at SLZ while the difference is 3° towards east for SIK. Rastogi *et al* (2010) found difference of 3° towards west for stations in east Brazil. For stations in central Brazil, however the H vector was aligned along the magnetic north (current vector perpendicular to the magnetic north) (Rastogi *et al* 2008).

The daily variations of ΔX and ΔY at SLZ and SIK for the three seasons are shown in figure 3(a). As expected, the daily variations of ΔX show maximum around noon with maximum values during

Figure 3(a). Seasonal average daily variations of the northward component ΔX and eastward component ΔY of the geomagnetic field at SIK and SLZ for each of the seasons of 1993–1994.

Figure 3(b). Seasonal average daily variations of the angle θ , the direction of H vector at SIK and SLZ for each of the seasons of 1993–1994.

equinoxes and minimum values during J-solstices at both the stations. The daily variations of ΔY for SLZ are also as expected with minimum values of -35 to -45 nT around noon though there is a tendency of it increasing in the post-midnight period with a peak at 06 h during E-months and J-months (5–10 nT). However, the daily variations of ΔY for SIK show maximum in the pre-noon hours and minimum in the afternoon hours during each of the seasons. The daily variations of Y at SLZ are negative throughout the day while positive values are evident in the forenoon hours for SIK. Does it signify varying current system at the edges of the anomaly belt of low declination?

The daily variations of the angle θ during the three seasons are shown in figure 3(b). Large values of the angle during night hours are not significant as discussed earlier (Rastogi *et al* 2010). For SLZ, the angle θ during day hours varies from about 18° W of north to 30° W of north during D-months, from 25° W of north to 30° W of north during E-months and from about 15° W of north to 25° W of

north during J-months. For the midday, the values are 20° W of north, 27° W of north and 25° W of north, respectively for the three seasons. The variation of the angle θ during day hours is comparatively more for SIK with values varying from 0° to 30° W of north during D-months, 15° E of north to 15° W of north during E-months and 5° W of north to 25° W of north during J-months. The midday values are 3° W of north, 5° W of north and 7° W of north, respectively for the three seasons.

The vector plots of the ΔX and ΔY for different hours during each season for the two stations are shown in figure 3(c). The declination angles at the two locations are also marked in the figure. For SLZ, the points lie along comparatively narrow ellipses pointing to 2 – 3° further west of the declination angle. However, the ellipses are little wider for SIK compared to those for SLZ, with orientations almost along the north during D and E-months and about 10° W of north during J-months.

The daily variations of the ΔX and ΔY at the two stations for each month are shown in figure 4. It must be noted that there is no data for SLZ during the months of July and August. Daily variations of ΔX show clear equinoctial maxima at the two stations with minimum during J-months. Though the variations during daytime are similar for each month, there are minor differences during night hours. In particular, the variations at SLZ show small increase (few nT) from midnight to morning hours in some months and a decrease in morning hours to below the night time levels of up to 10 nT.

The daily variations of the ΔY at SLZ show regular feature of westward component with peak around midday for each month. There are variations during night hours only. The variations at SIK are smaller but show eastward peak before noon and westward peak in the afternoon. Large morning peaks during June to September are significant. For most of the months the value of ΔY increases from 06 h to around 09–10 h and then decreases very rapidly to minimum shortly after noon. The fluctuations are largest during J-months. These features need greater scrutiny with larger set of data.

Few case studies of the daily variations are made on individual days. Figure 5 shows the daily variations of ΔX and ΔY at the two stations on 21 December 1993. The variation of ΔX at SLZ shows steady rise from midnight to 07 h (20 nT) and then rapid increase to midday (142 nT). It decreases rapidly till evening and then slow decrease till midnight. ΔY decreases steadily from midnight to 07 h to a value of -20 nT and then remains to almost same level till 14 h. It increases steadily to midnight. For SIK the variation of ΔX is similar to that at SLZ but with a lower magnitude (peak of 80 nT at midday). However, ΔY variation is

Figure 3(c). Plots of the seasonal average hourly values of ΔX plotted against ΔY at SIK and SLZ for each of the seasons of 1993–1994.

Figure 4. Monthly average daily variations of the northward component ΔX and eastward component ΔY of the geomagnetic field at SIK and SLZ for each months of 1993–1994.

somewhat different. After the slow decrease till 07 h (-10 nT) it increases to a value of 2 nT at 10 h and then decreases to almost -20 nT in the afternoon before recovering to night level.

The daily variations of ΔX and ΔY at SIK on 20 May 1993 and 7 September 1993 are shown in figure 6. The variations of ΔX are normal during day time with peak around midday and

Figure 5. Daily variations of the northward component ΔX and eastward component ΔY of the geomagnetic field at SIK on 21 December 1993 and 19 February 1993.

Figure 6. Daily variations of the northward component ΔX and eastward component ΔY of the geomagnetic field at SIK on 20 May 1993 and 7 September 1993.

magnitude of about 90 nT and 120 nT, respectively for the two days. However on both days, ΔX shows decrease of 18 nT and 30 nT from 05 h to 07 h, respectively on the two days. The variations of ΔY show eastward values in the morning with a peak of about 20 nT around 08 h and then decrease till

14 h with westward values of -30 nT and -40 nT, respectively for the two days. These appear to be morning counter electrojet events. On some days similar events are observed even before sunrise.

Next we computed deviations of hourly means from means of ΔX and ΔY at the two stations from the corresponding value at 0000 LT. Scatter plots of the deviations from mean of ΔX at the two stations for the three seasons are shown in figure 7. The correlation coefficients are also marked in the figure. There is fairly good correlation between the deviations in ΔX at the two stations with correlation coefficients of 0.60, 0.55 and 0.58, respectively for the three seasons of D-, E- and J-months, respectively. Considering the large separation in longitude between the two stations, correlation is significant. Rastogi *et al* (2007) reported correlation of 0.65 between the deviations at SLZ and at Ancon separated by about 33° in longitudes. The separation of the two stations SLZ and SIK is about 38° in longitudes and the correlation of about 0.6 is

Figure 7. Scatter plots of the deviations (from midnight) in ΔX at SLZ plotted against the deviations in ΔX at SIK for the three seasons. Correlation coefficients are also shown.

consistent with the value reported by Rastogi et al (2007).

However, the correlation between the deviations from mean of ΔY at the two stations is absent or poorer as shown for the three seasons in figure 8. The correlation coefficients are 0.02, -0.24 and -0.40 , respectively for the three seasons. Therefore the deviations in ΔY are uncorrelated during D-months. The negative correlation is poor for E-months and fair during J-months. The negative correlation in ΔY is due to the direction of current in opposite direction at the two stations for most of the day hours.

Contour plots of the deviations ΔX and ΔY for SIK are plotted in figure 9. The contours of ΔX in red represent northward values (eastward current). Equinoctial maxima around 11 h are clearly seen. The contours of deviations ΔY in blue colour represent eastward values. Eastward values are seen during equinoctial and J-months between 05 and 09 h. Maximum westward values are seen in the afternoon hours. Again a loop of large early morning high in July and low in January is clearly

Figure 8. Scatter plots of the deviations (from midnight) in ΔY at SLZ plotted against the deviations in ΔY at SIK for the three seasons. Correlation coefficients are also shown.

Figure 9. Contour plots of ΔX and ΔY at SIK plotted on a grid of local time versus months.

demonstrated. No such semi-annual variation can be interpreted for the afternoon values of ΔY .

4. Discussion

The annual average variations of ΔX at SLZ and SIK are almost similar with range at SIK higher by few nT and consistent with the declination angles at the two locations. The peak ΔH value obtained from ΔX and ΔY is 93 nT for both the stations. The values of ΔX at SLZ are not constant after midnight and show an increase from midnight to 05 h. Large differences are seen in the variations of ΔY , with maximum negative value of -35 nT around midday at SLZ while at SIK maximum negative value of -10 nT is seen in the afternoon hours. Though the magnitudes of ΔY are consistent with the respective declination angles at the two locations, the variation at SIK is distinct with negative deviation in the forenoon and positive deviation in the afternoon.

The direction of the H vector during daytime varies from 15° W of north in the morning to 30° W of north in the evening at SLZ. The variation is, however, more at SIK (15° E of north to 15° W of north). Compared to the declination angle, the H vector during midday is aligned around 2° towards west at SLZ and around 3° towards east at SIK.

The seasonal variations of ΔX are as expected with maximum values during equinoxes and minimum values during J-months at both the stations. The deviations in ΔX at the two locations are

fairly well correlated (correlation of 0.6). The deviations in ΔY are uncorrelated during D-months and negatively correlated during other seasons.

The present analyses suggest that the zonal and meridional components of the ionospheric current are only partially correlated with each other. A significant longitudinal variation exists in the daily variation of these currents.

5. Conclusion

Equatorial electrojet at Sao Luiz in eastern Brazil and Sikasso in the western Africa, situated in the region of rapid changes in the declination show similar daily variations of ΔX with peak around noon with maximum values during equinoxes and minimum values during J-solstices. Daily variations of ΔY differ with the maximum deviation of about -35 nT around noon at Sao Luiz and much smaller value of about -10 nT around 14 h LT for Sikasso. Also the ΔY values are positive in the forenoon and negative in the afternoon hours at SIK.

The plot of the deviations in ΔX and ΔY at different hours for the two stations show the points along narrow ellipses with major axis aligned along 22° W of north for Sao Luiz and along 3° W of north for Sikasso as compared to declination of 20° W for Sao Luiz and 6° W for Sikasso.

The deviations in ΔX at the two stations are fairly well correlated. However, the deviations in ΔY show poor or weaker negative correlation.

Acknowledgments

Rastogi and Chandra are thankful to the Director, Physical Research Laboratory, Ahmedabad for the facilities provided. Thanks are also due to the Indian Space Research Organization for the financial support.

References

- Anandarao B G and Raghavarao R 1987 Structural changes in the currents and fields of the equatorial electrojet due to zonal and meridional winds; *J. Geophys. Res.* **92** 2514–2526.
- Arora B R, Mahashabde M V and Kalra R 1993 Indian IEEY geomagnetic observational program and some preliminary results; *Rev. Bras. Geofis.* **11** 365–385.
- Baker W G and Martyn D F 1953 Electric currents in the ionosphere, 1, the conductivity; *Phil. Trans. Roy. Soc.* **A246** 281–294.
- Chapman S 1951 The equatorial electrojet as detected from the abnormal electric current distribution above Huancayo, Peru and elsewhere; *Arch. Meteorol. Geophys. Bioklimatol.* **A4** 368–390.
- Doumouya V, Vassal J, Cohen Y, Fambitakoye O and Menielle M 1998 Equatorial electrojet at African longitudes: First results from magnetic measurements; *Ann. Geophys.* **16** 658–676.
- Gangepain J, Crochet M and Richmond A D 1977 Comparison of equatorial electrojet models; *J. Atmos. Terr. Phys.* **39** 1119–1124.
- Fambitakoye O and Mayaud P N 1976a Equatorial electrojet and regular daily variations of SR-I. A determination of the equatorial electrojet parameters; *J. Atmos. Terr. Phys.* **38** 1–17.
- Fambitakoye O and Mayaud P N 1976b Equatorial electrojet and regular daily Variations SR-II. The Centre of the equatorial electrojet; *J. Atmos. Terr. Phys.* **38** 19–26.
- Forbes J M 1981 The equatorial electrojet; *Rev. Geophys. Space Phys.* **19** 469–504.
- Forbes J M and Lindzen R S 1976 Atmospheric solar tides and their electromagnetic effects, II, The equatorial electrojet; *J. Atmos. Terr. Phys.* **38** 911–920.
- Forbush S and Casaverde M 1961 *Equatorial electrojet in Peru*; Carnegie Institution of Washington, Report No. 620.
- Hirono M 1952 A theory of diurnal magnetic variations in equatorial regions and conductivity of the ionospheric E region; *J. Geomagn. Geoelectr.* **4** 7–21.
- Onwumechili C A, Kawasaki K and Akasofu S I 1973 Relationship between the equatorial electrojet and polar magnetic variations; *Planet. Space Sci.* **21** 1–16.
- Rastogi R G 1962 Longitudinal variation in the equatorial electrojet; *J. Atmos. Terr. Phys.* **24** 1031–1040.
- Rastogi R G 1972 Sudden disappearance of Es-q and the reversal of equatorial electric Fields; *Ann. Geophys.* **28** 717–728.
- Rastogi R G 1975 On the simultaneous existence of eastward and westward flowing equatorial electrojet currents; *Proc. Indian Acad. Sci.* **78** 80–92.
- Rastogi R G 1978 Theory of preliminary negative impulses in SSC in H at equatorial Stations; *Proc. Indian Acad. Sci.* **87** 57–60.
- Rastogi R G 1999 Ionospheric current system in Indo-Russian longitude sector; *Sci. Cult.* **65** 269–282.
- Rastogi R G 1989 The equatorial electrojet: Magnetic and ionospheric effects; In: *Geomagnetism* (ed.) Jacobs J, Academic Press **3** 461–425.
- Rastogi R G 2006 Sq and sfc currents at equatorial stations along the western and eastern African sectors; *Earth Planets Space* **58** 1475–1478.
- Rastogi R G and Chandra H 1974 Interplanetary magnetic field and the equatorial Ionosphere; *J. Atmos. Terr. Phys.* **36** 377–379.
- Rastogi R G and Chandra H 2002 Equatorial electrojet current flow directions; *J. Indian Geophys. Union* **6** 169–174.
- Rastogi R G and Iyer K N 1976 Quiet day variation of geomagnetic H field at low Latitudes; *J. Geomagn. Geoelectr.* **36** 377–379.
- Rastogi R G and Patel V L 1975 Effect of interplanetary magnetic field on ionosphere over the magnetic equator; *Proc. Indian Acad. Sci.* **82** 121–141.
- Rastogi R G and Trivedi N B 2009 Asymmetries in the equatorial electrojet around N-E Brazil sector; *Ann. Geophys.* **27** 1–17.
- Rastogi R G, Chandra H and Misra R K 1971 Effect of magnetic activity on electron drifts in the equatorial electrojet region; *Nature* **233** 13–15.
- Rastogi R G, Chandra H, Chakrabarty D K, Kitamura K and Yumoto K 2007 Day-to-day correlation of equatorial electrojet at two stations separated by 2000 km in Central South America; *Ann. Geophys.* **25** 1–6.
- Rastogi R G, Chandra H, James M E, Kitamura K and Yumoto K 2008 Characteristics of equatorial electrojet in Central South America; *Earth Planets Space* **60** 623–632.

- Rastogi R G, Chandra H and Yumuto K 2010 Equatorial electrojet in East Brazil longitudes; *J. Earth Syst. Sci.* **119** 497–505.
- Reddy C A 1989 The equatorial electrojet; *PAGEOPH* **131** 485–508.
- Richmond A D 1973 Equatorial electrojet, 1, Development of a model including winds and instabilities; *J. Atmos. Terr. Phys.* **36** 1083–1103.
- Ronchi C, Sudan R N and Similon P L 1990 Effect of short-scale turbulence on kilometer wavelength irregularities in the equatorial electrojet; *J. Geophys. Res.* **95** 189–200.
- Sarabhai V and Nair K N 1971 Morphology of the geomagnetic field variations and a study of the interplanetary magnetic field fluctuations in relation to the daily variations of the geomagnetic field at low latitudes; *Cosmic Electrodyn.* **2** 3–21.
- Sugiura M and Cain V C 1966 A model equatorial electrojet; *J. Geophys. Res.* **71** 1869–1877.
- Sugiura M and Poros D J 1969 An improved model equatorial electrojet; *J. Geophys. Res.* **74** 4026–4034.
- Untiedt J 1967 A model of the equatorial electrojet including meridional currents; *J. Geophys. Res.* **72** 5799–5810.

MS received 22 June 2010; revised 28 September 2010; accepted 8 November 2010