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Surface signatures of meridional currents in the equatorial electrojet

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The requirement that the surface magnetic field linked with the equatorial electrojet (EEJ) should be curl free is used to demonstrate that the electrojet has to have variations in the declination (*D*) component with well defined diurnal and latitudinal structures and an amplitude of around 5-10% of the electrojet strength. Data from the standard magnetic observatories in the Indian sector are used to identify the predicted signature of the electrojet-associated *D* variations. The pattern of time variations deduced from the data shows enhancement with respect to the theoretically predicted values in the afternoon sector, but the signatures appear to be suppressed in the forenoon sector. Since even a small displacement or meandering of the main eastward electrojet flow can produce changes in declination, various scenarios for the current flow are also considered, and temporal and latitudinal dependence of the *D* variation evaluated in a bid to identify the source of this forenoon-afternoon asymmetry. It has been shown that, in principle, the field due to deviation of the flow from pure eastward direction can be responsible for, at least, a part of the observed asymmetry. There may also be contributions from the channelling of the induced currents round the southern peninsula in the lower crust and upper mantle.

1 Introduction

Empirical models[1,2] treat the equatorial electrojet (EEJ) as a narrow band of strong eastward flowing E-region currents (**J**) localized to within around ±5° of dip equator. The current system is envisaged as fixed in space, as its strength varies with longitude. As the earth rotates under this fixed current system, a surface magnetic observatory in the electrojet belt records the well known diurnal pattern of the EEJ. While such a picture is very convenient for modeling EEJ, as it requires essentially the northward component (*H*) of the observed electrojet field, a serious conceptual problem arises as the resulting fields are longitude dependent. In such a framework, the requirement of the conservation of current ($\nabla . \mathbf{J} = 0$) is not met and, consequently, the surface magnetic field, **B**, computed from such a model need not be curl free[3]. The current system will produce a longitudinally varying northward component of the magnetic field without a corresponding latitude dependent eastward field (*D*), and this would be supported by vertical currents which are orders of magnitude higher than what are known to exist in the highly resistive lower atmosphere. It follows directly that the eastward flowing electrojet currents are closed by meridional or vertical currents capable of producing *D* variations that are consistent with the *H* variations derived from the above model of the electrojet. In fact, if the distribution of *H* variations is available, *D* variations can be obtained by solving the differential equation describing the vertical component of the curl free condition. The solution provides a unique latitudinal profile subject to a constant which has to be obtained from data. Such an approach for evaluating *D* variations provides an important check on the empirical models that are, otherwise, successful in reproducing the observed electrojet variations in the horizontal component, *H*, and the vertical component, *Z*, provided that they also reproduce the observed *D* profile. There is one more important ramification associated with the present methodology. While no one denies the requirement that the equatorial electrojet should have a closure path, very little has been done in evaluating the implications in terms of the *D* variations. Even the efforts, which have been otherwise thorough[2], tacitly assume that the observed *D* variations are a part of the smoothly varying global S_q current system. The present approach to the problem is to demonstrate that this need not be so.

In this paper, the electrojet variations refer to the part of the low latitude diurnal change that rises or falls abruptly within a few degrees of the dip equator. The latitudinal structure of such variations cannot be described by sine or cosine functions of the latitude. The field outside this region can be expanded in terms of trigonometric functions (or spherical harmonics) and the evaluated coefficients can be used to extrapolate the global field to the vicinity of the dip equator. The global field thus determined will not only include contributions from the global S_q (including inter-hemispheric field aligned currents) and magnetospheric current systems, but can also have a component due to currents flowing out of the electrojet region and spreading out to higher latitudes. In fact, in the absence of westward currents in the fringe of the electrojet region, meridional currents associated with the electrojet can merge with the global S_q. The arguments presented here ignore the subsurface-induced currents which may also have to be invoked to account for the observed D variations in the peninsular India.

Though the EEJ D variation may, in future studies, help to examine the long standing controversy on whether the S_q and EEJ currents are independent or part of the same current system, the issues are not relevant to the approach and conclusions of the current study. The aim of the present study is to show that sharp latitudinal changes in the H variations, close to the dip equator, have to be accompanied by corresponding D variations within the electrojet belt.

The declination is a measure of the angle that the local magnetic field makes with the local geographic north and is generally expressed in degrees east or west as the case may be. Temporal changes in declination are produced by magnetic field variations perpendicular to the magnetic field at a given place. Since the aim of the present calculation is to identify the currents responsible for generating such changes, it appears more reasonable to express D in terms of the magnetic field associated with it. Throughout this paper D is, therefore, expressed in nT, first by converting the changes in degrees to radians and then multiplying it with the strength of the horizontal component of the magnetic field at the place.

A major part of the variations in H and D can be understood using a simplified model geometry wherein the dip equator is everywhere perpendicular to the geomagnetic field and the primary (eastward) electrojet currents do not produce significant changes in D. This is the generally accepted scenario and forms the basis of the theoretical discussion in Sec. 2 and preliminary interpretation of the observations in Sec. 3. It should , however, be noted that, in general, there can be no H or D axis in the global or even regional scale, as the direction of the ambient horizontal component of the geomagnetic field can vary from location to location. The field due to the current systems has to be evaluated at each point and the H and D components be determined by taking the components of the calculated field along and across the ambient direction of the local geomagnetic field. This is the approach adopted in Sec. 4 of the paper while examining the possibilities of various deviations of the electrojet flow direction, accounting for the observed pattern of the D variations deduced in Sec. 3 for the stations in the peninsular India.

2 *D* variations deduced from curl free condition

For the slowly changing magnetic fields typical of the equatorial electrojet quiet day variation, the vertical (radial) component of the curl of the surface magnetic field is given by

$$\mu_0 \mathbf{J}_r = (\nabla \times \mathbf{B})_r = \frac{1}{r_E \cos\lambda}\left[-\frac{\partial}{\partial\lambda}(D\cos\lambda) + \frac{\partial}{\partial\phi}H\right] \quad \ldots (1)$$

where

$\mu_0 = 4\pi \times 10^{-7}$ (the permeability of free space)

r_E = Radius of the earth,

λ = Latitude coordinate measured positive northwards,

ϕ = Longitude coordinate measured positive eastward from 75°E.

H = Horizontal component of the magnetic field (positive northward)

Hereafter H and D will refer to the time varying component of the magnetic field. It is to be noted that the standard expression for the radial component of the curl of the magnetic field in the spherical coordinate-ordinate system[3] is recovered by changing from latitudes to colatitude coordinate.

Assuming that the rotation of earth under fixed current system produces the observed diurnal variation, we replace time by longitude coordinates and substitute the value of 6371 km for the radius of the earth. We use the fact that on the surface $\mathbf{J}_r = 0$ and compute the D variation for the resultant differential equations. For the present computations, we assume a realistic latitudinal dependence for H in the form

$$H = H_c \exp\left\{-\left(\frac{\lambda-\lambda_c}{5}\right)^2\right\} \quad \ldots (2)$$

where, λ_c is the latitude of the centre of the electrojet and H_c is the corresponding value of H. The assumed form ensures that the field drops to e^{-1} of its maximum value at ±5° latitude. The function is, however, positive throughout, and it has been tacitly assumed that no reversal of currents are involved within the electrojet belt. The diurnal variation is specified through the diurnal pattern of H_c. The assumption that the latitudinal and temporal dependencies can be separated, simplifies calculations and renders our conclusions, related to qualitative features, more transparent. A more complicated functional form may be called for in quantitative modelling of the data.

Results in this section corresponds to $\lambda_c = 0$. It is also assumed that the ϕ dependence is equivalent to time variations ignoring the regional differences in the electrojet. Indeed, the MAGSAT data[4] for the dawn and dusk sectors indicate that differences between the different longitude sectors are of second order. Moreover, it is presumed that these differences, if any, will not produce qualitative changes, and conclusions arrived at will still be valid.

The ϕ dependence used in the present calculation is consistent with the pattern of diurnal variation provided by the annual means of the electrojet fields. The basic time (longitude) structure is derived from the annual mean daily variation of 1978 data of Trivandrum (dip lat. 0.2°N), close to the centre of electrojet in the Indian region, and normalized to produce peak value at 100 nT at the dip equator.

The differential Eq.(1) is integrated after substituting $\frac{\partial H}{\partial \phi}$, calculated from the data for each hour and latitude, to get latitudinal profile for D. There is a constant of integration that has to be derived from the actual D data for each hour. This constant of integration which can vary with time has a physical significance. Conservation of current ($\nabla . \mathbf{J} = 0$) only demands that any reduction (or increase) in eastward current flowing into a point has to produce a corresponding increase (or reduction) in the meridional current flowing out of it, but does not specify whether such a flow is northward or southward. The constant determines how exactly the meridional currents flow and can only be obtained from the data. However, given the constant, the latitudinal profile is uniquely determined. In the present paper, the effect of the boundary condition is a parameter, Y, representing the D value at the northern fringe of the electrojet.

The resultant latitudinal profile is presented in Fig. 1(a). The separability of the latitudinal and temporal structures assumed for the H variations in Eq. (2) ensures that the latitudinal profile of the EEJ D remains the same throughout the day except for a multiplicative factor whose magnitude and sign is determined by the temporal structure provided in Fig. 1(b). To obtain the D variation at any latitude and local time (LT), one has to assign an appropriate value of Y, read out the latitudinal scaling from the upper half [Fig. 1(a)] and multiply it with the value provided in the lower half [Fig. 1(b)] for the selected LT. When Y=0, the time variation of electrojet D at the dip equator shows a well defined westward maximum of around 6-8 nT in the forenoon and eastward maximum of around 6 nT in the afternoon sector. This time structure is a signature that is looked for in the actual data. The importance of the parameter, Y, in defining the direction of flow of the return currents can be summarized as follows:

Case 1: When $Y = 0$ in Fig.1.

This corresponds to the case when the return currents do not flow into or out of the electrojet belt in the northern hemisphere. The immediate

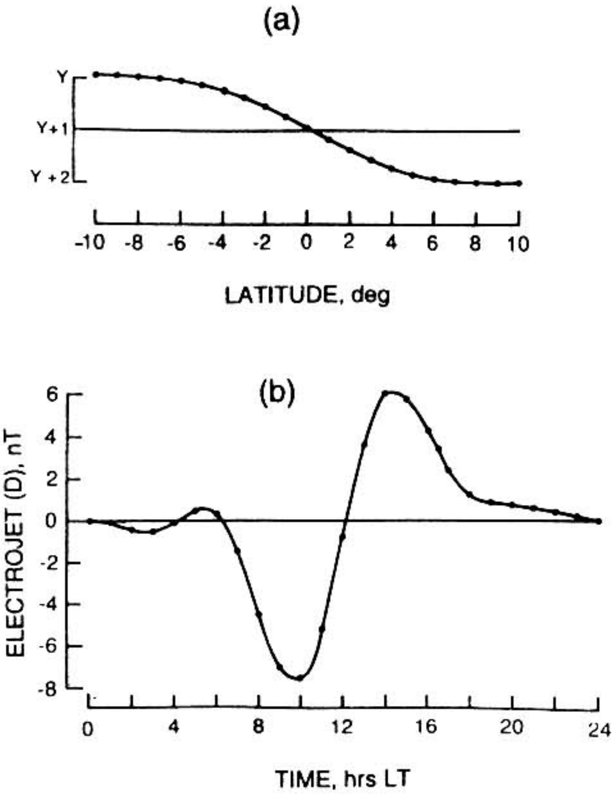

Fig. 1—(a) Latitudinal profile of D required for the surface magnetic fields to be curl free [When $Y = -1$, currents flow out symmetrically into the two hemisphere from the center of the electorojet; $Y = 0$ and $Y = 2$ represent cases when the meridional currents flow out entirely into the southern and northern hemispheres, respectively.] and (b) Local time variation of electrojet D [When $Y = 0$, this will represent the variations at the dip equator.]

consequence of this is that all the return currents flow across the dip equator into the southern hemisphere and all the stations in the electrojet belt in both the hemispheres will record variations in D, resembling that of a typical southern hemispheric location. A station like Trivandrum at the dip equator will record a pattern of D variations indicated in Fig.1 with an amplitude of about 6-8 nT

Case 2: When $Y \sim -1$ in Fig. 1.

This will correspond to the case when the return currents flow symmetrically into the two hemispheres. There is no current flow across the dip equator and the amplitude of D variation vanishes there. The pattern of D variation reverses across the dip equator. This could be the typical situation under the equinoctial conditions.

Case 3 : When $Y \sim -2$ in Fig. 1.

This is the case wherein no current, associated with the equatorial electrojet, flows across the southern fringes of the electrojet. All the return currents originating in the southern hemisphere flow across the dip equator and ultimately flow out of the electrojet region in the northern hemisphere. The pattern of D variations at all the electrojet stations in both the hemispheres will resemble a typical D variations at a northern hemispheric station. A typical equatorial station will record an amplitude of around 6-8 nT as in *Case* 1, but the sign will be reversed.

It is also essential to examine how the D variations evaluated above can be identified in the real data. We can define EEJ D as D in the electrojet region minus the large scale D variation outside the northern boundary of the electrojet extrapolated to the electrojet belt using any suitable polynomial fit. The definition is consistent with techniques used in literature to remove large scale magnetospheric and S_q fields in H in order to identify the equatorial electrojet. It is also a convenient definition for us, since only data from the northern hemisphere are available in the Indian region.

In order to understand what sort of signature of the electrojet D will be found through the procedure adopted, one has to note that D profiles in Fig. 1 (which level off to a constant value beyond the electrojet belt) are drawn from Eq. (2) which is strictly valid only within the electrojet belt. One cannot assume, in general, that the meridional currents will flow out indefinitely or close just outside the fringes of the electrojet without adopting a reasonable model for the evolution of the low latitude field outside the electrojet. However, it is instructive to examine these two extreme cases to get a feel for the problem.

If the actual scenario corresponds to *Case* 1 ($Y = 0$), the subtraction will remove only the field of global nature and the resulting diurnal pattern of EEJ D at the dip equator is shown in Fig. 1(b). However, it is important to note that even in the other two cases, an identical pattern will emerge if the meridional currents of EEJ merge with the global system instead of closing within itself. As the computed D will vary smoothly outside the electrojet region, one notes from the latitudinal profile [Fig. 1(a)] and in the absence of a closure mechanism, that the currents will form a part of the global field to be subtracted out. After subtraction, the D variations at the dip equator will then correspond to the boundary condition that mimics the situation given by $Y=0$ or the *Case* 1 discussed above. The pattern of D variation obtained through subtraction will resemble what one intuitively expects for a southern hemispheric station based on a hemispherically symmetrical closed current loop model for the equatorial electrojet.

However, if the currents do close before reaching the low latitude outside the electrojet belt, the pattern of D variations at the dip equator deduced from the suggested mode of analysis of the data will depend on how the current systems close at the ionospheric heights and one can expect considerable day-to-day and seasonal variabilities.

It is necessary to comment on the sensitivity of the present results to certain model details. It is to be pointed out that the latitudinal profile in Fig. 1(a) is sensitive to the assumed initial profile. Sharper the latitudinal distribution of the H variations, sharper will be the changes in the D profile. If there are reversals in H incorporated in the initial profile, D will not vary monotonically with latitude, but will decrease in magnitude after crossing the latitude of reversal and may even vanish beyond a certain latitude. That will be indicative of the closure of the electrojet current within itself or, in other words, will establish the equatorial electrojet as an independent current system.

The magnitude of the electrojet D in the temporal variations shown in Fig.1(b) is, however, not sensitive to the exact nature of the profile. It depends on the magnitude of the latitudinally integrated eastward electrojet current and its temporal variations. After all, any build-up (or decay) of the electrojet current has to be accompanied by flowing in (or out) of currents from somewhere and, in the absence of reversals in H in the latitudinal profile, the currents will have to ultimately either merge with the global current system or join up with the electrojet current systems in the opposite hemisphere through field-aligned currents. If the electrojet current closes locally within the ionospheric dynamo region, the largest temporal variations will be at the latitude of the electrojet H field reversal.

Finally , it should be emphasized that the D variation patterns presented here follow from the fundamental laws of electrodynamics. The observed profile can deviate from the predicted pattern only if there are additional sources of the H variations. One candidate for such contributions is lateral subsurface conductivity gradient which has not been taken into account here. Secondly, it is also not right to assume that there are no longitudinal differences in the equatorial electrojet field. The second possibility can be examined only if stations more closely placed in longitude become available.

3 Identification of electrojet *D* from the real data

Using the data from a chain of geomagnetic observatories, we have tried to detect the signatures of the electrojet associated variations in declination, so that results obtained in Sec. 2 can be compared with the real data. The observed magnetic data at six Indian magnetic observatories, along 75° EMT have been analyzed. Of these, Trivandrum (dip lat., 0.2°N) and Annamalainagar (dip lat., 3.4°N) are situated in electrojet belt, while Hyderabad (dip lat. 11.0°N), Alibag (dip lat., 13.2°N), Ujjain (dip lat., 18.1°N) and Jaipur (dip lat., 23.0°N) are non-electrojet stations. The data used for this analysis are the hourly values of declination on geomagnetic quiet day ($A_p < 7$) for the period 1977-1984.

The method of analysis adopted here is not different from what is traditionally used to separate the electrojet variation in the horizontal component of magnetic field from the background variations originating in global solar quiet day (S_q) and magnetospheric current systems. The strength and latitudinal dependence of the global variations obtained from observations outside the electrojet belt, are used to remove the contribution from global current system at the electrojet stations. The assumption involved in the procedure is that the variation due to large scale currents should not change abruptly in the narrow latitudinal range defined by the electrojet belt and that any such change should have electrojet origin.

For each hour 75°E time, ΔD, the monthly average of departure of declination hourly values from their local midnight level, is computed for each calendar month. The process is repeated for each of the years for the entire period, and the mean diurnal patterns for each calendar month thus obtained are superposed and averaged out. This is carried out for each of the stations. Similar computations are carried out with horizontal component, ΔH, for Trivandrum (TRD) and Alibag (ABG) data to estimate the equatorial electrojet strength given by the hourly difference ΔH (TRD)$-\Delta H$ (ABG). To estimate the total contribution to ΔD from large scale current system, a fit of the form

$$\Delta D^{G}(\lambda) = A\cos\lambda + B\sin\lambda \qquad \ldots (3)$$

(λ being the dip latitude) is obtained by least squares for each hour using only non-electrojet stations. Just as an example, the local time dependence of the coefficients A and B so obtained is depicted for the month of May in Fig. 2(a).

The large forenoon eastward peak and relatively smaller westward peak in the afternoon are features of B, the coefficients of the sine function, whose contribution is small in the vicinity of the dip equator. On the other hand A is characterized by an early afternoon westward peak and relatively small forenoon eastward peak. The contribution of A is significant in the vicinity of the dip equator. It is probably made up of contributions from the magnetospheric current systems, inter-hemispheric field aligned currents and currents penetrating from southern hemisphere into the northern hemisphere, and may also include a component originating in the meridional currents flowing out of the equatorial electrojet and masquerading as part of global current system outside the electrojet belt as discussed in Sec. 2.

Equation (3) is used to compute ΔD for each hour for each of the stations. The latitudinal profile of the synthesized D variations for entire chain of stations is presented in Fig. 2(b), again for the month of May . Note the shift of the westward peak to earlier hours and shrinking of the forenoon peak as one approaches the dip equator. Hence, the most significant contribution of the global currents, in the region of the equatorial electrojet, is the large westward D in the early afternoon

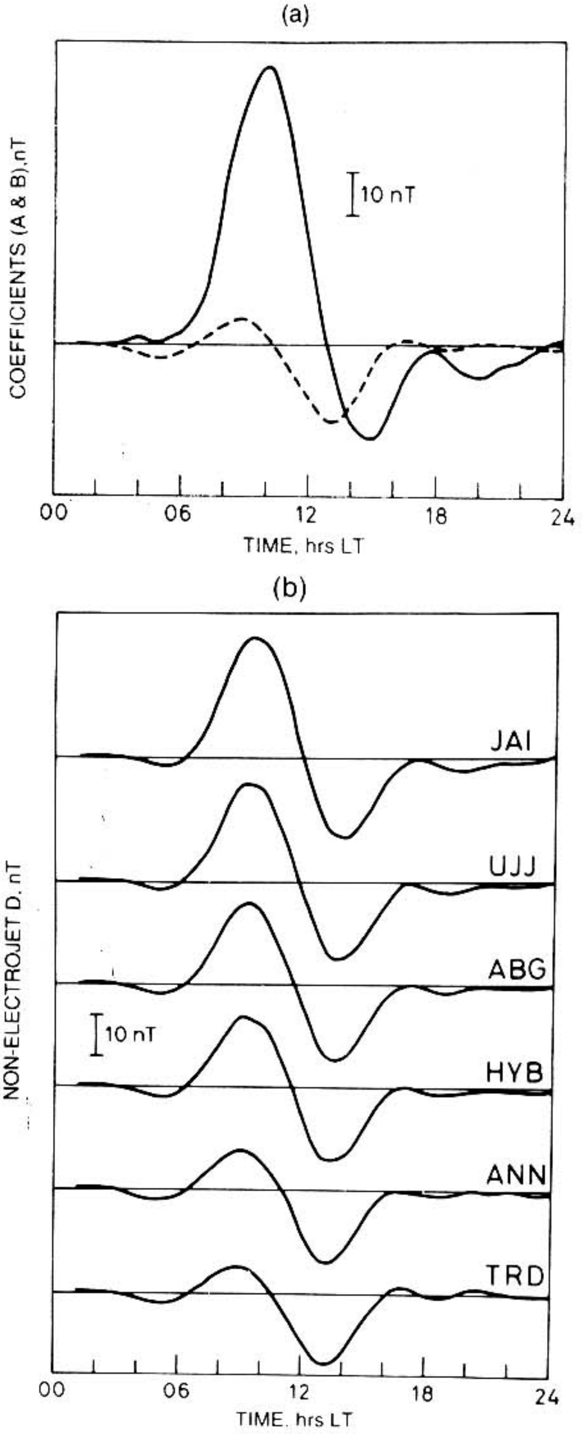

Fig. 2—(a) Diurnal pattern of the coefficients A (broken lines) and B (full lines) obtained for the non-electrojet D for the month of May, and (b) Synthesized latitudinal profile of the global D variations for the month of May obtained from the coefficients A and B in (a) above.

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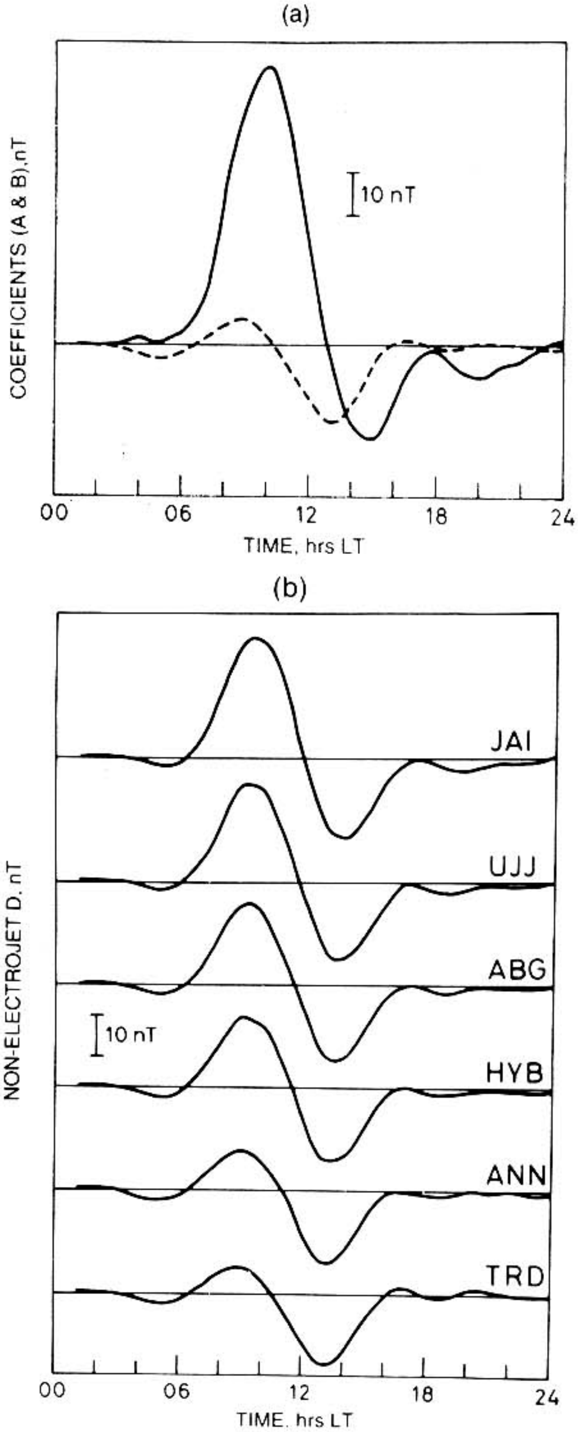

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hours and a smaller forenoon eastward peak. The *D* value from the electrojet stations has not been used to arrive at the profile, but these features should be present in the electrojet belt if the contributions are from large scale current systems. If we subtract the synthesized fields from the actual *D* at such latitudes, we can expect to obtain contribution from the meridional currents in the equatorial electrojet.

Next we subtract synthesized *D* from the ΔD at the electrojet stations to get electrojet *D*, and at the non-equatorial station to check up whether the global components are adequately represented by the fit. The process is carried out for each calendar month and results are shown in Fig.3. The shaded zones in the each of the graphs are the envelope within which the residuals (after subtraction of the synthesized *D*) at all non-electrojet station are confined to. It is clear from the narrow extent of the shaded regions that the *D* variations at all non-electrojet stations are almost entirely accounted for by the synthesized global field. The number of days of data which have gone into each plot is provided in Table 1.

It is obvious from Fig. 3 that there is a clear and stable eastward field signature in the afternoon sector at the electrojet stations. This is as expected from the results in Sec.2 assuming that the currents

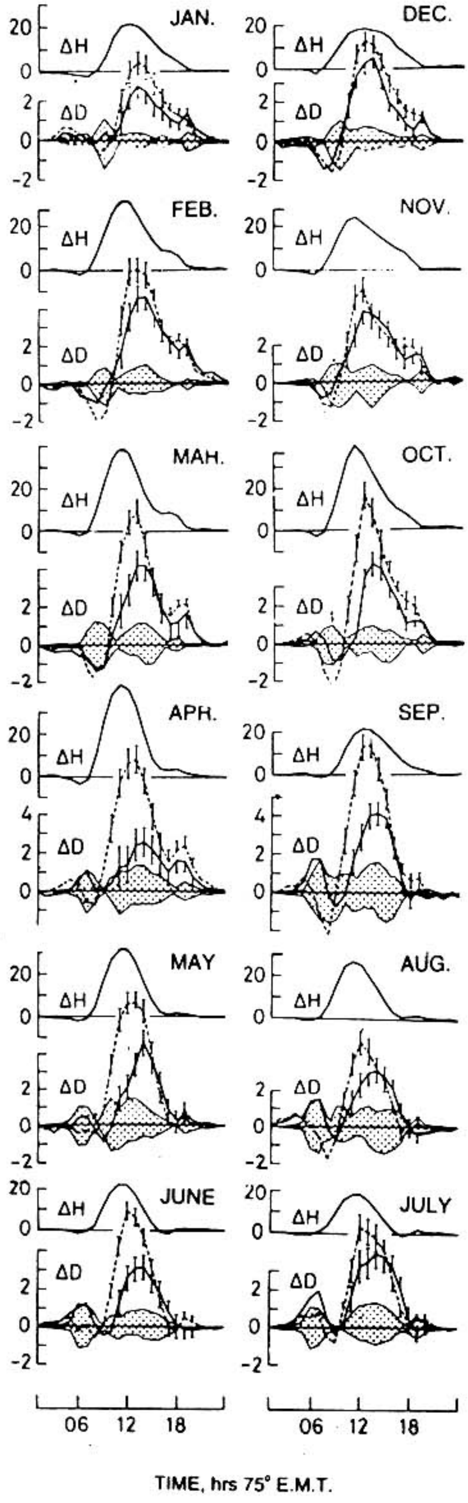

Fig. 3—Daily variation of the declination changes that can be associated with the electrojet current system. [Variations at Trivandrum are denoted by the dotted lines, while those at Annamalainagar are represented by solid lines; ΔH, equatorial electrojet strength for each month is also shown].

Table 1—Number of days of data to obtain characteristic *D* profiles depicted in Figs 2 and 3

Month	No. of days
Jan.	79
Feb.	49
Mar.	68
Apr.	39
May	69
June	74
July	67
Aug.	68
Sep.	54
Oct.	67
Nov.	66
Dec.	84

escaping from the electrojet region end up as a part of a current system extending through the region of the S_q current systems. The basic pattern of the variations is the same in each of the calendar months,though seasonal effects also manifest themselves. The narrow extent of residuals at the non-electrojet stations confirm the authenticity of the technique. The error bars are standard errors obtained from the dispersion of the declination at each hour at Trivandrum and Annamalainagar. In the computation of the standard errors, not only the variability of the departure of declinations at each hour from the local midnight values has been considered but the dispersion due to the variability of the midnight base from day to day and year to year has been added to it. To estimate the latter, the secular variation estimated from the annual means has been subtracted out. Since this subtraction is never perfect, dispersion is bound to be overestimated. The error bars can, therefore, be interpreted as upper bound for the error.

Results shown in Fig.3 can be compared with Fig. 1 which shows local time variation of electrojet *D* derived from curl of **B** condition. Apart from a base line shift, our results show similar semidiurnal pattern for each of the calendar month with a minimum in the forenoon and maximum in the afternoon hours. The morning minimum is, however, subdued and considering that the actual electrojet strengths depicted in Fig.3 are much less than the 100 nT level used to in Fig. 1, the afternoon maximum is enhanced considerably.

Comparing the results with the latitudinal profile in Fig. 2(b), it appears that at least in the afternoon sector, electrojet return currents find their way into the higher latitudes. A part of the contribution to the afternoon westward peak has its origin in the meridiaonal currents flowing out of the electrojet belt. The peak in that case will not be as prominent in the *D*, variations at Trivandrum and Annamalainagar and the subtraction of extrapolated *D* can produce signatures seen at these stations in the plots.

At the same time, it is possible that meridional currents do not reach the latitude of the non-electrojet stations in the forenoon hours (the forenoon eastward peak is much weaker) or the peak is not adequately determined due to the presence of a much larger peak in the coefficients *B* at the same local time. Either of these may partially account for the apparently smaller electrojet *D* variations seen in the forenoon hours. However, the overall time structure of variation is consistent with the expectation of curl free nature of the surface magnetic field variation.

4 Other possible contributions to electrojet *D*

The *D* variations, arrived at from the curl free condition on the surface field (Sec. 2) and those obtained from the data (Sec. 3), match favourably in the afternoon sector, but some differences are obvious in the forenoon period. One could argue that this could be due to idealization of the model current system. The primary eastward currents in the model are everywhere normal to the ambient magnetic field and, hence, do not contribute to the declination component. Considering that variations in *D* are of the order of a few nano teslas accounting in magnitude for less than 10% of the *H* variations, even fluctuations in the field caused by very small deviations from the purely west to east flows cannot be ignored. In this section, we examine if reasonable deviations in the electrojet flow direction can produce sizable declinations variations in the equatorial electrojet belt and thus account for the above discrepancies. Idealized numerical models of the equatorial electrojet[5] ignore the difference between geographic and geomagnetic equators to simplify calculations and the resultant principal current flow is eastward and parallel to the common equator. Even in this case, we do not expect any contribution to *D* only because of tacit acceptance of the logic based on plane earth models. To an observer on the surface of a spherical earth, a west-to-east current will appear to have vertical upward component in the western horizon and downward component in the eastern horizon. If, in addition, there is a local time dependence of current strength, the fields due to these oppositely directed currents of slightly differing magnitudes can generate declination changes slightly away from the equator.

Possibilities of the currents flowing along the geomagnetic equator, or even some mean equator that takes into account the position of the geographic and geomagnetic equators, have been considered in literature[6] , but the impact of the choice on the D variation has not been considered. The most common view is that the electrojet follows the dip equator which can be determined from an appropriate International Geomagnetic Reference Frame (IGRF) model. But here again, the local dip equator can deviate from the IGRF dip equator and this can produce its own contribution to D.

In what follows, we examine possible deviations of the current flow directions from the standard idealized plane earth picture and find out the nature of contributions made to the declination variations. Thus, in this paper latitudinal distribution of D is presented in terms of distance from the dip equator. It is not intended to provide a quantitative evaluation of D variation, but to present a flavour of qualitative changes introduced by various minor deviations in the current flow patterns.

The currents are assumed to flow at a height of 100 km. The latitudinal profile used is of the form

$$J = J_0 \exp\left\{-\left(\frac{\lambda-\lambda_c}{5}\right)^2\right\} \qquad \ldots (4)$$

where both J_0 and λ_c are functions of longitude. The time variations are synonymous to longitudinal variation with respect to the longitude of the sun. The time variations are thus generated by moving the observer position with respect to the longitude of the sun or the peak of the electrojet current (which occurs slightly earlier) to reproduce the standard electrojet daily variation at a fixed station. The time structure for J is in the form assumed for H in Sec.2. Note that the width and strength of the electorrojet is same for all the models and the position and direction of flow is determined by the functional dependence of λ_c on longitude. Local direction of the current is tangent to the line of constant $\{\lambda\text{-}\lambda_c(\phi)\}$.

The field on the surface is calculated using the Biot-Savart's law[3] for infinitesimal current elements of the electrojet and then integrating the field over a wide range longitudes centered around the local meridian of the observation. The integration in latitude was over the span of the electrojet width and in longitude over ±50° centered around the local time of the observation.

There are certain complications involved in the interpretation of the nature of D variations that are related to the basic definition of declination. Geomagnetic field is expressed in terms of the scalar magnitude of the horizontal component (H), its deviation from the true geographic north (D) and the vertical component Z. Since the variations in the magnetic field are very small compared to the ambient field, the variations in H at any fixed station is given by the component of the variations along the ambient direction of the horizontal component at the place. The changes in declination are proportional to the component of the field perpendicular to the local magnetic field and can be readily expressed in nT by multiplying the deviation in radians with the magnitude of the local magnetic field.

In all but the cases discussed in the following sub-sections 4.1 and 4.5, the calculation are valid for longitude 77°E, i.e. for the Indian sector. For determining the D variations, consistent with the observatory data, it is necessary to know the local direction of ambient geomagnetic field. This was computed for each latitude using coefficients of the GSFC (12/83) model[4]. The H and D variations due to the model current system were then computed by taking the components along and perpendicular to this field. As mentioned earlier latitudinal D profile is presented as a function of the dip latitude.

The cases depicted in Fig. 4 [(a)-(e)] pertain to the D variations corresponding to the geometry of the currents described and discussed in detail in the subsections followed. The results are presented in a format similar to Fig.1. The latitudinal profiles of the D variations at 15 hrs LT are shown in the right hand section of Fig.4, while the apparent electrojet variations are obtained by subtracting the time profile of D at 6° N from that at the dip equator. The profile of the H variations are only marginally affected and are, therefore, not presented here.

4.1 Idealized Electrojet-model [case (a)]

This pertains to the situation where the difference of the geographic and geomagnetic equators is ignored. The D variations in the model correspond to the eastward field variations, since the ambient H will be due north everywhere. Only contribution to D originates in the sphericity of the

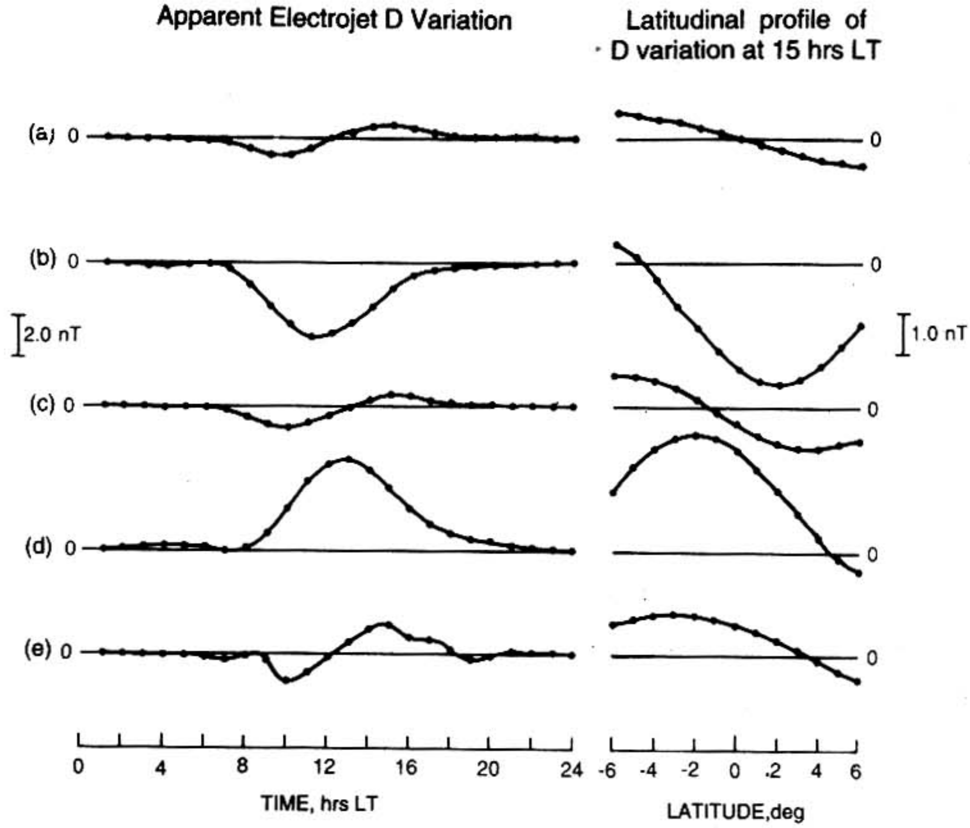

Fig. 4—Latitudinal profile of D at 15 hrs LT and the diurnal pattern of apparent electrojet D at the dip equator for the current systems described in Sec.4. [Detailed definition of cases (a)-(e) can be found in the text.]

earth. Note that the diurnal pattern mimics the field obtained from the curl free condition as described in Sec. 2, but its magnitude is much smaller. Furthermore, the latitudinal profile peaks at the edge of the region depicted in Fig. 4 and decays thereafter. The D variations do not merge into the $S_q D$ as in the case considered in Sec.2.

4.2 Currents flow along the geomagnetic equator [case (b)]

This is not realistic case and only presented as an extreme scenario. The diurnal pattern bears no resemblance to the observation.

4.3 Electrojet flowing along the IGRF dip equator [case (c)]

This is perhaps the most realistic case considered, and the diurnal pattern as well as the latitudinal profile resemble the case (a). In both cases the diurnal pattern has a maximum deviation of about 1 nT from the nighttime base and exhibits considerable forenoon/afternoon symmetry in the amplitude of deviation (though the signs are in opposition).

4.4 Electrojet current flowing along the local dip equator [case (d)]

The local dip can deviate from the dip equator obtained by using IGRF coefficients. Surveys have been conducted from time to time to study the profile of the dip equator in the subcontinent as well as its secular migration over the years[7,8]. Recent survey[8] indicates that the variation of the dip latitude with longitude is not quite linear but has a curvature. In this paper, we have assumed a linear variation of the latitude λ_D of the local dip equator with the longitude ϕ (geographic) with a uniform slope, $\frac{\partial \lambda_D}{\partial \phi} = 0.005$, extending to over a wide range of longitudes to facilitate computation. A constant factor is chosen in such a way that the correct position of dip equator is obtained around the longitude of Trivandrum. The extremely small slope of 0.005 is more appropriate for the eastern part of the subcontinent (cf Ref. 8) and represents the dip equator that is closely aligned parallel to the geographic equator. The resultant field [cf case (d) in Fig. 4] is an eastward deviation in declination which can suppress the westward swing in the forenoon sector and enhance the eastward swing in the afternoon sector to bring model values of Fig. 1 closer to the observed variations in Fig. 3.

It is to be pointed out that the slope considered is very small, as the mean rate of change of the dip equator over the entire region is many times more than this value and this would lead to much smaller eastward deviation of the field. The low value of the slope considered here should be regarded as an illustration of a possibility. The fact that the tidal forces are ordered with respect to the geographic coordinates could also contribute to the closer alignment of the flow to the geographic equator.

4.5 Local time variation of the electrojet axis [case (e)]

Flambitakoye and Mayaud[2] had shown that the axis of the electrojet shifts by as much as a fraction of a degree during the course of the day and the pattern of variation of the electrojet axis in Fig.5 is based on Fig.11 of their paper. The diurnal pattern and the latitudinal profile of *D* presented in Fig.4 are computed using the diurnal pattern of variation in λ_c given in Fig.5. The model used is the same as in the case (a), except for this local time variation in λ_c . The resultant pattern shows a forenoon/afternoon asymmetry with enhanced period of the eastward afternoon regime. The latitudinal profile given in Fig.4 is for a particular local time, namely, 15 hrs LT, and in this case there are changes in the profile with local time.

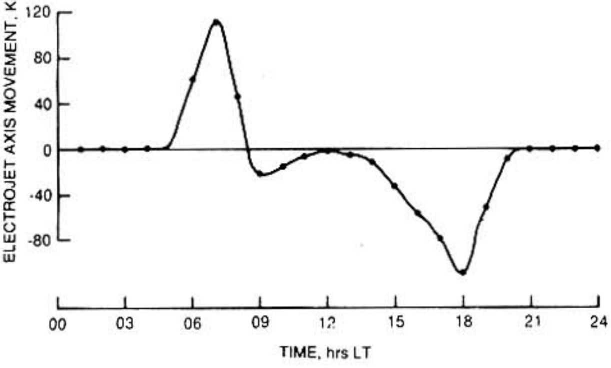

Fig. 5—Pattern of movement of electrojet axis during the course of the day, based on Fig.11 of Ref.2.

5 Conclusions

It has been shown through the requirement of curl free nature surface magnetic field that a significant *D* variation with a clearly identifiable diurnal as well as latitudinal structure is associated with the equatorial electrojet. We have also identified, from the analysis of the magnetic observatory data in the Indian sector, a clear equatorial electrojet-associated *D* variation which bears considerable resemblance to the predicted signature, especially, in the afternoon sector.

Other possible sources of *D* variation in the equatorial electrojet region have also been demonstrated, which, though small, could be identifiable in future with increased stability and sensitivity of the magnetometers. A deviation of the equatorial electrojet flow due to the closer alignment of the local dip equator to the geographic latitudinal contours could add to the fields deduced from the curl free condition to bring the net field closer to observations. Finally, we note that the study of equatorial electrojet-associated *D* variation is likely to become very meaningful in future with the ushering in of a new generation of magnetometers that have 0.1 nT sensitivity and corresponding baseline stability over a day. Though the fields of 5-6 nT associated with electrojet *D* variation may appear too small at first sight, it should be borne in mind that the noise levels in the *D* fluctuation are smaller, as magnetosphere fluctuation also contributes less to the declination component. It may, therefore, become necessary to use *D* variation in the future empirical model of the equatorial electrojet.

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