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PRINCIPAL COMPONENT ANALYSIS OF EQUATORIAL GEOMAGNETIC AND IONOSPHERIC DIURNAL VARIATIONS

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Mean diurnal variations of the H and D components of the geomagnetic field and the Total Electron Content (TEC) at selected stations, close to the dip equator, at low latitude away from the equatorial electrojet influence and close to the latitude of the Sq focus are examined through the method of Principal Component Analysis for strong electrojet, weak electrojet and counter electrojet days. It is shown that the strength of the electrojet influences H and D variations at even higher latitudes largely through the second principal component. For D, in particular, the first component is shown to be largely unaffected by the changes in the electrojet strength.

Key words: Principal Components; Equatorial Electrojet; Counter electrojet; Total Electron Content.

ANÁLISE POR PRINCIPAIS COMPONENTES DO CAMPO GEOMAGNÉTICO EQUATORIAL E DAS VARIAÇÕES IONOSFÉRICAS DIURNAS - *As médias diurnas das variações dos componentes H e D do campo geomagnético e do conteúdo total de elétrons (TEC) em estações selecionadas, próximas ao equador magnético, em baixas latitudes, distantes da influência do eletrojato equatorial e próximas às latitudes de abrangência do Sq, são examinadas através do método de Análise por Principais Componentes, para indicações de presença de manifestações fortes, fracas, ou contra-eletrojato. É demonstrado que o eletrojato afeta as variacões H e D em latitudes mais altas, principalmente através da segunda principal componente. Para D, em particular, a primeira componente não é afetada pelas variações do eletrojato.*

Palavras-chave: *Componentes Principais; Eletrojato equatorial; Contra-eletrojato; Conteúdo total de elétrons.*

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INTRODUCTION

The equatorial electrojet and its varying geomagnetic signatures have been discussed in sufficient details in the past four decades, as also the associated enigmatic phenomenon of counter equatorial electrojet (CEJ) (Gouin & Mayaud, 1967; Mayaud, 1977; Rastogi, 1989; and references therein). The role of neutral winds and the tidal modes of atmospheric oscillations in controlling the variability of the electrojet currents and the westward flow during CEJ events have also been examined without firm conclusions on the causative mechanisms (Hanuise et al., 1983; Anand Rao & Raghava Rao, 1987; Stening, 1989; and others). Initial correlation analysis between the daily variation of the H field at low latitudes and that in the equatorial zone in the same longitude sector indicated poor correspondence (see review Kane, 1976) but some results suggested that the movement of the planetary Sq currents towards or away from the equator is related to the strength of the equatorial electrojet (Tarpley, 1973; Kane, 1974; Mita Rajaram, 1983). Rastogi (1993b) examining individual cases of the diurnal variations on normal and CEJ days at different latitudes showed that a perceptible change in the pattern between the two categories could be seen well beyond the electrojet belt even up to the latitude of Sq focus. While Sastri & Bhargava (1980) did not find any signature of the CEJ currents in Declination in the equatorial zone, Rastogi & Verma (1994) suggest that even as the basic Sq(H) and Sq(Y) patterns are retained, a semidiurnal component is superposed affecting both H and D variations. These and several other studies reveal that the complexities of EJ and CEJ currents and their geomagnetic signatures are yet to be fully understood.

The method of Principal Component Analysis (PCA) or Natural Orthogonal Components (NOC) has been shown to be eminently suited when a given field is to be separated in terms of linearly independent systems with distinctive characteristics (Faynberg, 1975; Mita Rajaram, 1980). Mita Rajaram (1983) used the technique to determine the focus of Sq and its day-to-day variability. Gao Yufen & Zhu Geng (1990), who studied the spatio-temporal variations of the principal components in H and D over China, provide an illustrative example of the efficacy of the methodology.

When the geostationary satellite ATS-6 was moved over the Indian region, between October 1975 and July 1976, the circularly polarized radio beacon at 140 MHz was used to derive the Total Electron Content (TEC) at a network of Indian stations. Rastogi & Klobuchar (1990) have shown that on normal electrojet days, a maximum in TEC is noticed over 15 to 20 deg. dip latitude indicating that the equatorial fountain is efficiently operational lifting up the plasma from over the equator to the anomaly crest region. On counter electrojet and/or on extremely weak electrojet days, the anomaly is shown to be conspicuously absent.

In this communication, we use the technique of PCA on carefully selected data sets of geomagnetic H and D variations at three representative latitudes and the TEC variations for the same set of days.

DATA ANALYSIS

Bhargava et al.(1983) provided an objective criterion for quantifying the equatorial electrojet strength and the afternoon CEJ events, using the difference in the daily variation of the H field at a pair of stations - one close to the dip equator and the other in the same longitude but away from the influence of the daytime equatorial electrojet. The CEJ index was based on the intensity of the afternoon depression relative to the night time reference level while the EJ index was based on the noontime excess over the night base. These indices were used to identify three categories of days between October 1975 and July 1976 when ATS - 6 was over Indian sector. The groups are classified as (i) Strong Electrojet days, (ii) Weak Electrojet days, and (iii) Counter Electrojet days.

The basic data analysed are the geomagnetic field variations of H and D at Trivandrum (TRD), Alibag(SBG) and Sabhawala (SAB), and TEC at Ooty, Bombay (BOM) and Ahmedabad (AMD). Table I lists the coordinates of the stations. Mean hourly values of H and D, corrected for non-cyclic variations, were derived as departures from local midnight values. For TEC, however, no reference level need to be used, as it is usually close to zero in early dawn. There were 37 days, 32 days and 26 days under the three categories of large, small and counterjet days respectively. The index Ap of magnetic activity was less than 7 for all these days, and therefore, they can be considered geomagnetically 'quiet'. The data matrix consisting of these hourly values (as columns) for different days (as rows) was then subjected to PCA using the cross products of individual columns. In addition, the difference field (TRD - ABG) was also analysed to yield information on the nature of the equatorial electrojet through its Principal Components.

In PCA, the magnitude of the eigen values determines the relative contributions of the corresponding eigen vector and the principal component (which is nothing but the projection of the original time series along the new direction defined by the eigen vector) to the total variance. It is seen that most of the variance is accounted for by the first two principal components, and therefore, further discussions are restricted to the first and second eigen vectors and the average patterns only. The local time dependence of the eigen vectors for the three elements H, D and TEC are discussed in the following sections.

RESULTS AND DISCUSSION

The mean daily variations of H at TRD, ABG and SAB as also the electrojet field (TRD - ABG) are depicted in Fig. 1. The choice of days was made on the basis of the difference field and this is clearly reflected in the diurnal patterns of the difference (TRD - ABG). It is noteworthy, however, that all the three groups of days exhibit an afternoon minimum confirming Bhargava et al.'s (1983) assertion that the afternoon CEJ is not a rare event in the Indian longitudes. The three curves for Alibag, on the other hand, are practically similar (to within error limits) indicative of their independence with respect to the equatorial electrojet. Sabhawala, a station close to the Sq focus, does indicate a different diurnal behaviour when electrojet strength is small. It is well known (Rastogi, 1993a) that in the winter solstice, the Sq current loop practically vanishes and H and D variations over locations close to the focus could be considerably erratic. The distribution of days in the analysis is marginally biased towards winter for small jet days (18 out of 32 days) and more so towards summer for CEJ days (20 out of 26 days).

The first two eigen vectors, indicative of the diurnal pattern of the first two principal components, are shown in Fig. 2. It may be borne in mind, that the eigen vectors can, without loss of generality, be scaled by factors or even inverted (scale of -1) to avoid confusion with regard to increase/decrease. The individual day's variation is obtained as a weighted combination of the eigen vectors (the weights, conventionally being called the 'coefficients'). It may also be pointed out that the 24 elements of the individual eigen vectors plotted are dimensionless numbers and the coefficients would be in nT, min. of arc or TEC units as are appropriate.

As would be expected, the first vectors for all the stations and the difference field, provide the diurnal

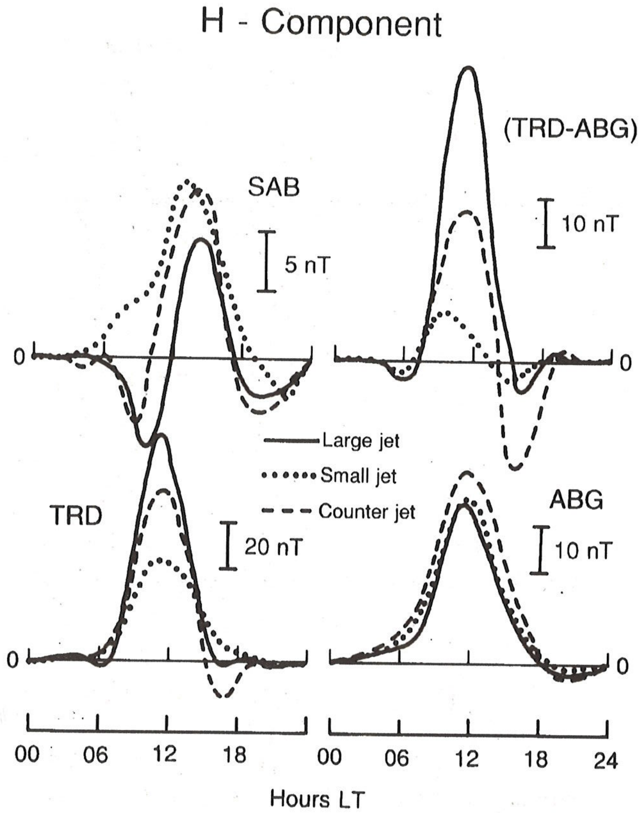

Figure 1 - Mean diurnal variation of horizontal component at Trivandrum (TRD), Alibag (ABG) and Sabhawala (SAB) for three selected groups of days. Diurnal variation (TRD - ABG) is representative of the time variation in the equatorial electrojet strength.

Figura 1 *- Média diurna da variação do componente horizontal em Trivandrum (TRD), Alibag (ABG), e Sabhawala (SAB) para três selecionados grupos de dias. A variação diurna (TRD - ABG) é representativa da variação temporal da força do eletrojato equatorial.*

behaviour appropriate for the corresponding groups of days: large jet, small jet or counter jet days. In contrast to the average curves of Fig.1, one could notice the influence of enhanced electrojet strength on the diurnal variation of H at low latitudes (ABG) with a sharp rise to maximum and a rapid fall later as against a much slower two-stage rise to maximum on days of small and counterjet activity at the equatorial zone. This is indicative of the difference in the build-up and decay of the east-west global Sq electric currents. The difference should then be more pronounced close to the Sq focus. The dependence of the first eigen

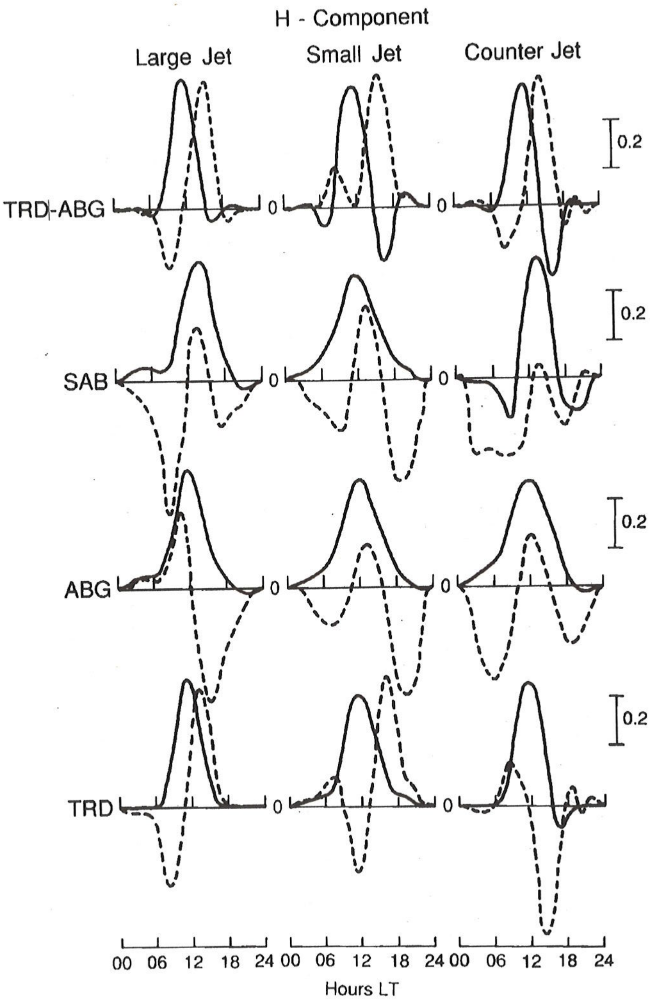

Figure 2 - Time variations of the first (continuous line) and second (broken line) eigen vectors derived from the horizontal intensity data of three Indian stations and the difference field (TRD - ABG) for three groups of days. Note that the units for eigen vectors are dimensionless numbers and the vectors are normalized (sum squares of the 24 elements of each vector add upto unity).

Figura 2 *- Variações temporais do primeiro (linha contínua) e segundo (linha tracejada) dos autovetores derivados dos dados de intensidade de três estações da Índia, e do campo diferencial (TRD - ABG) para três grupos de dias. Notem que as unidades dos autovetores são números sem dimensão e os vetores são normalizados (soma dos quadrados de 24 elementos de cada vetor totalizam uma unidade).*

vector on the strength of the electrojet currents is indeed clearly manifested in the diurnal variation on small jet and counter jet days when compared to strong jet days, at Sabhawala (SAB). The difference field (TRD - ABG) reemphasises the fact that the counter jet signature is clearly brought out in the first vector even when the choice of days was only for small jet strength. The results of H variations corroborate the findings of Arora et al.(1993) and Rastogi (1993b) that the influence of CEJ extends to latitudes further north in the Indian zone, with the station closest to the Sq focus indicating a strong dependence.

The second eigen vector is expected to bring out characteristics, unrelated to the first as the eigen vectors are orthogonal to each other, by definition. A close examination of the diurnal patterns of the second vector shows that its dependence on the strength and/or the direction of the electrojet is more clearly manifested both at Alibag and at Sabhawala than for the first vector. A semidiurnal wave is dominant at low latitudes on days of CEJ and small jet strength while a forenoon/late afternoon extrema contribute to the variations on days of large electrojet strength. These are clearly indicative of the fact that different modes of tidal oscillations are effective for the different groups of days. At Sabhawala, the role of the second vector is rather ill-defined and complex, but the semidiurnal nature is still prominent on CEJ or small jet days.

Close to the equator, the second component contributes mainly to a phase shift on CEJ and large jet days (as seen in TRD and TRD - ABG vectors) but on days when the electrojet is weak the difference field has a complex second component associated with it. If the variations depicted by the second component on magnetically quiet days are attributed to large-scale tidal winds with appropriate diurnal/semidiurnal modes (Somayajulu, 1988), then the higher order harmonics noticeable in the electrojet field could be attributed to the distortions caused by local winds (Devasia, 1986).

DIURNAL CHANGES IN DECLINATION

The equatorial electrojet current being dominantly eastward, and on its reversal on CEJ days mostly westward, the geomagnetic signature of any meridional (N/S) currents associated with jet strength should be correspondingly small. However, to see whether prominent variations could be noticed even in Declination, the daily variation of D for the three groups of days were analysed in a fashion similar

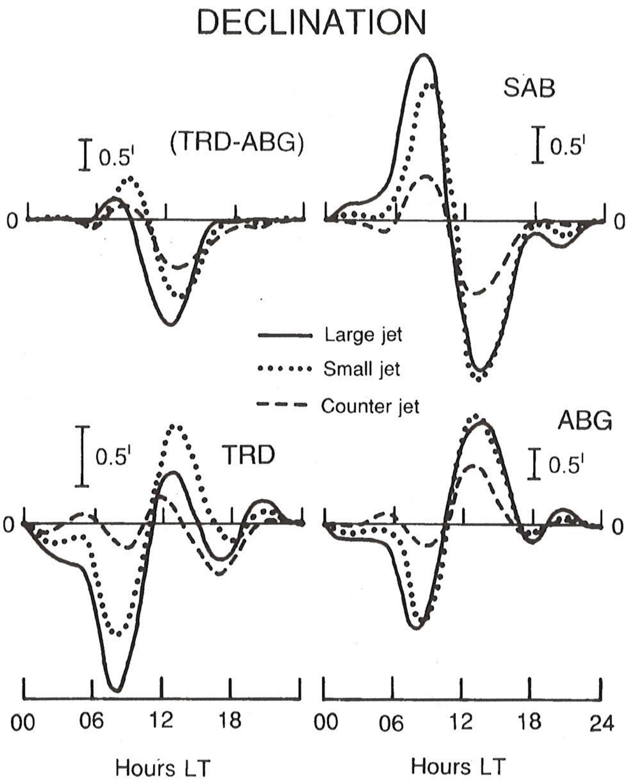

Figure 3 - Mean diurnal variation of Declination, as in Fig. 1.

Figura 3 *- Média diurna da variação da declinação, como na Fig. 1.*

to H. The average curves are shown in Fig. 3 and the first two eigen vectors in Fig. 4.

On days of counter electrojet, the diurnal pattern at TRD and ABG are dominated by a 8-hour component in contrast to the semidiurnal term seen on large or small jet days. At SAB, D variations on CEJ days have diminished magnitude. The difference field (TRD - ABG), is not much influenced by the strength of the electrojet either in regard to the amplitude or the phase of the diurnal variation. This suggests a change in global meridional Sq currents on CEJ days.

The first eigen vector for TRD, ABG or SAB do not show much difference for the three groups of days except for the secondary maximum on CEJ at Trivandrum, which in turn, should have caused the third harmonic to be prominent in the average pattern. A similar conclusion could be arrived at regarding the second vector too, except for a noticeable change at Alibag and Sabhawala between large and small jet/CEJ days. Thus, any change seen in D at low latitudes away from the dip equator could be considered as the manifestation of the weakening of the tidal modes of Sq and/or the relevant phase changes introduced by higher harmonic oscillations.

The only feature worthy of note in the difference field is the extremum in the first vector on days of strong jet and rapid change in the field direction compared to the weak jet/ CEJ days. This suggests a flattening of the overhead SQ current incorporating less N/S and more E/W extenuation of the Sq loop as a function of longitude (local time), when equatorial electrojet is stronger. One of the models proposed by Mayaud (1965) does consider such a process linked to the equatorward movement of Sq currents causing enhanced electrojet strength.

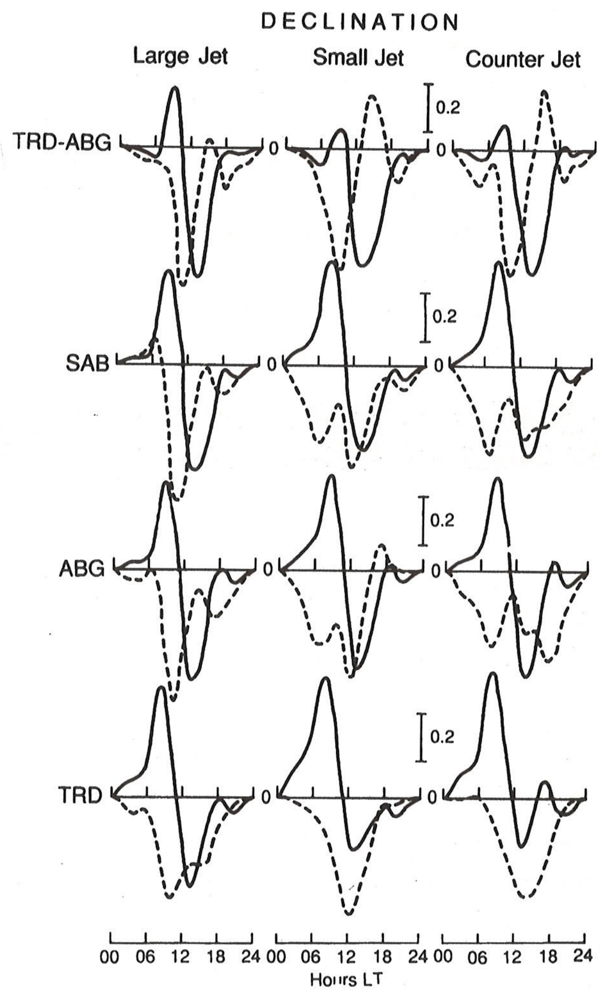

Figure 4 - Time variations of the eigen vectors derived from Declination data, as in Fig. 1.

Figura 4 *- Variações temporais dos autovetores derivados dos dados de Declinação, como na Fig. 1.*

DIURNAL VARIATION IN TOTAL ELECTRON CONTENT (TEC)

The PCA was extended to the TEC measurements made at Ooty in the electrojet region, Bombay (nominally below the latitude of the anomaly crest) and at Ahmedabad (located close to the mean latitude of peak foF2 or peak TEC). Table 1 provides details of the locations. The mean diurnal variation in TEC for the three groups of days are shown in Fig. 5. There is no dependence on the strength of electrojet at Ooty but at Bombay, there is an increase in peak TEC magnitude in association with large jet days. Only at Ahmedabad, a clear dependence of peak TEC on the strength of the electrojet is discernible. To bring out the change in the nature and the efficacy of the equatorial fountain, pair-wise difference in the diurnal patterns for the three categories are shown in Fig. 6. An excess near noon for large jet days seen for (AMD - OOTY) and (AMD - BOM) indicates that the anomaly crest was clearly well beyond Bombay, close to Ahmedabad for these group of days. A negative diurnal variation on small jet days seen for (AMD - BOM) and (AMD - OOTY) clearly indicates that the TEC over the equator throughout the day was larger and no diffusion along the magnetic field line could have been effective. This is in conformity with the case studies

Station	Code	Geographic *Lat.*	*Long.*	Dip. Latitude *(Approx.)*
TRIVANDRUM	TRD	8.5°N	75.9°E	0.8°S
OOTY	OOTY	11.4°N	76.7°E	3.0°S
BOMBAY	BOM	19.1°N	72.9°E	13.3°S
ALIBAG	ABG	18.6°N	72.9°E	13.1°S
AHMEDABAD	AMD	23.0°N	72.6°E	18.6°S
SABHAWALA	SAB	30.4°N	77.8°E	26.6°S

Table 1 / ***Tabela 1***

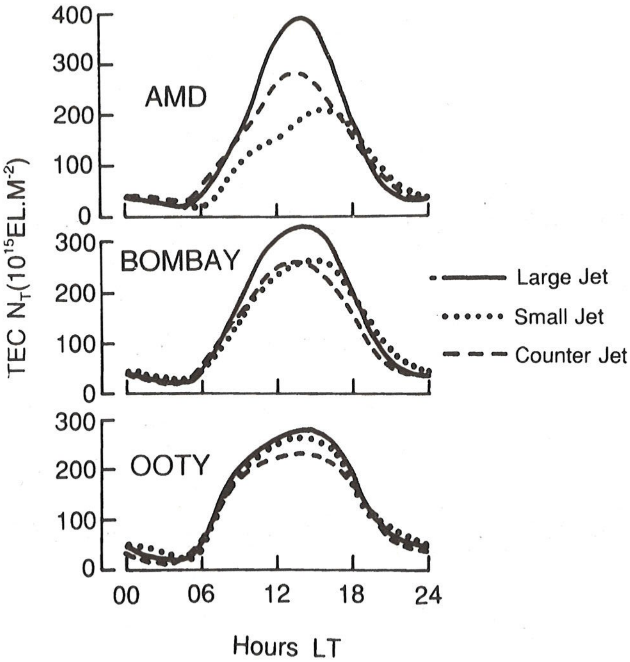

Figure 5 - Mean diurnal variation of Total Electron Content (TEC) for three stations in the Indian zone for three groups of days.

Figura 5 *- Média diurna da variação do conteúdo total de elétrons(TEC) para três estações na faixa da Índia, para três grupos de dias.*

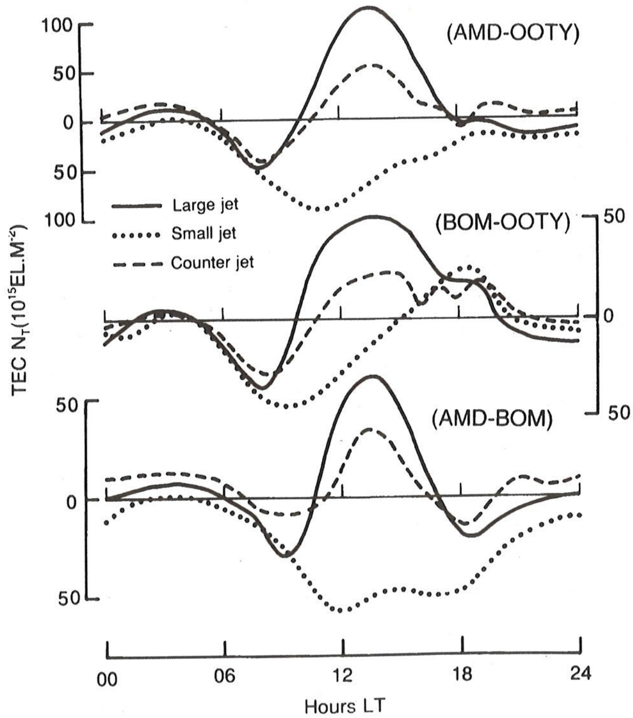

Figure 6 - Diurnal variation of the difference in hourly TEC values for pairs of stations: (i) Ahmedabad - Ooty (AMD - OOTY); (ii) Bombay - Ooty (BOM - OOTY); and (iii) Ahmedabad - Bombay (AMD - BOM).

Figura 6 *- Variação diurna da diferença em valores TEC horários, para pares de estações: (i) Ahmedabad - Ooty(AMD-OOTY); (ii) Bombay - Ooty; e (iii) Ahmedabad - Bombay (AMD - BOM).*

of TEC contour plots for days of small jet strength presented by Rastogi & Klobuchar (1990). They found that when H(TRD - ABG) was close to zero throughout the day, the 'high' in TEC as a function of local time and latitude was located close to the magnetic equator. On the days of counter electrojet, the difference curves resemble those on large jet days. There is no typical signature in TEC in association with the afternoon counter electrojet phenomenon.

The first two eigen vectors for the three groups of days are shown in Fig. 7. the first vector appears to show a shift in the phase of maximum TEC at Ahmedabad between large and small jet days with CEJ almost similar to large jet days. At Ooty, this phase shift is absent. Even at Bombay, the diurnal pattern of the first eigen vector is nearly the same for all the three categories. It is suggested that the equatorial electrojet strength influences the phase of the first principal component only at locations close to the anomaly crest and afternoon counterjet lasting only for a few hours does not leave detectable imprint in TEC variations near the anomaly crest region.

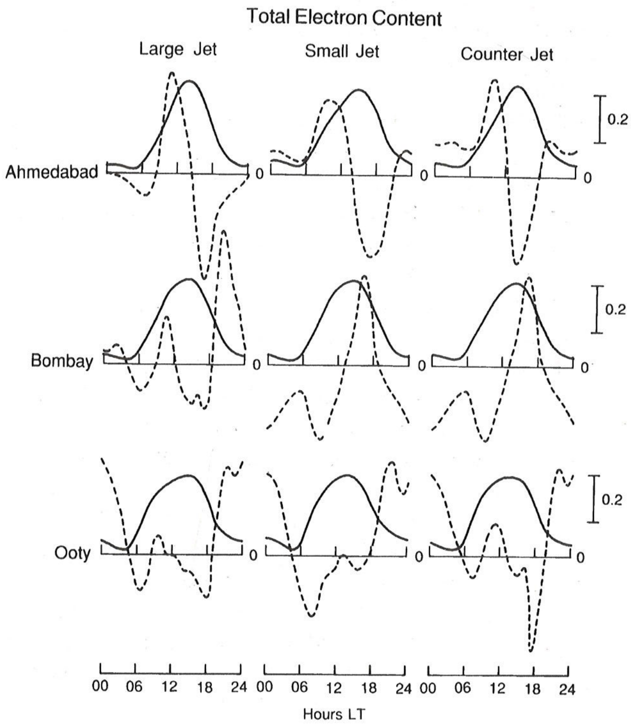

Figure 7 - The first (continuous line) and second (broken line) eigen vectors derived from the TEC data for three groups of days at Ahmedabad, Bombay and Ooty.

***Figura** 7 - O primeiro (linha contínua) e o segundo (linha tracejada) autovetores derivados dos dados TEC para três grupos de dias em Ahmedabad, Bombay e Ooty.*

The second eigen vector is rather complex and no special significance could be attached to its local time variations at both Ooty and Bombay. Only at Ahmedabad, near the anomaly crest, the second vector exhibits phase quadrature with respect to the first. The transition between the extrema is confined to a narrow time span on large jet days compared to days associated with weak jet. Close the magnetic equator, the second vector provides major contribution only during local midnight. Such anomalous night time enhancement in TEC was studied earlier by Janve et al. (1979) with winter months having largest frequency. Close to the anomaly crest, the second vector has negligible magnitude.

SUMMARY AND CONCLUSIONS

Principal Component Analysis (PCA) is carried out on an appropriately chosen data base consisting of the daily variation of H and D components of the geomagnetic field and TEC. The stations are located close to the dip equator (Trivandrum and Ooty), at low latitudes away from the jet center (Alibag and Bombay), close to the latitude of Sq focus (Sabhawala) or to the crest of equatorial anomaly (Ahmedabad). The diurnal variation in the second eigen vector for H at low latitudes clearly shows its dependence on the strength of the electrojet with a dominant 24-hour component on large jet days being replaced by a semidiurnal one on weak jet days. Evidently the planetary Sq currents are distorted by higher harmonic tidal modes of the atmospheric oscillations. It is worthwhile noting that Stening (1989) invokes an antisymmetric semidiurnal tide to simulate a large counterelectrojet event. Arora et al. (1993) also find that the equivalent currents for the excess field on CEJ days over normal days fit closely with the theoretical ones computed by Stening (1989).

Our analysis clearly shows that the first PC of H at low latitudes is unaffected by the electrojet variations. However, close to the Sq focus, even the first component shows a degree of relationship particularly when the afternoon jet direction is reversed on CEJ days. This could be considered as one more evidence of the link between the geomagnetic field variations close to the Sq focus and near the magnetic equator complementing the earlier results of Tarpley (1973) and Mita Rajaram (1983).

The first vector for Declination seems to be unaffected by the electrojet strength at all latitudes upto the Sq focus at least. The second vector depicts a noticeable change at low latitudes when the jet strength weakens or reverses in the afternoon. In general, however, diurnal variation in Declination is not controlled by the vagaries of the equatorial electrojet.

The Total Electron Content, as a measure of the equatorial ionosphere, retains the basic diurnal pattern of predawn minimum and postnoon maximum at all latitudes for all the three categories of days. The efficacy of the equatorial plasma fountain is reduced during weak jet days, with the anomaly crest practically absent. This change is largely brought about by the second vector which has a semidiurnal structure over Ahmedabad in contrast to the more complex pattern observed at Bombay or Ooty. The second component also seems to contribute to the anomalous nighttime enhancements occasionally observed in different stations. A similar exhaustive analysis using chain of magnetometers in other longitude sectors will confirm the inferences drawn here.

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