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The equatorial counter electrojet: Part of a worldwide current system?

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[1] The method of natural orthogonal components was applied to the ground geomagnetic data in the Central Asian sector (72–83°E), during the summer months of 1995, in an attempt to identify additional current systems that are superposed on the normal Sq current vortex and related to the equatorial counter electrojet (CEJ). The principal components, when examined in equivalent current representation, provide useful insights into the behavior of ionospheric current systems on different days. Statistical analyses performed in the present work suggest a possible relationship between the CEJ field and the noontime *D* variation observed at low latitudes. The results are in conformity with an earlier global simulation model. *INDEX TERMS:* 2415 Ionosphere: Equatorial ionosphere; 2437 Ionospheric dynamics; 2409 Current systems (2708); 2411 Electric fields (2712)

1. Introduction

[2] Analysis of quiet-time geomagnetic field variations due to the equatorial electrojet often leads to these questions: (1) Is the ionospheric current system responsible for these variations different from the normal solar quiet (Sq) current system principally driven by the (1, −2) diurnal tide and that has its focus beyond 25° dip latitude? (2) What drives the counter electrojet (CEJ) whose signature is seen under quiet geomagnetic conditions as a negative depression in the horizontal magnetic field (H) at dip equatorial latitudes during afternoon/morning hours? Towards the first question, the daily range in the H field at electrojet stations is poorly correlated with the range at low latitudes [*Kane*, 1976]. Some workers believe that the position of the Sq focus would alter the strength of the equatorial electrojet [*Tarpley*, 1973 for example] and the correlation improves when this effect is taken into account [*Kane*, 1976]. The electrojet itself is treated by some authors as a separate current system flowing at lower altitudes (∼110 km) and having its own return current at low latitudes [*Onwumechili*, 1997, for a review on this subject].

[3] Another problem mentioned above refers to the counter electrojet phenomenon. Several efforts towards modeling the abnormal field variations have led to the belief of one school of thought that an appropriate combination of tidal modes, in particular, the (1, −2), (2, 2) and (2, 4) modes, would generate the reverse current at the magnetic equator which causes the negative perturbation in the ground magnetic field variations [*Stening*, 1977; *Marriott et al.*, 1979; *Singh and Cole*, 1987, to state a few]. On the other hand, vertical winds and gravity wave associated shearing winds were shown to be capable of producing such current reversals in narrow latitude and altitude regions [*Raghavarao and Anandarao*, 1987, and references therein]. The scenario is complicated by the fact that on many occasions the CEJ manifests in a narrow latitudinal zone and often in a narrow longitude sector that prompted the second school of thought to place emphasis on a local cause.

[4] The present work examines the current systems in the Indian sector over the latitudes that are under the influence of the Sq and equatorial electrojet fields. The closely spaced magnetic observatories in a narrow longitudinal zone permit a study of this kind possible. It will be shown that the afternoon counter electrojet conditions often reflect an additional current system superposed on the normal Sq current vortex.

2. Method of Analysis and the Selection of Data

[5] The method of natural orthogonal components is a proven technique in the field of geomagnetism that enables the researchers to separate the normal and the abnormal field variations [*Vertlib and Wagner*, 1970; *Faynberg*, 1975]. *Rajaram* [1983] applied this method to the Indian geomagnetic data to determine the latitude of Sq focus and arrive at a relationship between the Sq focal latitude and the variation in the strength of the electrojet. *Alex et al.* [1998] adopted this technique to examine the abnormal field variations on days of low equatorial ΔH.

[6] The procedure involves expanding a given field in an orthogonal basis and solving the resultant eigen value problem to arrive at the 'principal components'. We will not repeat the details of the technique here as they are well discussed in the literature cited above. The method when applied to a significant number of days provides useful information on the field pattern common to all days and the abnormal field peculiar to each of these days under consideration.

[7] The principal component analysis is applied to the geomagnetic data from the chain of magnetic observatories located in the longitude range 72–83°E, Trivandrum (0.4°N), Ettaiyapuram (1.1°N), Kodaikanal (2.9°N), Pondicherry (4.5°N), Hyderabad (11.4°N), Alibag (13.4°N), Nagpur (15.4°N), Ujjain (18.7°N), Sabhawala (27.3°N), Kashi (39.2°N) and Novosibirsk (59.0°N), the numbers within brackets referring to their respective dip latitudes. The H and D observations from all these observatories are converted to X and Y variations after applying a suitable non-cyclic correction and removing the nighttime base level. It may be noted that the baseline values of declination D are negligible ($<|3|°$) over the Indian stations and therefore the differences between X and H are small when compared to their baseline values and the D variations contribute little to the X variations. The variations in Y are directly proportional to the variations in D, with H variations contributing little to the Y variations. The H and D variations at each hour from every observatory are used to obtain a field vector that is rotated 90° in the clockwise direction to yield an equivalent current vector.

[8] The counter electrojet is known to be more frequent during solar minimum solstice months [*Mayaud*, 1977, for a review]. For this reason, the summer month, July, of the low sunspot year, 1995, was selected for the present analysis. A large number of quiet days with $A_p \leq 6$ (19 days in total) in this month provides an opportunity to examine the equivalent current systems responsible for the ground geomagnetic field variations. The principal components were derived for each of the days after subjecting all 19 quiet days of July 1995 to the analysis.

3. Results

[9] As an example to show how close the first two principal components represent the measured field variation, we present in Figure 1 the results for the X (top panel) and Y (bottom panel) field

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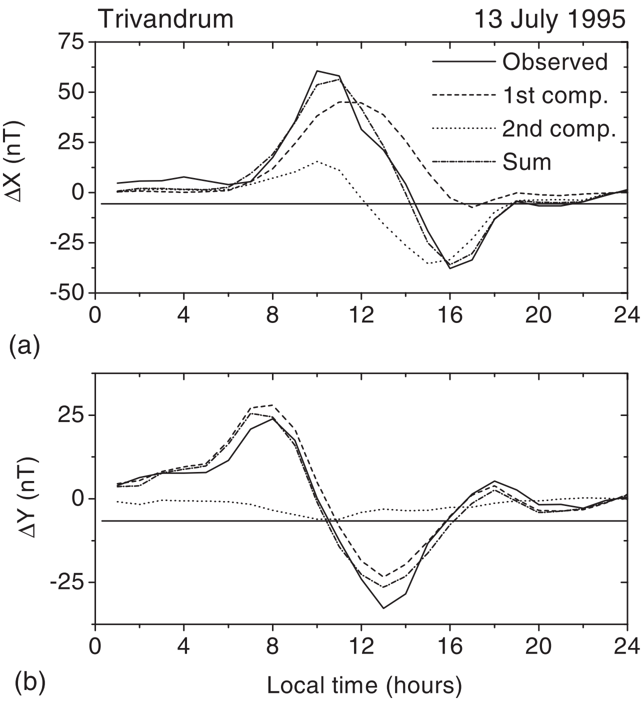

Figure 1. (a) The X field variation (full curve) observed at Trivandrum (0.4°N dip latitude) on 13 July 1995 along with the computed principal components (dashed curve representing first component and dotted representing the second) and their sum (dash-dot curve). (b) Same as (a) but for Y field variation.

variations at Trivandrum, an electrojet station, on 13 July 1995. The observed (continuous curve), the first two components (dashed and dotted, respectively) and their sum (dash-dot) for 13 July 1995 are plotted. The observed field in X reveals an afternoon counter electrojet feature, with a large negative deviation ($\sim$35 nT) centered around 1600 LT. The first principal component for X represents a normal field for this day with a maximum around noon hours whereas the second component reveals a small northward field ($\sim$10 nT) in the pre-noon hours and a southward field as large as the strength of the observed variation in the afternoon hours. The latter represents the counter electrojet condition for this day. The corresponding eigen coefficient obtained from the principal component analysis will be negative for this day, and yields a measure of the strength of the CEJ field.

[10] In the east-west field (Y) the second component contributes little (westward field of $\sim$5 nT throughout the day) as the first component closely follows the observed field variation. Eastward field representing southward current in the morning hours and westward field representing northward current in the afternoon hours, characterize the Sq behavior.

[11] When the equivalent current vectors derived from the principal components corresponding to X and Y field variations were examined, it was found on many CEJ days the current vectors for the second component are less oriented in a regular fashion except for a tendency to orient northward around noon hours. The latter feature will be discussed in this section later with reference to the example presented below.

[12] The CEJ day, 26 July 1995, is selected as an example, to show the behavior of the current vectors associated with the first and the second principal components. 22 July happened to be the nearest quiet day when the afternoon CEJ signature was not observed. In Figure 2 we present the observed X and Y magnetic field variations on 22 (dashed curves) and 26 (continuous) July 1995 for all the available stations in the Central Asian sector.

[13] For many stations, the difference in the X field variations (left panel) between the two days (26 and 22 July) is positive in the morning hours and negative in the afternoon hours. The Sq focus on both the days is situated north of Sabhawala (SAB). The east-west field (right panel) on 22 July shows the normal Sq behavior, namely, southward currents in the morning hours and northward currents immediately after noon. There is an excess northward current all along the longitudinal chain on 26 July when compared to the observations on 22 July. The difference in Y field variations between these days is largest around noon hours at many of the stations examined. The above features in X and Y together imply that on the CEJ day (26 July) there is possibly an additional current system with westward flow in the afternoon hours detected by the ground stations at electrojet latitudes and northward flow at noon hours detected at low and mid latitudes. This inference is strengthened by further analysis whose results are presented below.

[14] For the CEJ day, 26 July, we present in Figures 3a and 3b the equivalent current maps for the principal components derived from both X and Y variations. The first component in Figure 3a shows the typical anti-clockwise current loop representing the normal Sq current system believed to be driven by the (1, -2) tidal mode with a current focus close to 30° dip latitude. In Figure 3b we present the sum of the contributions from the other principal components (2, 3, 4 and 5). Inclusion of components other than the second does enable to bring out clearly the "abnormal" field. The resultant current map shown in Figure 3b reveals an additional current system flowing in a clockwise direction in the afternoon hours. It may be noted that the length of the current vectors is enlarged four times so that the direction of the current whorl can be markedly seen. The time scale is chosen to lie in the range 0600–2000 LT. Perhaps, there is another current system in the morning hours with an anti-clockwise current vortex but this is not as clearly evident as the clockwise vortex in the afternoon hours.

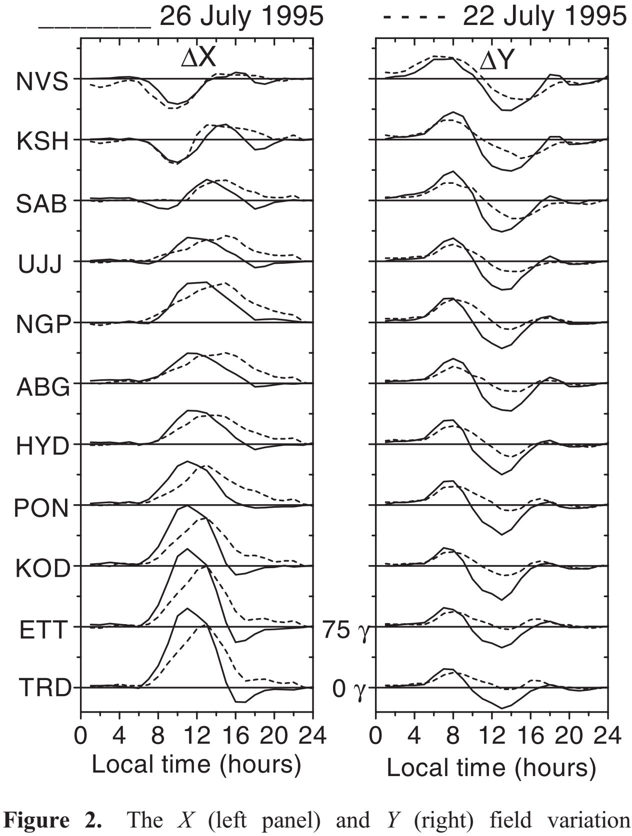

Figure 2. The X (left panel) and Y (right) field variations measured at various stations in the 72–83°E longitude sector. The station codes are given on the left of the plot.

[15] An important feature to be noted in this analysis is the intense northward current at low latitudes around noon hours on a CEJ day that is clearly associated with the additional current system dominant in the afternoon hours. As pointed out earlier, on most CEJ days an enhanced northward current is likely to be present at low latitudes around noon.

[16] The above analysis is extended to all the 19 selected quiet days of July 1995. In addition 13 quiet days of June were also considered in order to strengthen the inferences made. The day-to-day variation of the eigen coefficient for the second principal component of *X* for Trivandrum representing the strength of the afternoon CEJ is then compared with the observed variation in *Y* at 1300 LT Alibag, a low latitude station under the Sq current loop. The results are plotted in Figure 4. Intense afternoon CEJ events, as noticed in the *X* field at the electrojet station, are clearly accompanied by large negative variations (westward field) in *Y* at the low latitude station. This westward field would correspond to a northward current that flows out to latitudes north of the respective current focus. Another feature to be noted in Figure 4 is that in contrast to the CEJ events, there are days (for example, day 26 which is 22 July in the data set) when an excess northward field, as reflected in the positive eigen coefficient for the second principal component, was observed. Further, on these days, the westward field (northward current) at low latitudes around noon hours tends to disappear as noted for 22 July 1995 in Figure 2. The northward current associated with the normal Sq current whorl appears to be cancelled by a southward current possibly contributed by an additional current vortex on a few of the non-CEJ days. This will be examined in one of the future studies of the author.

[17] A scatter plot between the eigen coefficient representing the abnormal variation in *X* field at Trivandrum and the observed *Y* variation at Alibag yields a correlation coefficient of 0.67 estimated at 95% confidence level. It is inferred from this analysis that the additional current system associated with the afternoon CEJ flows as northward return current in the clockwise direction.

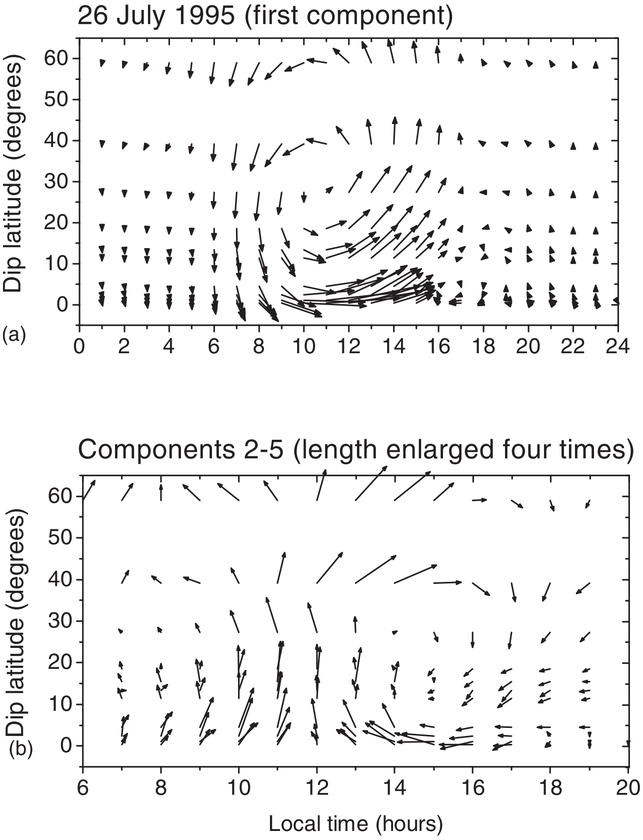

Figure 3. Equivalent current vector representation of the computed principal components for 26 July 1995. (a) First component. (b) Sum of components two to five. The length scale for the vector is: 1 cm ≡ 90 nT. See text for more details.

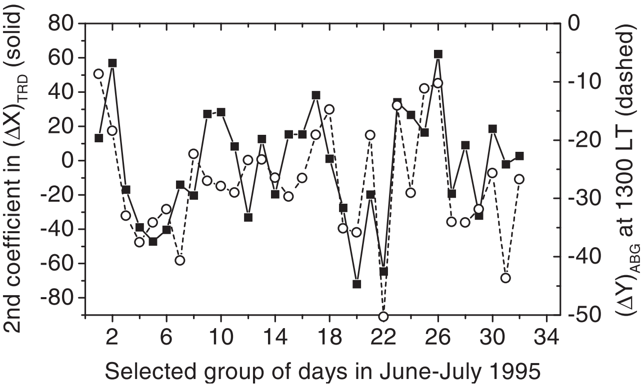

Figure 4. Comparison of the eigen coefficient associated with the second principal component of the *X* field variation at Trivandrum and the observed *Y* field variation at 1300 LT observed at Alibag for individual days.

4. Discussion

[18] Since the work of *Gouin and Mayaud* [1967] several researchers have attempted to understand what causes the reversal in the equatorial electrojet in the morning/afternoon hours. If the global tidal modes are responsible for this reverse current at the equator, the associated changes in the magnetic field elements should occur globally [*Stening*, 1977]. There is a need to explain why tidal modes of global origin do not always produce such changes in Sq pattern globally.

[19] In the present work the author reveals a scenario wherein the CEJ field at electrojet sites reflects a part of a clockwise current system in the afternoon hours superposed on the normal Sq current vortex. Equivalent current vector maps derived from the ground geomagnetic data illustrate this feature. Statistical analysis performed for 32 quiet days of June–July 1995 confirms the linkage between the westward current at equatorial latitudes and the northward current at low and mid latitudes thus adding credence to the inference of a superposed worldwide current system under CEJ conditions.

[20] From the ground geomagnetic data in the Indian sector, *Bhargava and Sastri* [1977] determined an additional field, northward in the morning and southward in the afternoon, that is superposed on the normal quiet-day electrojet field. The analysis was carried out for data sets spread over all seasons and on days when counter-electrojet signature was clearly noticed in the ground geomagnetic data. The variation in the vertical field at the fringe of the electrojet was used to confirm the presence of this additional abnormal field. It is important to note that a similar abnormal *H* field behavior was noticed in the present work (refer to Figure 1) though using a different statistical methodology. With a conviction that the CEJ effects were caused by an additional current system, *Stening* [1977] observed deviations elsewhere at the same time as the CEJ and proposed that the latter would be associated with an additional current system generated by a semi-diurnal tidal mode.

[21] *Hanuise et al.* [1983] performed a three-dimensional global simulation of ionospheric currents under varying electrodynamical conditions. When a fit was made to the deviations in the *H* element at the magnetic equator and the *D* element at mid-latitudes, they obtained a consistent solution to the problem of the electrical connection between the CEJ and the Sq current system. The

solution offered two horizontal current vortices of opposite directions to flow on each side of the noon sector, anti-clockwise in the morning and clockwise in the afternoon. These current vortices produce a poleward current flow at low latitudes at noon.

[22] The results presented in this work are similar in many ways to the simulation results of *Hanuise et al.* [1983]. The reasonably good correlation between the strength of the CEJ field and the noon-time *D* variation at low latitudes (Figure 4) conforms with the electrical connection between the CEJ and the low latitude Sq current layers suggested by *Hanuise et al.* [1983]. The latter reproduced the CEJ event when an appropriate combination of the (2, 2) and (2, 4) solar semi-diurnal tidal modes was modeled. It was assumed in their model simulation that in order to generate the correct CEJ signature in the ground magnetic data the (1, −2) diurnal tide amplitudes were negligible.

[23] With a large number of radar sites coming up at various geographical locations in recent years, it should be possible to coordinate global campaigns in an attempt to identify the dominant tidal modes and their longitudinal differences, which can be incorporated in three-dimensional simulation models such as those of *Hanuise et al.* [1983] and *Singh and Cole* [1987].

[24] **Acknowledgments.** The author acknowledges the World Data Center, Kyoto, for making available the magnetic data for Kashi and Novosibirsk. The Indian Institute of Geomagnetism routinely publishes the geomagnetic data from the chain of the Indian observatories.

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