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Main field control of the equatorial electrojet: a preliminary study from the Oersted data

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Abstract

There are very few phenomenon in the upper atmosphere that are as sensitive to the strength and distribution of the earth's core field as the equatorial electrojet. The Oersted initial field model (OIFM) along with the earlier IGRF models have been used to provide insight into the secular changes in the global patterns of the position and strength of the equatorial electrojet (EEJ). A northward drift in the location of the dip equator (hence the position of the axis of the EEJ) to the extent of 1.0 degree per decade is seen around 300°E. In contrast, in the Pacific, east of Australia, there is practically no drift. It is also observed that the largest secular variation in the Cowling conductivity occurs in the South American sector with a possible 4.0% increase per decade for the same level of ionisation in the E-region. The Oersted main field model does not suggest any changes or reversal of these trends. A very significant result is that the magnetic field at the dip equator need not be perpendicular to the line of zero dip and this deviation from the idealized scenario of the equatorial electrojet can result in significant contribution of the equatorial electrojet to the declination component. The scalar data from 57 orbital passes from four representative quiet days, covering the forenoon to afternoon hours, on the other hand, provides a greater insight into the relative importance of geomagnetic field structure and tidal control. This is obtained through a study of the day-to-day variability of the equatorial electrojet and its longitudinal variations. The Equatorial Electrojet can be clearly identified on almost all the passes with the peak always lying on the dip equator. There is a clear indication of zonal variation in the electrojet strength at satellite height. The largest amplitude is found in the American sector where the Cowling conductivity attains its maximum value. The electrojet strength at the satellite height also exhibits other maxima at around 100 and 190°E longitude consistent with the earlier observations of POGO. Variations at these longitudes could perhaps be linked with longitude dependent forces associated with background winds or non-migrating tides. The width of the electrojet at satellite height also seems to show a maximum in the South American sector. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The equatorial electrojet (EEJ) is the high concentration of ionospheric current flowing from west to east in a narrow belt flanking the dip equator in the sun-ward hemisphere. This is related to the fact that in the region of the dip equator, the magnetic lines of force are horizontal and as a consequence a large vertical polarization electric field, mainly responsible for the enhanced eastward currents, can be set up. The EEJ arises as a direct consequence of the structure of the main geomagnetic field. There are very few phenomenon in the upper atmosphere that are as sensitive to the strength and distribution of the Earth's core field as the EEJ. The latitudinal position of the electrojet axis is dictated by the position of the dip equator at that longitude; while the Hall conductivity that is the main source of the enhanced strength of the EEJ is sensitive to the magnitude of the magnetic field. While these features are fairly well brought out by ground based and satellite observations (Rastogi, 1962; Cain and Sweeny, 1973; Langel et al., 1993), a detailed study of the longitudinal structure of the main field in relation to the strength and position of the EEJ is essential for understanding the phenomenon and its long term variability. Furthermore, there is a need to examine the idealized scenario assumed by models in the context of the actual geometry of the geomagnetic field in different longitudes. For example, models assume that the electrojet currents flow primarily along the dip equator and are at the same time perpendicular to the direction of the horizontal component of the Earth's magnetic field. A close look at the dip equator positions and declination maps (cf. Fig. 1.3 in Onwumechili, 1997) will show that around 300–330°E longitude zone, the declination (or the angle that the horizontal field makes with the north) changes rapidly from 8 to 20°W. The dip equator orientation changes very little through this region. The angle between the geomagnetic field and the line of zero dip cannot remain constant (and hence cannot be 90° everywhere). The angle between the magnetic field and the line of zero dip is evaluated explicitly for different longitude zones to bring out the importance of including this parameter in future electrojet models.

Finally, the EEJ strength is also subject to day-to-day variability and strongly influenced by the tidal forces and enhancements in the ionization due to the solar radiation. The tidal motions are ordered with respect to the geographic equator while the electrical conductivity of the ionosphere is controlled mainly by the dip equator. The understanding of the equatorial electrojet is very essential if it has to be used as diagnostic tool for the systematic study of upper atmospheric motions. At the same time the effective use of the equatorial electrojet for the study of the subsurface conductivity also requires a clear understanding of the spatial structure of the electrojet.

The combination of geomagnetic and geographically controlled dynamic forces can be expected to lead to longitudinal variations in the EEJ. More than 70% of the area covered by the dip equator lies in the oceanic region; thus Global coverage of the EEJ is possible only by satellite data. The satellite must collect magnetic field data at relatively low altitude and must also have near noon global coverage. The Oersted satellite meets this unique requirement and constitutes a very valuable set of data for studies of the EEJ. Amongst the first papers dealing with the studies of the EEJ from satellite data is the work using the POGO satellite scalar data undertaken by Cain and Sweeney (1973) and one of the early papers that review the satellite measurements of the EEJ is by Onwumechili (1985). The Magsat collected valuable vector and scalar magnetic field data at low altitudes; despite the restriction imposed by the fact that its orbit was in the dawn dusk sector, nevertheless, the vector data from this satellite has made major contributions to EEJ

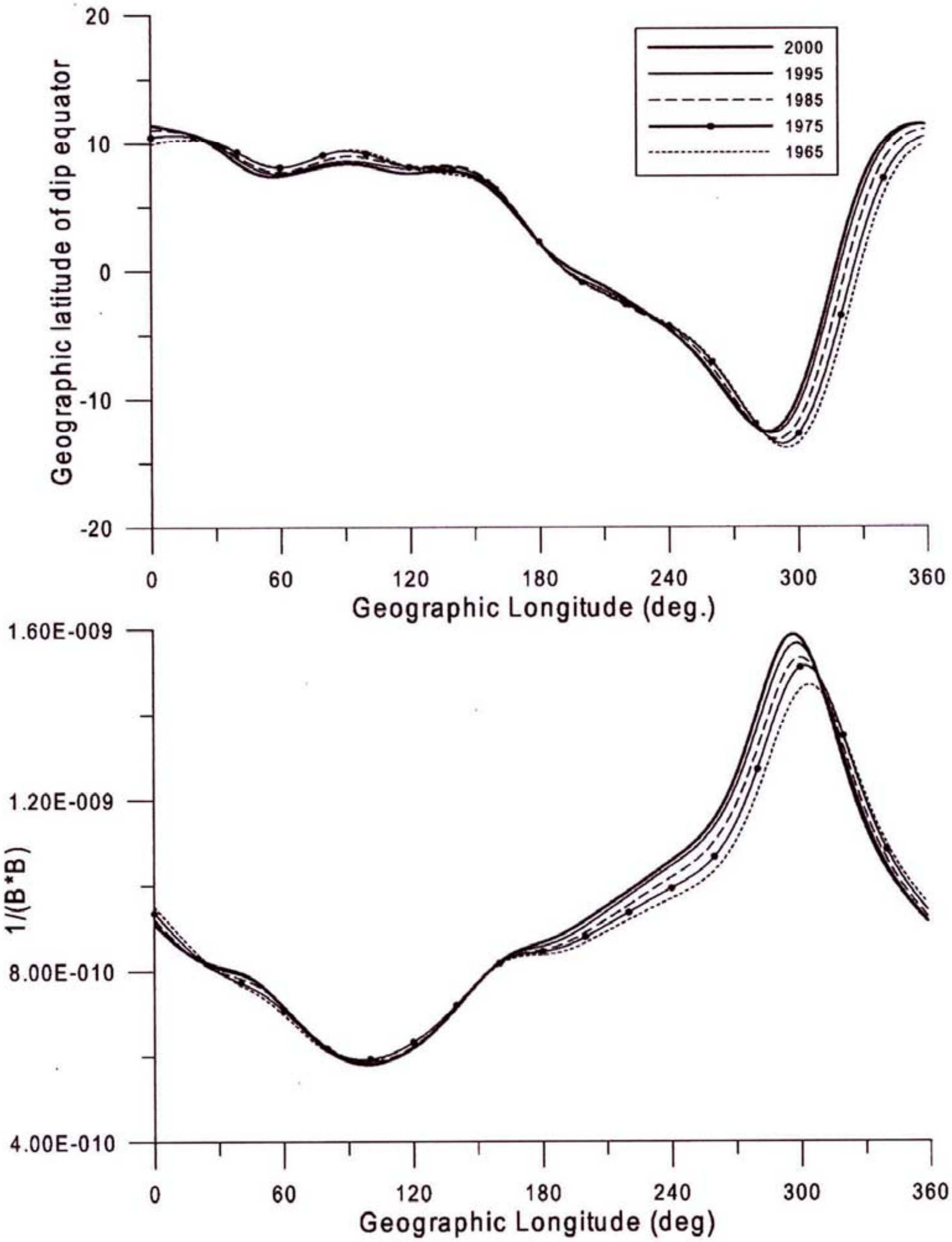

Fig. 1. Longitudinal variations of parameters derived from the four different IGRF models from 1965 to 1995 and OIFM 2000: (a) geographic latitude (in degrees) of the location of the dip equator (above), (b) $(1/B^2)$ in nT^{-2} at the dip equator (bottom).

studies (e.g. Langel et al., 1993) and it established the presence of the meridional current system (Maeda et al., 1985).

The Oersted satellite was launched on 23 February 1999 with an apogee of about 849 km, and a perigee of around 638 km. The satellite instrumentation consisted of an Overhauser proton magnetometer for scalar measurements and a compact coil Fluxgate magnetometer for vector measurements. The Oersted satellite orbit is a near polar one, with a small drift with respect to the local time. In the period from April to December 1999, it covers local time ranging from 14:00 to 10:00 in the day-side hemisphere and constitutes a very unique data-set for studies of the EEJ.

In the present paper, the IGRF models are used to infer the broad features as well as the secular variations that could be expected in the EEJ strength and position. We also investigate the orientation of the horizontal magnetic field (H) with respect to the dip equator as in all theoretical EEJ models this is tacitly assumed to be 90°. The individual orbit data analysis is restricted to the scalar magnetic field data and used to study the detailed structure of the EEJ field and its longitudinal and day-to-day variability.

2. Main field models and the EEJ

The basic model of the equatorial electrojet that can describe the equatorial enhancement of the diurnal variations of the global current system at the dip equator is well known and can be found in Onwumechilli (1997). In a co-ordinate system that has x-axis along the ambient magnetic field and y-axis pointing eastward, the net eastward current J_y at the dip equator can be expressed as,

$$J_y = \left(\frac{\sigma_2^2}{\sigma_1} + \sigma_1\right)E_y = \sigma_3 E_y$$

where E_y is the eastward electric field which is a part of the global current system, σ_1 is the Pedersen conductivity, σ_2 is the Hall conductivity and σ_3 is referred to as the Cowling conductivity in literature. The Pedersen conductivity is essentially dependent on ion-neutral collision frequency while Hall conductivity is inversely proportional to B, the strength of the geomagnetic field. In the dynamo region of the ionosphere, Hall conductivity is larger than the Pedersen conductivity and Cowling conductivity becomes inversely proportional to B^2. Note that the enhancement of the currents at the dip equator presented above is made possible by the build up of a large vertical polarization electric field. Since the geomagnetic field lines are highly conducting this is possible only at the dip equator as away from the dip equator the charges will leak away along the field lines. Thus the position of the axis of the equatorial electrojet in any longitude zone should be at the position of the dip equator in that longitude while the strength of the current system will vary from longitude to longitude roughly as inverse of B^2. We examine these dependencies on the strength and position of the equatorial electrojet and its secular variation.

There have been improvements in the basic model of the equatorial electrojet that include the vertical currents at the equator, the latitudinal variations in the inclination of the geomagnetic field etc. and these are extensively discussed in literature (Onwumechilli, 1997). But two basic ingredients remain in all the models:

1. the principal electrojet current flows along the dip equator; and
2. the ambient magnetic field is perpendicular to the dip equator.

As discussed in the introduction, this is not always true. If the magnetic field is not perpendicular to the line of zero dip, some component of the electrojet currents will flow along the magnetic field and we can expect significant declination associated with the equatorial electrojet. This is not considered in the models. We show how the actual magnetic field deviates from the ideal orientation perpendicular to the dip equator in different longitude zones.

We first examine how the secular variation in the main field as represented by the different models will also produce a secular variation in the position and strength of the EEJ. We, therefore, examine the Oersted initial main field model (OIFM) (Olsen et al., 2000) generated from the Oersted data in the context of long term changes in the longitudinal pattern of the equatorial electrojet. To study the effect of the main field models on the location of the peak of the electrojet, we calculate the location of the dip equator (where the vertical component of the geomagnetic field is zero) from the different IGRF models from 1965 to 1995 epochs and OIFM 2000. Fig. 1a plots the location of the dip equator (geographic latitude) in the different longitude sector, on ground, as derived from the four different IGRF models from 1965 to 1995 and from OIFM 2000. This is basically similar to the average latitude of EEJ centres observed by POGO at various longitudes (Cain and Sweeney, 1973). From this plot we find that the dip equator swings from north to south around 190°E longitude and swings back north at around 320°E, also seen by Rangarajan (1994). It is also observed that from epoch 1965 to 2000, the minimum variation in location of the dip equator is in the longitude zone 155–215°E; whereas, the maximum shift lies in the longitude zone from 290 to 360°E and extends to 10°E (see Fig. 1a). The most significant feature is the drift of the location of the dip equator (hence the position of the axis of the EEJ) to the extent of 1.0° per decade around 300°E. In the Indian zone, the dip equator is migrating southward and this supports the observation of Rangarajan and Dekka (1991) while in the South American sector it is migrating northwards. As noted earlier, the main driving force of the EEJ comes from the Cowling conductivity that varies as $(1/B^2)$. To check it's longitude variation, in Fig. 1b a plot is made of $(1/B^2)$ at the dip equator, calculated from the main field models at different epochs, as a function of longitude. Clearly this has a high in the South American sector with a maximum around 290°E and a low around the Indian zone as also observed in the EEJ variations on ground (Rastogi, 1962). Further, the secular variation in this term is practically negligible up to around 180° and a maximum in this secular variation is from 210 to 300°E with the magnitude of $1/B^2$ increasing continuously. It is also observed that the largest secular variation in the Cowling conductivity occurs in the South American sector with a possible 4% increase per decade for the same level of ionisation in the E-region. It is significant to note that the Oersted main field model (Olsen et al., 2000), does not suggest any major changes or reversals of the secular trends in the electrojet. There is some indication of the slowing down of the secular changes in the location of the dip equator and the Cowling conductivity as one approaches the European zone from the Atlantic.

We next examine how far the horizontal geomagnetic field direction deviates from the 'ideal' direction that is perpendicular to the dip equator in different longitude zones. From Fig. 1a, we get the location of the dip equator in different longitudes. It is a straightforward problem to identify the vector along the line of zero dip at each longitude. One can also determine, at the dip equator, the direction of the magnetic field (which is horizontal by the definition of the dip equator). We can then compute, α, the angle between the two directions. We define the 'ideal' direction as 90° and define the deviation of the magnetic field direction as $90-\alpha$. This deviation is plotted in Fig. 2 for two epochs namely 1965 and 2000. Note that in the zone east of 300°E longitude, the deviation is around 12° which would mean that if the electrojet flows along the dip equator its contribution to the eastward declination component could be almost 20% of the H variations. This is significantly larger than the D components associated with the phenomenon.

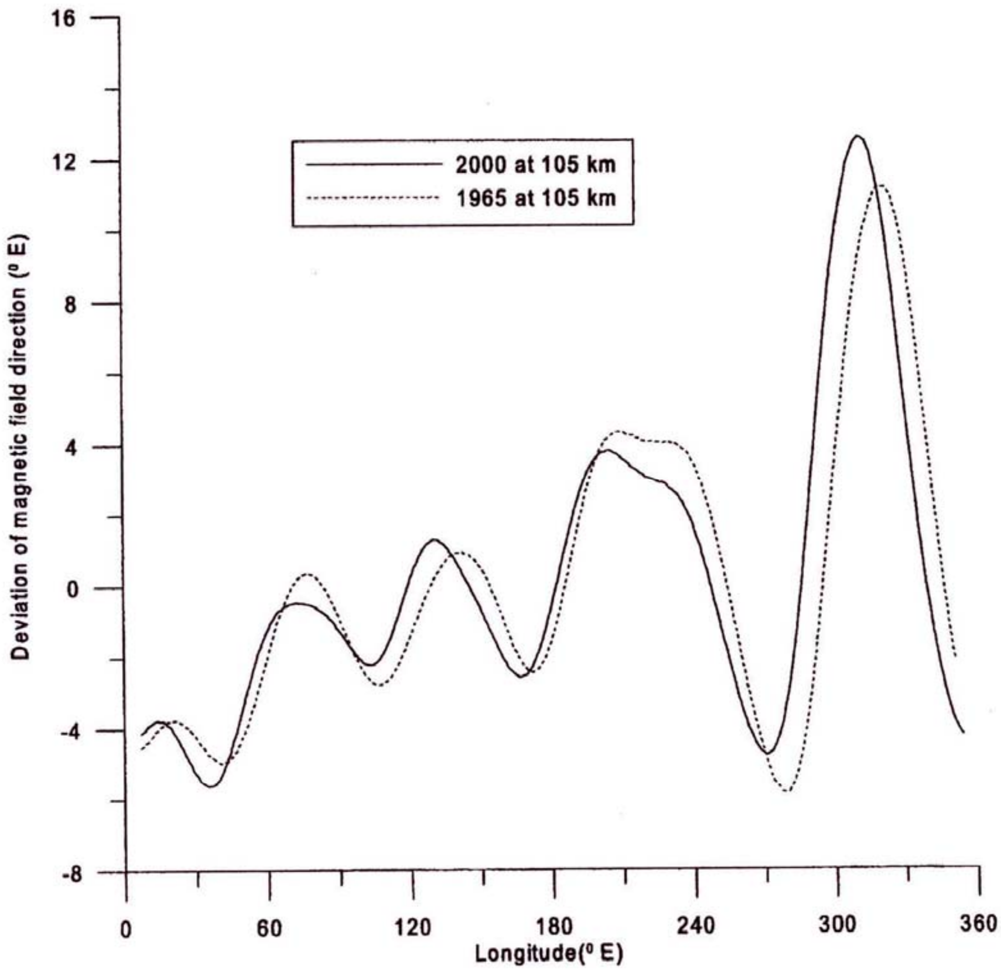

Fig. 2. Deviation of the direction (in degrees E) of the magnetic field at the dip equator, from the normal to the line of zero dip for the epochs 1965 and 2000. (Electrojet models assume that the magnetic field is normal to the line of zero dip everywhere.)

Exact estimates would require augmentation of the model for this sector. We also note that the deviations can be east or west of the 'ideal' direction depending on the longitude under consideration. There is also a westward drift of the pattern as a whole from 1965 to 2000 AD. This can bring about significant secular longitudinal drift in the 'anomaly'. A closely spaced network of electrojet stations would be of considerable use. Since a major part of the zone lies outside land, vector observations of Oersted satellite will also be invaluable in any such investigation.

3. Data analysis and discussions

A typical EEJ signature at satellite height is a minimum at the dip equator accompanied by 'shoulders' of increased field on either sides (Cain and Sweeney, 1973; Onwumechili, 1985). Such a signature is also consistent with empirical models of the equatorial electrojet (Onwumechili, 1997) and is, therefore, used for identifying the EEJ in the Oersted data.

In the present analysis only data collected during magnetically quiet days ($Ap \leqslant 4$) are used. Only satellite total field data between dip latitude 20°N and 20°S are considered. Retrieval of the EEJ signature from the satellite data requires the removal of the variations due to the main field. This is achieved using the OIFM (Olsen et al., 2000) which gives main field contribution up to degree and order 19 for internal, and 2 for external, source fields; it also includes 3 coefficients that account for the Dst dependent part of the external dipole. The secular variation coefficients are also as used by Olsen et al (2000) (provided to us by personal communication). Since the OIFM takes care of ring current contribution through the use of *D*st index, the residual magnetic field contains only ionospheric contributions from the Sq and equatorial electrojet current systems. The latter is confined to the equatorial region only. Three distinct situations are encountered: (1) In many of the cases considered, the residual field showed the typical EEJ signature. (2) In some cases only one of the shoulders and a minimum around the dip equator appear. In these cases the latitude of the shoulder was identified as the edge of the EEJ. Field values obtained for latitudes on either side of the dip equator with magnitudes greater than the latitude of this shoulder maximum were then used to obtain a quadratic fit that was removed from the latitudinal profile of the field. (3) In some cases only a minimum was obtained around the dip equator. In this case field values for 20–15°N and 15–20°S were used for a quadratic fit that was subtracted out from the latitudinal profile.

These residual plots were generated for the five IQ days of the months April–December, 1999 during which the satellite passes covered day-side local times ranging from afternoon to forenoon. For each day the satellite covers on average 15 longitude sectors in the day-side sector. In this paper, four such IQ days including 57 satellite orbital passes, covering different local times (LT) and satellite radial distance from the Earth (at the equatorial crossing), are presented. Fig. 3 is a plot of the variation of electrojet as a function of dip latitude between −20 and +20 degrees, spanning the entire globe for different longitude sectors (marked in brackets). The four representative quiet days include: (a) 11 May 1999 (LT≈13.3 h; altitude ≈660 km); (b) 4 July 1999 (LT≈12.45 h; altitude ≈870 km); (c) 14 August 1999 (LT≈11.8 h; altitude ≈730 km); (d) 25 September 1999 (LT≈11.2 hrs; altitude ≈710 km).

EEJ can be clearly identified on almost all the passes; in contrast to the ground observation where one sees a peak, at satellite height it appears as a minimum at the dip equator accompanied by two maxima (hump) on either side. In some cases, one of the humps is not distinct, instead, a distinct change in the slope of the latitudinal variation is observed. In all the plots, the minimum corresponding to the centre of the electrojet is seen to lie on the dip equator, quite consistently. It may be pointed out that the distance of the centre of the EEJ with respect to the dip equator, depends upon the main field model used; we find that by using OIFM, the centre of the EEJ generally falls very close to the dip equator. The electrojet peak seen in the Oersted data is sharp and a latitudinal shift of 1–2° discernible. To verify this, we also simulated the expected shift in the electrojet peak as seen at the satellite altitude for a 1–2° shift in the center of electrojet current system at 106 km. and found that the shift was clearly discernible.

There is a clear indication of zonal variation in the electrojet strength; largest amplitude is found in the American sector. It is because of this large variation in amplitude that we are forced to use different scales for the plots in the different longitude sectors. And as a consequence it is difficult to directly visualize the longitudinal variations from the Figure. We, therefore, calculate *S*, the strength of the EEJ in nT, as observed at the satellite height for each day and longitude

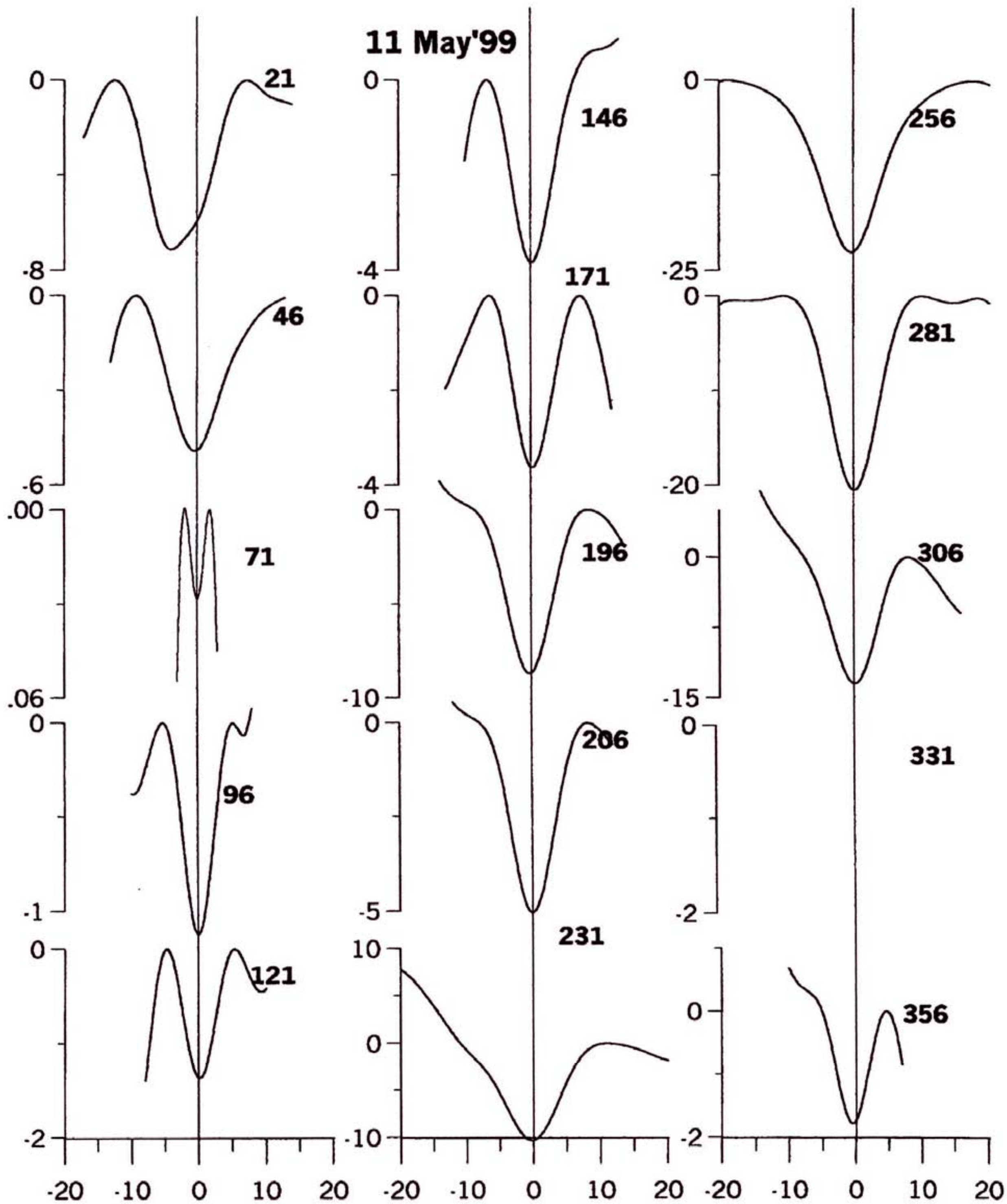

Fig. 3(a). Plot of the equatorial electrojet strength (in nT) as a function of dip latitude over different longitude zones (shown in brackets) for Oersted day-side passes on following IQ days: (a) 11 May 1999; (b) 4 July 1999; (c) 14 August 1999; (d) 25 September 1999 (*continued on next page*).

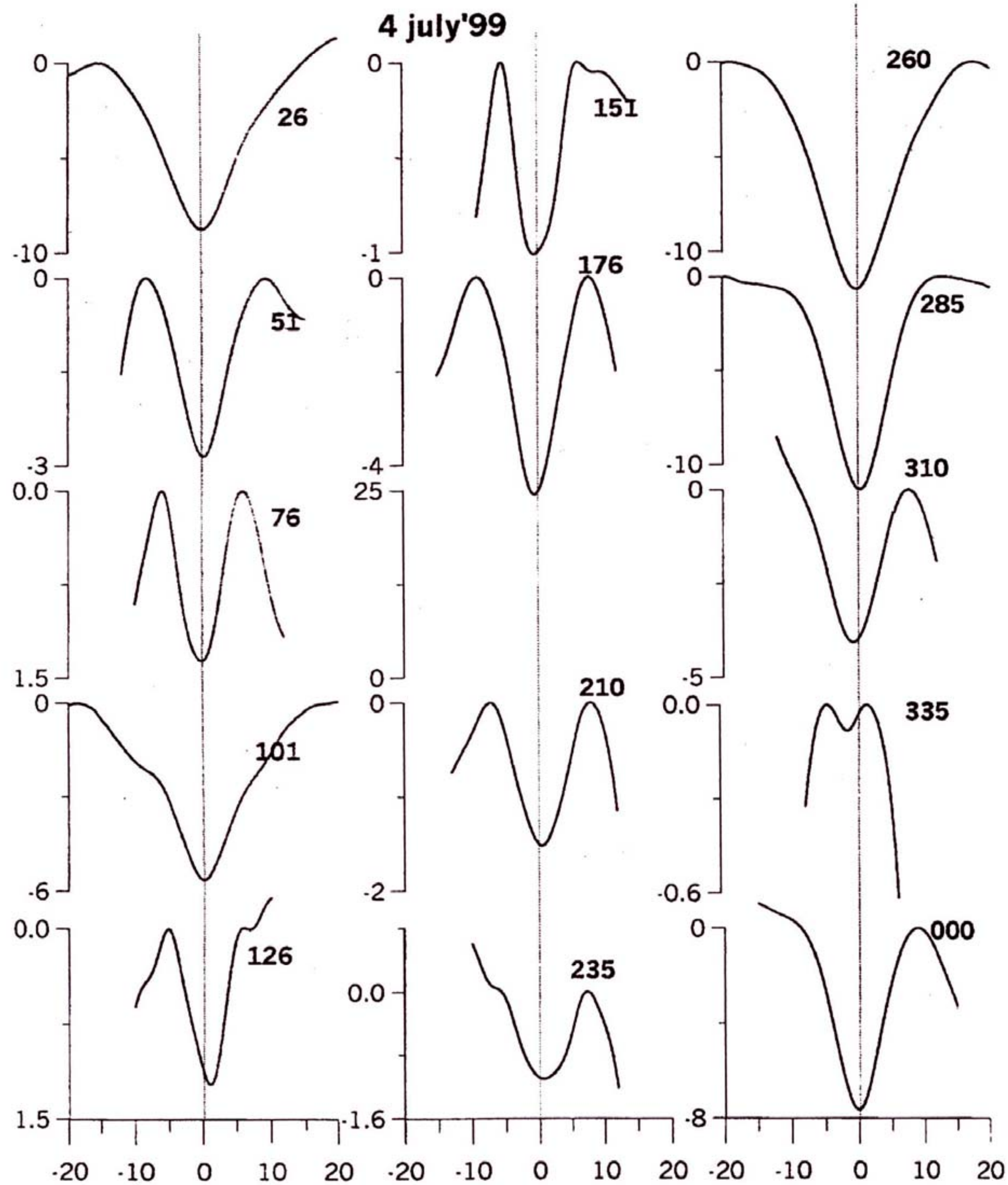

Fig. 3(b). (*continued*)

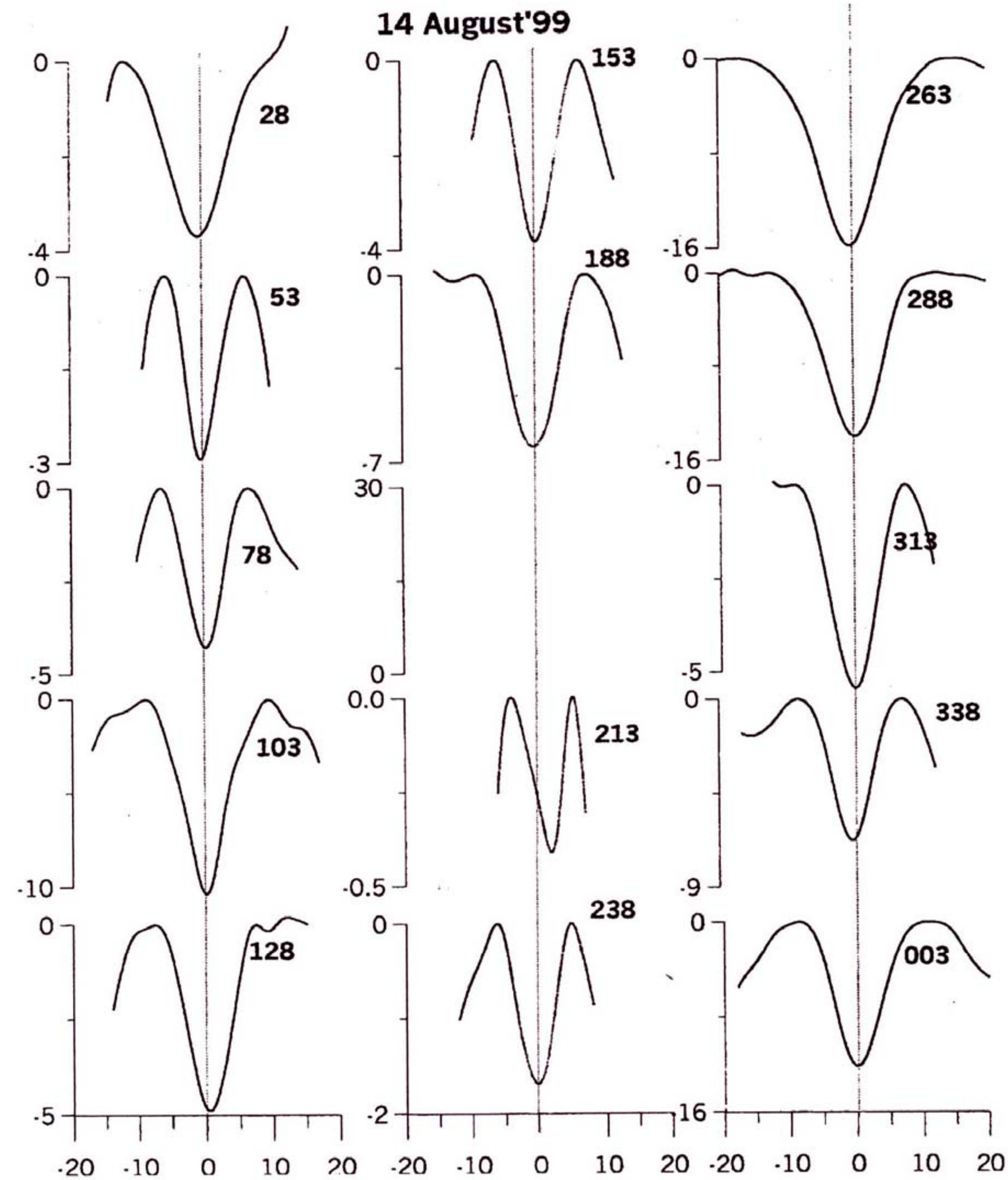

Fig. 3(c). (*continued*).

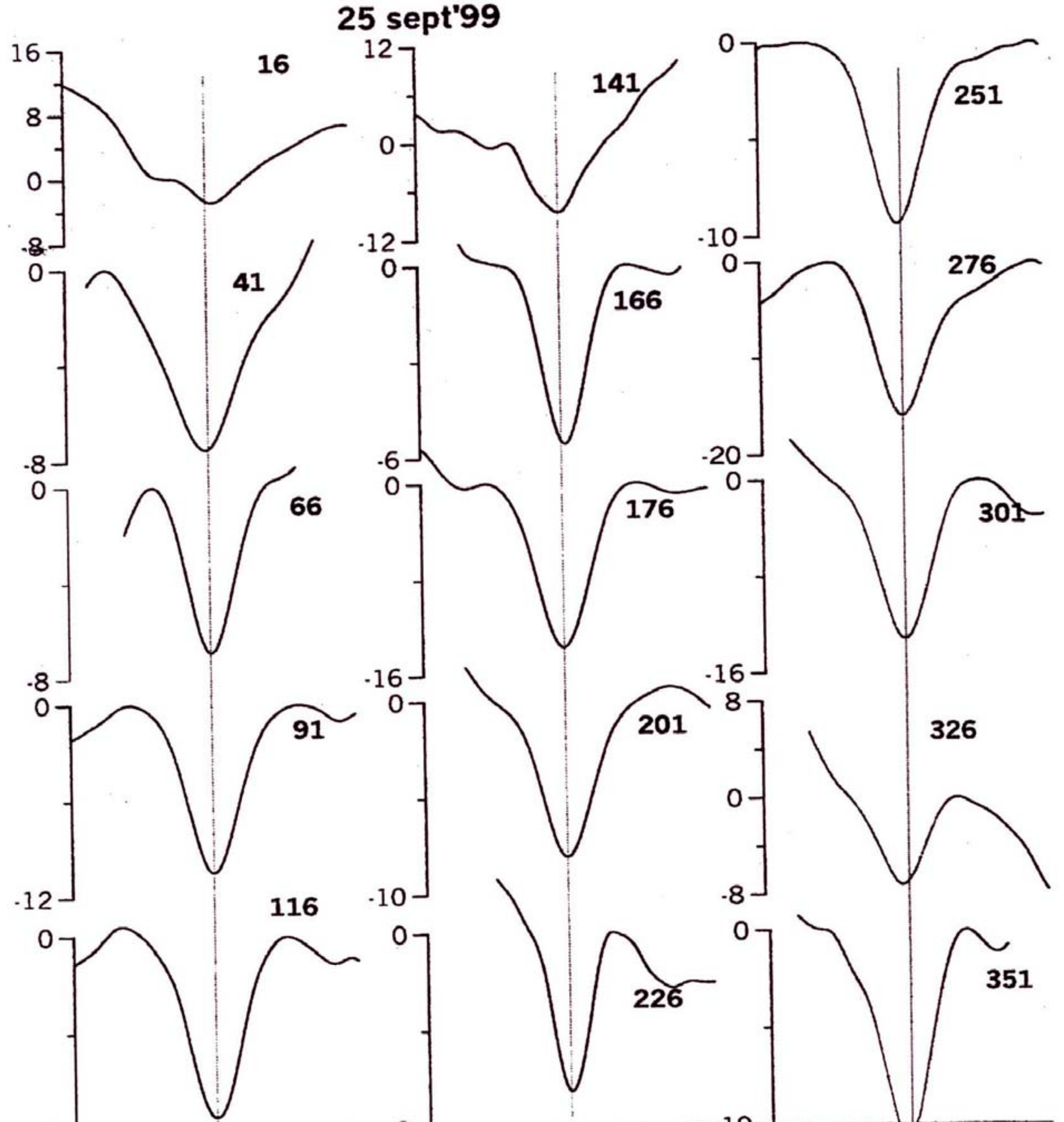

Fig. 3(d). (*continued*).

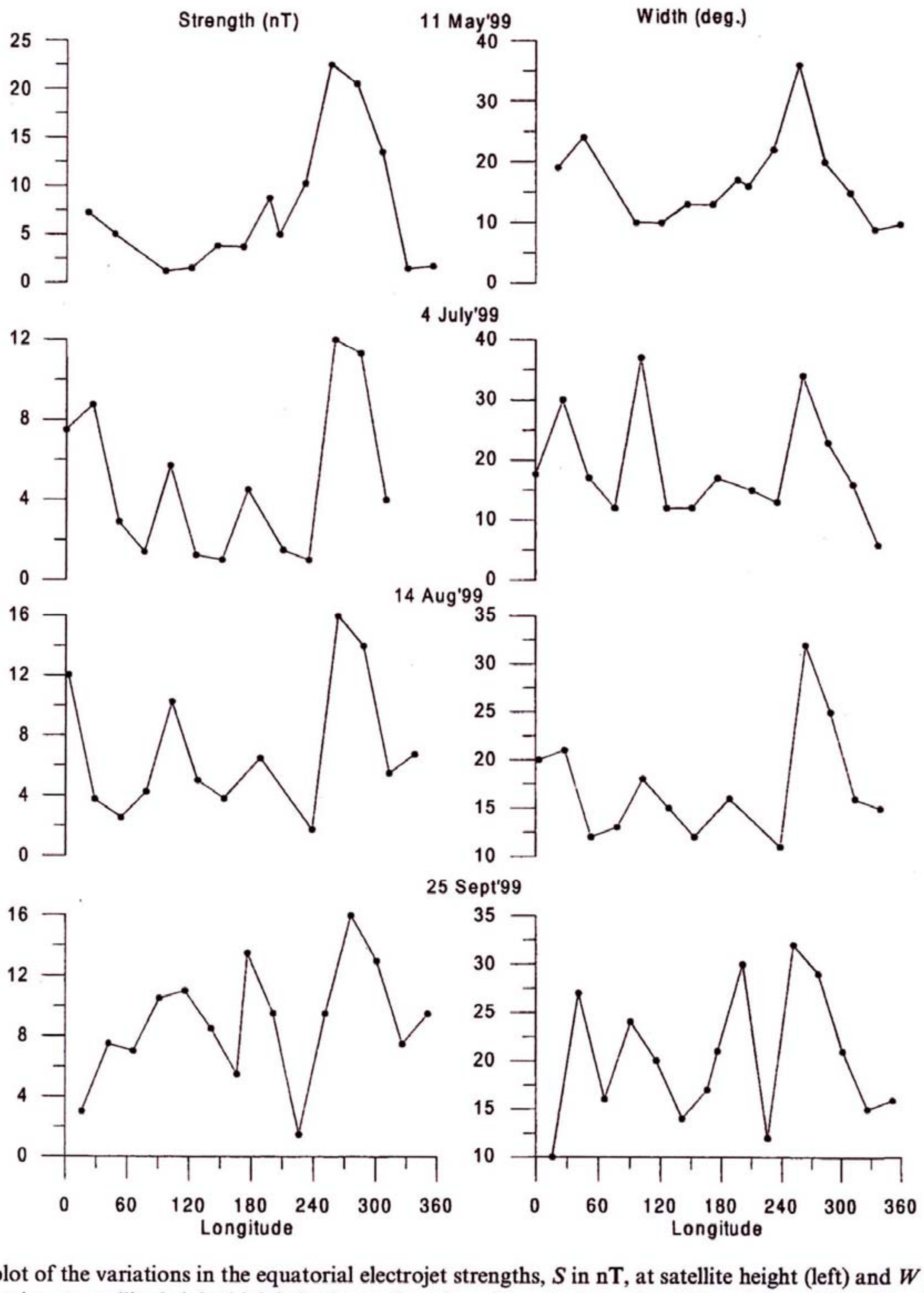

Fig. 4. A plot of the variations in the equatorial electrojet strengths, *S* in nT, at satellite height (left) and *W* in °, width of the electrojet, at satellite height (right), both as a function of longitude on the different days: (a) 11 May 1999; (b) 4 July 1999; (c) 14 August 1999; (d) 25 September 1999.

sector. In this paper, S is taken as the deviation of the value of the field at the dip equator from that at the hump/change in slope. It may be added here that the actual EEJ current strength can only be calculated based on a model specifically chosen for the EEJ. Fig. 4 is a plot of the variations in the EEJ strengths, S, as a function of longitude on the different days. It may also be noted that the Oersted provides a unique data set in which on a given day, the satellite height at the equatorial crossing does not vary significantly. The electrojet signatures at different longitudes can be directly compared without resorting to specific models. This was not possible using the POGO data.

We find that the EEJ strength, S, at the satellite height, on all the four days plotted, shows a stable maximum distinctly higher than the rest, in the longitude zone around 290°E, in the South American sector. There exist other subsidiary maxima typically around 190 and 100°E. The amplitudes associated with these show considerable day-to-day variability on all the 4 days presented, with the peak at 100°E appearing as a crest on 11 May and as a very well defined maximum on 25 September. The position of these peaks are consistent with Onwumechilli's (1985) observation of the peak eastward intensity J_0, and total eastward current having maxima around 100 and 280°E longitude with subsidiary maximum at around 190°E. We also observe a peak around the Greenwich meridian on all the days. The high degree of day-to-day variability in the peaks other than the principal peak at 290°E, suggests that these maybe due to the external tidal parameters which are likely to be more variable. Onwumechilli (1985) has suggested that a possible explanation may come from regional prevailing winds and possible gradients at electrojet altitudes. A standard migratory tide usually adopted in EEJ modeling, however, cannot produce such longitudinal differences. We are led to the conclusion that variable background winds or non-migrating tides may be likely candidates. It may be pointed out that non-migratory tides have been observed in the mesosphere and lower thermosphere and are currently topic of extensive investigations (Hagan et al., 1997).

In the same Fig. 4 is also plotted the width, W in degrees, of the EEJ at satellite height, as a function of longitude for the various days. Here the width, W, is defined as the distance in degrees between the two humps (in Fig. 3) and does not represent the actual width of the current system in the ionosphere but may be related to it. We find that the width also shows a maximum in the South American sector, around 290°E longitude. There is also a subsidiary peak around 190°E; the other peaks vary from day-to-day in location and amplitude and may not have any real significance.

4. Conclusions

Using the Oersted initial field model along with the earlier IGRF models, the possible long term secular changes that could have occurred in the global patterns of the position and strength of the EEJ have been examined. The most significant feature that appears through the analysis is the northward drift of the location of the dip equator (hence the position of the axis of the EEJ) to the extent of 1.0° per decade around 300°E. In contrast, in the Pacific, east of Australia, there is practically no drift. It is also observed that the largest secular variation in the Cowling conductivity occurs in the South American sector with a possible 4% increase per decade for the same level of ionisation in the E-region. A very significant result is that the magnetic field at the dip equator need not be perpendicular to the dip equator itself and this deviation from the idealized scenario of the equatorial electrojet can result in significant contribution of the equatorial electrojet to the declination component. An augmentation of the existing models and a more detailed study of ground and satellite data in 300°E sector is called for to examine the consequences of this apparent anomaly.

The EEJ has also been studied using the scalar data of the individual passes of the Oersted satellite. Global data from four International quiet days in the day-lit side that included data from 57 satellite orbital passes covering the different longitude sectors has been used to show that the EEJ peak coincides with the dip equator. The strength of the EEJ, at satellite height, shows a very stable maximum in the South American sector on all days emphasizing the importance of control of the geomagnetic field. Secondary peaks are also seen around 0, 100 and 190°E. These peaks exhibit day-to-day variability and could be related to variable migratory tides. The longitudinal differences in the EEJ will have implications on the modeling of global subsurface conductivity probing in induction studies.

Only the results of a preliminary analysis of the Oersted data has been presented here to bring out the immense possibilities of utilizing the Oersted data for a comprehensive study of the equatorial electrojet. A more comprehensive study using a larger database along with a model to bring out the electrojet parameters is already under way and results will be presented in due course of time. Finally, the availability of good quality vector data in near future will enable very important studies that can yield the vertical extent of the 3-dimensional current loop associated with the equatorial electrojet.

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