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COMPARISON OF TWO VIEWS ON THE STRUCTURE OF IONOSPHERIC CURRENTS

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ABSTRACT

There are two views on the structure of ionospheric currents, here symbolized as VIEW 1 and VIEW 2. The essential difference between them is that VIEW I supports the existence of two ionospheric current layers in the dip equatorial zone as measured by many rockets (Onwumechili,1992b,c). Contrary to the rocket measurements, VIEW 2 believes that ionospheric currents in the dip equatorial zone flow in only one current layer. This paper presents 11 relevant experimental results for explanations by VIEW 1 and VIEW 2 side by side. After reviewing many papers on related topics and judging the performances of the two views, it emerges that VIEW 2 is conjectural and has feasibility problems. On the other hand, VIEW 1 is based on observational results, and it simply and naturally explains the experimental results.

Key words: ionospheric currents, current layers, magnetic dip equator, abnormal phase quiet days, counter equatorial eletrojet.

INTRODUCTION

Onwumechili (1992a) reviewed the evidences that accumulated over the years on the return current of the equatorial electrojet (EEJ). Stening (1995) (henceforth referred to as RJS95) discussed a contrasting view on the structure of ionospheric currents. Although many authors had discussed the structure of ionospheric currents leaning one way or the other, the above two papers have highlighted two clearly contrasting views on the subject. We shall symbolize them as VIEW 1 and VIEW 2.

The first view (henceforth referred to as VIEW 1) may be outlined as follows. In the dip equatorial region, ionospheric currents flow mostly in two separate but often coupled layers. The upper current layer extends from the equator to 77° dip latitude and is taken to be worldwide. Poleward of the Sq focus, ionospheric currents flow mostly in a single layer being this upper current layer. Its zonal component is eastwards equatorward of Sq focus but westwards poleward of Sq focus. In the neighbourhood of the dip equator, the two current layers contribute to observed Sq. It is therefore useful to refer to the upper current layer as the worldwide part of Sq (WSq) current layers. Normally, the lower current layer is much more intense than the upper current layer and exhibits most of the characteristics of EEJ. It is therefore useful to refer to the lower current layer as the EEJ part of the Sq current layers. The zonal component of the lower current layer is eastwards equatorward of its focus close by the flanks of the dip equator but westwards poleward of its focus. The EEJ current returns mostly equatorward of WSq focus. For some reasons not yet established, a part or the whole of a current layer can reverse direction for some hours.

The following comments may be made on the above elements of VIEW 1. The elements of VIEW 1 are mostly based on observational evidences. In daytime within 0^0 to 2^0 dip latitude, over 60% of ionospheric current profiles measured by rockets from 1957 to 1973 flowed in two layers (Onwumechili 1992b). In some cases the two layers were coupled as in Shuman (1970) but in others the layers were not coupled as in Maynard and Cahill (1965). Rockets observed that both the eastward and westward parts of the lower current layer density peak at the altitude of 106 ± 1 km. The altitude of the peak current density of the upper current layer observed by rockets is 136 ± 8 km within 0^0 to 2^0 dip latitude then it decreases with latitude such that its average from the edge of EEJ to 77^0 dip latitude is 118 ± 7 km (Onwumechili 1992c). Somayajulu et al. (1994) showed observational evidence of the evolution of the reversal of the lower current layer, and Onwumechili et al. (1996) found evidence that the upper current layer can also reverse, both for a period of a few hours.

We now turn to VIEW 2. Following RJS95 the second view (henceforth referred to as VIEW 2) on the structure of ionospheric currents may be outlined as follows. There is only one relatively constant current system in one current layer, "including both the EEJ and Sq with other superposed current systems mostly driven by semidiurnal tides. The EEJ is an enhancement of the Sq current at the magnetic dip equator with its variations linked to changes at higher latitudes".

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Within the current layer there is a minimum current density at about 5^0 dip latitude and "a transition from a maximum current density near 107 km at the dip equator to a maximum in the 115-120 km region beyond 6^0. These are no two separate current systems, but rather reflect the change from a dominance of the Hall and Cowling conductivities near the equator to the Pedersen conductivity at higher altitudes".

The following comments may be made on the above elements of VIEW 2. Since VIEW 2 is not clearly based on observational evidences, what then are its bases? There are two approaches to ionospheric dynamo calculations . The first is to use observed Sq to calculate the potential of the driving electric field. The wind is then calculated using the electric field (Maeda 1955). The second approach is to calculate the electric field from observed winds. The Sq current and magnetic field are then calculated using the electric field (Harper 1977, Rees 1979). However, before wind measurements became available, this second approach engaged in what Forbes and Lindzen (1976a) called diagnostic studies (Stening 1969, 1981, Tarpley 1970). The objective is to diagnose which tidal mode wind is likely to contribute significantly to the electric field that drives Sq. Then a cocktail of tidal mode winds is freely selected. The amplitudes and phases of the selected tidal mode winds are arbitrarily adjusted in a bid to simulate observational data.

Although observed winds are now available, some authors have continued with diagnostic studies with tidal mode winds. The cocktail of tidal mode winds is a far cry from real winds. Real winds can be of internal gravity wave or tidal origin or a mixture of the two. Real winds comprise mean winds and mostly coupled modes that can only be artificially decomposed into Hough modes extensions (Forbes and Hagan 1982). Indeed, after showing awareness of mode coupling, Stening (1981) himself criticized diagnostic studies as follows. "In addition, the usually assumed variations of amplitude with latitude of the tidal winds become height dependent. The use of simple tidal modes to describe the winds in the region under study is thus questionable (Champion and Forbes 1978). Yet, for the sake of simplicity, most workers continue to use combination of tidal modes in their studies". It is not only questionable. It is a construct of doubtful physical reality because decomposition into the Hough tidal modes is artificial. Yet RJS95 based most elements of VIEW 2 on diagnostic studies with tidal mode winds.

Both VIEW 1 and VIEW 2 agree that there are three fundamentals of established electric current. There must be electric field to drive the current. There must be conductivity in the medium to support the current. And the current must be divergence-free. It is therefore essential to ask questions about all the three fundamental elements. The ionosphere is pervaded by electric fields but current can only flow at altitudes that have conductivity. Wherever current flows it must have return paths. It is essential to ask where the return currents flow and to seek their return paths.

It is normal to test contrary views in science by the extent to which they consistently explain observational and experimental results. The objective of this paper is to place side by side, in section 2, how VIEW 1 and VIEW 2 explain some observational and experimental results, and results derived directly from observations and experiments.

EXPLANATIONS OF RESULTS OF EXPERIMENTS AND OBSERVATIONS BY VIEWS 1 AND 2

Double Layer Structure of Ionospheric Currents in Equatorial Electrojet Zone.

The two current layers measured by the rocket of Maynard and Cahill (1965) are shown in Fig. 1. Over 60% of the altitude profiles of ionospheric currents measured by rockets within ± 2^0 dip latitude have two layers (Onwumechili 1992c). The altitude profile of the vertical electric field E_z measured by Sartiel (1977) at about local noon close to the dip equator peaks at about 101 km altitude and decreases to zero at about 115 km altitude. Above that altitude an upper layer is observed from 0^0 to 77^0 dip latitude but its altitude decreases somewhat with dip latitude. So far no rocket has observed two current layers at dip latitudes higher than 20^0. Are these rocket measurements in agreement with VIEW 1 and VIEW 2?

The VIEW 1 accepts the above measurements, which are parts of its bases. The last three sentences of the paragraph suggest that the lower current layer is the EEJ layer because the E_z drives the main component of the EEJ. The characteristics of the upper current layer in Onwumechili (1992c) identify it as the WSq current layer. The VIEW 1 explains that the eastward dynamo electric field E_y pervades the ionosphere but current flows only where there is significant conductivity to support it. Within about $\pm 1^0$ dip latitude where the Hall field E_H is approximately E_z, when zero vertical current is

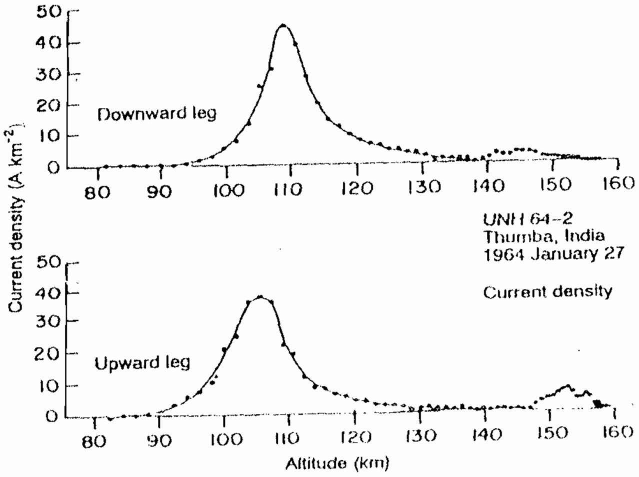


Figure 1 Altitude profiles of current density A km^{-2}, during rocket flight UNH 64-2 from 0.2°, dip latitude at 09 37 hr local time; bottom, on the ascent and top, on the descent (after Maynard & Cahill 1965).

assumed, the current densities of the WSq (j_W) and EEJ (j_E) are given by

$$j_W = \sigma_1 E_y \qquad (1)$$

$$j_E = \sigma_2 B x E_z / B + \sigma_1 E_y \approx (\sigma_2^2/\sigma_1 + \sigma_1) E_y = \sigma_3 E_y \qquad (2)$$

where $\underline{B}$ is magnetic field, σ_1 is Pedersen conductivity, σ_2 is Hall conductivity and σ_3 is Cowling conductivity. The current density peaks of the layers are largely influenced by the peaks of σ_1 and σ_3 respectively.

RJS95 states the stand of VIEW 2 as follows. There is only one current layer. But there is an altitude transition from a maximum current density near 107 km at the dip equator. Then the current density decreases to a minimum around 5^0 dip latitude. Thereafter the current density maximum occurs in the 115-120km region beyond 6^0. This reflects the change from a dominance of the Hall and Cowling conductivities near the equator to the Pedersen conductivity at higher altitudes.

As comment we note that what VIEW 2 is missing here is that the maximum Pedersen conductivity also extends to the dip equator. It is also noted that in their three-dimensional simulation of ionospheric currents caused by S(1,-2) tidal winds, Takeda and Maeda (1980a) found evidence of the two current layers as observed by rockets. They stated, "At noon it is clear that the usual Sq currents flow at about 120km in low latitudes, and the EEJ flows around 105 km apart from them".

Westward Currents on the Flanks of the Magnetic Dip Equator.

Only two rockets have so far measured currents around 5^0 dip latitude (Cahill 1959 and Maynard 1967). Both of them observed westward current in the lower current layer and eastward current in the upper current layer. This is the location where analyses of observed data find maximum westward current without incorporating local winds (Oldenburg 1976, Onwumechili and Ezema 1992, Oko et al. 1996). Using observed electron density, observed winds and local magnetic field, Raghavarao and Anandarao (1987) find maximum westward current at the same dip latitude. This may be regarded as direct derivation from observed data in support of the rocket measurements. Do VIEW 1 and VIEW 2 accord with these observed results?

The VIEW 1 accepts these observational results and explains them as follows. On the flanks of the dip equator local downward electric fields E_l is produced by three sources: (a) local zonal winds with vertical shear, (b) the effect of curvature of magnetic field lines through the dynamo region, and (c) the divergence of zonal currents due to high conductivity gradients close to the dip equator (Raghavarao and Anandarao 1987, Singh and Cole 1987, Onwumechili 1992a). These combine constructively to cause maximum resultant downward electric field E_z around 5^0dip latitude. The Ez drives the westward Hall currents. The currents peak at the altitude of 106 $\pm$ 1 km like the EEJ (Onwumechili 1992c). Meanwhile, the upper current layer of Eq. (1) continues flowing eastwards as observed by the rockets (Cahill 1959 and Maynard 1967).

From RJS95 the stand of VIEW2 is as follows. Local emfs at low latitudes produced by (2,2) tidal modes drive currents in the opposite direction to the electrojet. "The presence of tidal modes like (2,3) is likely to yield complex variations in the vicinity of the equator with current profiles similar to those observed by rockets. It is easy to conceive of a local wind structure, varying with height, which could give rise to the currents observed by these rockets".

As comment we note that the model of Sugiura and Poros (1969) found the westward currents at 6° dip latitude without incorporating local winds. The numerical model of Takeda and Maeda (1983) for 1800 hr L.T. covering 90 km to 600km altitude in Fig. 2, reproduced qualitatively the structure of ionospheric currents observed by rockets. Quantitative reproduction is not expected because of their simplifying assumptions

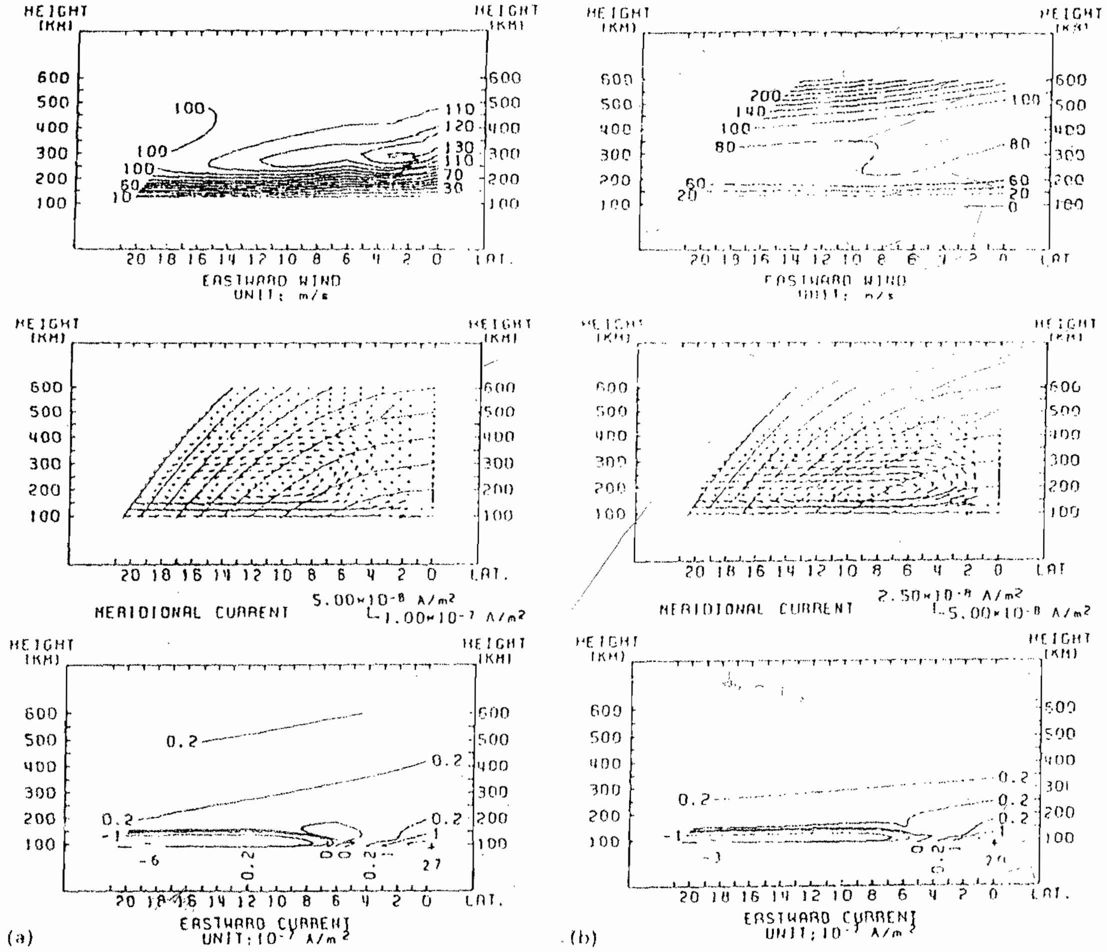


Fig 2. Eastward winds (top), meridional currents and magnetic fieldlines (middle) and eastward currents (bottom) for sunspot number R = 280 (a) and R = 100 (b). After Takeda and Maeda (1983)

including the coincidence of the dip, geographic and dipole equators, and their winds were not real. They described essential features of the bottom panel of Fig. 2 as follows: "the EEJ centered at the dip equator and 105 km altitude (its peak value is 2.7 A/km^2 and 2.0 A/km^2 respectively for sunspot number R = 280 and 100), a negative (westwards) current sheet which flows in the E-region beyond 6.5^0 (R= 280) or 4^0 (R=100) latitude and –0.62 A/km^2 and -2.7 A/km^2 at 105 km altitude and 18^0 latitude for R = 280 and 100 respectively, and positive (eastward current) layer of about 0.02-0.03 A/km^2 in the F-region". Note that the altitude of their upper current layer decreases with latitude like the one observed by rockets (Onwumechili 1992c). Note also that their ratio of the peak westward current density to the peak eastward current density of the lower current layer is –23% for R = 280 and –14% for R = 100 as compared with –23% from Onwumechili and Ezema (1992) and –24% from Oko et al. (1996). The numerical model of Stening (1985) similarly covered 90 km to 500 km altitude but he failed to reproduce the observed structure. One wonders if his use of equivalent circuit method (Stening 1968) contributes to his failure. With all the corroborations of westward currents from observations, data analyses and numerical calculations by various authors cited above, we need not comment on the wrong reasons suggested by RJS95 why the continuous distribution of current density model finds the westward currents on the flanks of the dip equator like other workers.

Depressed and Enhanced Shoulders of ΔH Latitudinal Profiles.

On the flanks of and below the eastward EEJ, on the ground, depressed shoulders of ΔH latitudinal profiles have been observed by Hutton (1967), Fambitakoye and Mayaud (1976), and Hesse (1982). But on the flanks of and above the eastward EEJ, on satellites, enhanced shoulders of ΔH latitudinal profiles have been observed by Cain and Sweeney (1973) and Ravat and Hinze (1993). Are these results in accordance with VIEW 1 and VIEW 2?

The VIEW 1 accepts these observational results and explains them as follows. It is noted that ΔH is positive below and negative above the current axis at about 106 km altitude in dip equatorial region. In low latitudes where two current layers have been observed, the observed ΔH_T is made up of ΔH_E from the EEJ (lower) current layer and ΔH_W from the WSq (upper) current layer;

$$\Delta H_T = \Delta H_E + \Delta H_W \tag{3}$$

At the dip equator ΔH_E and ΔH_W have the same sign. Therefore ΔH_T is positive below the EEJ on the ground but negative above the WSq on satellites. On the flanks of the eastward EEJ where the westward currents flow, ΔH_E is negative but ΔH_W is positive. Therefore:(a) on the ground there, the negative ΔH_E of the westward current depresses the shoulders of the observed ΔH_T below the background of ΔHw. But (b) on the satellite, the positive ΔH_E of the westward current enhances the shoulders of the observed ΔH_T above the background of ΔH_W. The Fig. 3 showing the magnetic field components for 1800 hr. L. T calculated by Takeda and Maeda (1983) from Fig. 2 demonstrates the contrast between the negative ΔH_E at the dip equator and positive ΔH_E on the flanks of dip equator due to the EEJ at satellite altitude. Thus on a satellite at about 400 km altitude, the positive ΔH_E from the westward currents enhances the shoulders of ΔH_T latitudinal profile. On the ground the opposite occurs and the shoulders of the ΔH_T latitudinal profile are depressed as observed.

Following RJS95 the explanations of VIEW 2 are as follows. "There may simply be a minimum in the eastward current flow. If there is a larger dip

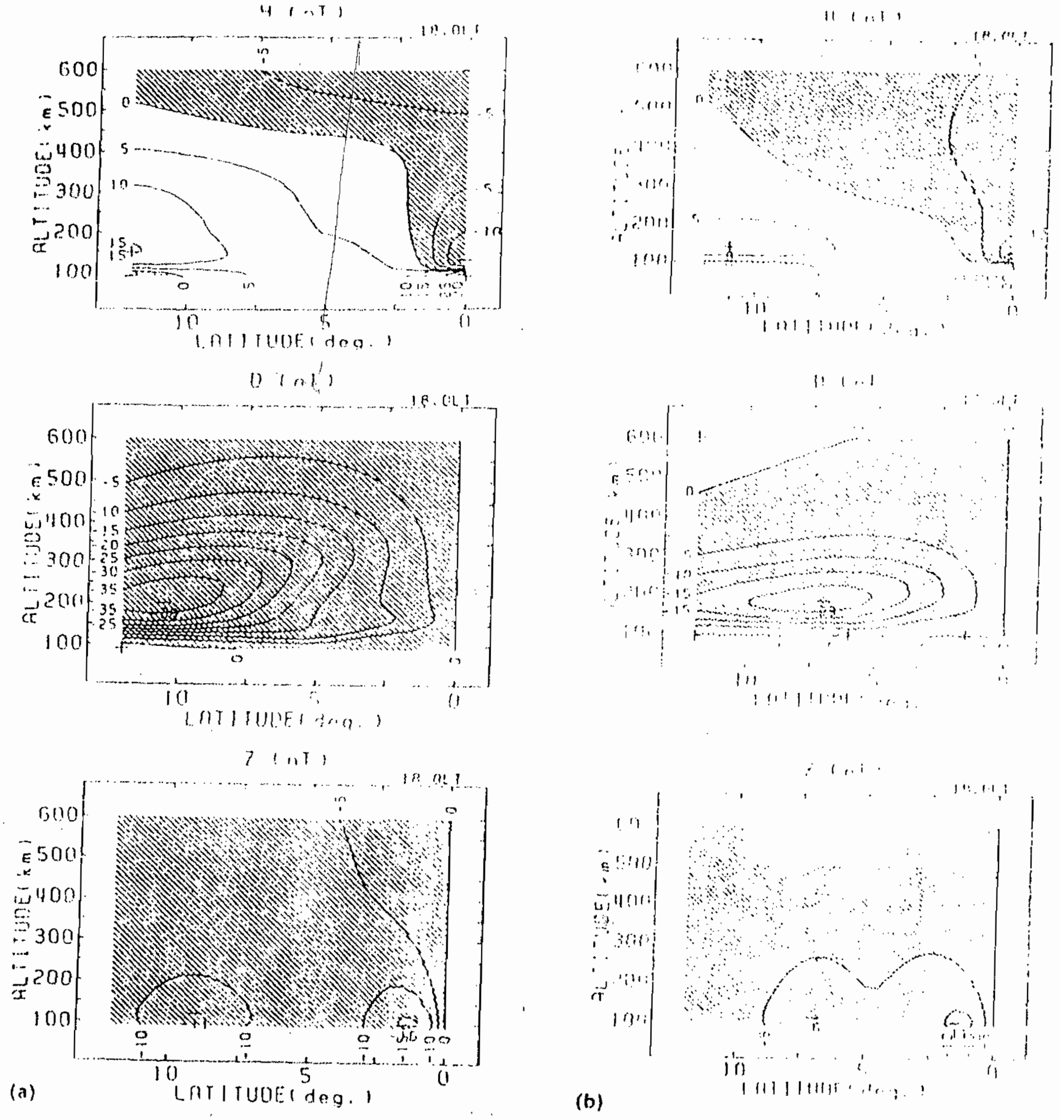


Fig. 3 Contours of H (top), D (middle), and Z (bottom) components of magnetic field variation for sunspot number R = 280 (a) and R = 100 (b). Contour lines are drawn in every 5 nT and hatches are made where values are negative. After Takeda and Maeda (1983).

in the magnetic field profiles, as seen by Hutton (1967), then there may or may not be a westward current flow at some height: it will depend on the structure of the local winds responsible. These emfs, which may be variable if the (2,2) mode plays a big part, may be responsible for the currents producing the dips in ΔH observed by Hutton. An alternative explanation may be that the shoulders are due to the satellite passing through a field-aligned current which it encounters on each side of the dip equator".

As comment we note the surprising attempt of VIEW 2 above to play down the very existence of depressed shoulders on ground-based profiles. Indeed, RJS95 declared, "there is no real negative shoulder seen on an average ground-based profile". But Stening (1985) accepted the existence of the depressions as follows, "Hutton (1967) shows a depression on the ΔH profile at about 5.5^0 north of the dip equator". "Fambitakoye and Mayaud (1976) also frequently finds an afternoon depression at stations near 3.5^0 latitude". He then tried unsuccessfully to model it. RJS95 also tried to rubbish enhanced shoulders of satellite observed profiles. It ignored the typical profiles given by Cain and Sweeney (1973) and chose to discuss the profile they labeled atypical because it was affected by magnetic anomalies.

Evolution of Magnetic ΔH Signature of Counter Equatorial Electrojet.

The characteristic ΔH signature of counter equatorial electrojet (CEJ) is well known because it has been observed and displayed many times. The daytime ΔH is unexpectedly depressed for a few hours, sometimes below the nighttime level but sometimes still above it. In either case, when the corresponding ΔH at a low latitude off-electrojet station on the same longitude is subtracted, the difference is certainly negative and below the nighttime level. What currents produce this signature?

Another observation in Fig. 4 indicates the changes in the electric field associated with CEJ. The cause of CEJ responsible for the obvious changes of vertical polarization electric field E_Z in Fig. 4 is yet unknown. There are three suggestions: (a) vertical winds varying with height most likely of gravity wave origin (Raghavarao and Anandarao 1980); (b) zonal winds of gravity wave or tidal wave origin varying with height (Somayajulu et al.1993); and (c) abnormalities in global Sq. (Marriot et al. 1979). Suggestion (a) has reproduced the features of CEJ very well. The problem with (b) is that most calculations show that it cannot reverse the Hall field E_H at the dip equator but only from about 2^{0}dip latitude and beyond. The problem with (c) is that the nature of the abnormalities is not clear. The Fig. 4 could be due to vertical or zonal winds varying with height. The authors of Fig. 4 (Somayajulu et al.1994) prefer zonal winds of gravity wave and tidal origin. The VIEW 1 and VIEW 2 should explain the observed characteristic ΔH signature of CEJ in the context of its associated observed changes in the electric field.

The VIEW 1 elucidates the CEJ ΔH signature as follows. In a normal CEJ, the upper current layer is not affected. Even if the wind extends to its altitude, σ_2 is too small there (Raghavarao and Anandarao 1987). Therefore ΔH_W is positive and extends from the dip equator to other latitudes. This is the positive background in the ΔH latitudinal profile during CEJ. Fig. 4 shows that the reversal of the lower current layer can commence at its top, bottom or elsewhere but eventually it consolidates at the lower altitudes. The vertical field E_Z is downward and Esq disappears at all the altitudes where EEJ is reversed. When the magnitude of ΔH from the reversed altitudes exceeds ΔH from eastward altitudes, the ΔH_E of Eq. (3) is negative. Then $\Delta H_T < \Delta H_W$ in Eq. (3) and is depressed below the background ΔH_W as observed. Whether or not the whole EEJ (lower) current layer is reversed or not at the equator, $\Delta H_T \leq 0$. If $\Delta H_T < 0$, it is full CEJ below nighttime level. But if $\Delta H_T > 0$, it is partial CEJ above the nighttime level. In both cases, as is observed at EEJ and off-EEJ stations:

$$\Delta H_T(\mathrm{EEJ}) - \Delta H_T(\text{off-EEJ}) = (\Delta H_E + \Delta H_W) - \Delta H_W = \Delta H_E < 0, \qquad (4)$$

and therefore the difference is below nighttime level as observed. This resembles the suggestion of two current layers, one at 105 km altitude and the other 140 km altitude by Kane (1976).

As additional evidence, we note that in their numerical model calculations using S (1,-2) tidal mode, Takeda and Maeda (1980a) reported, "The most remarkable feature appears at 1800 L.T. At this time, westward currents exist only near the equator, while currents flow eastwards outside of the equatorial region. At 1800 L.T.j_ϕ (eastward current density) reversed only in the equatorial

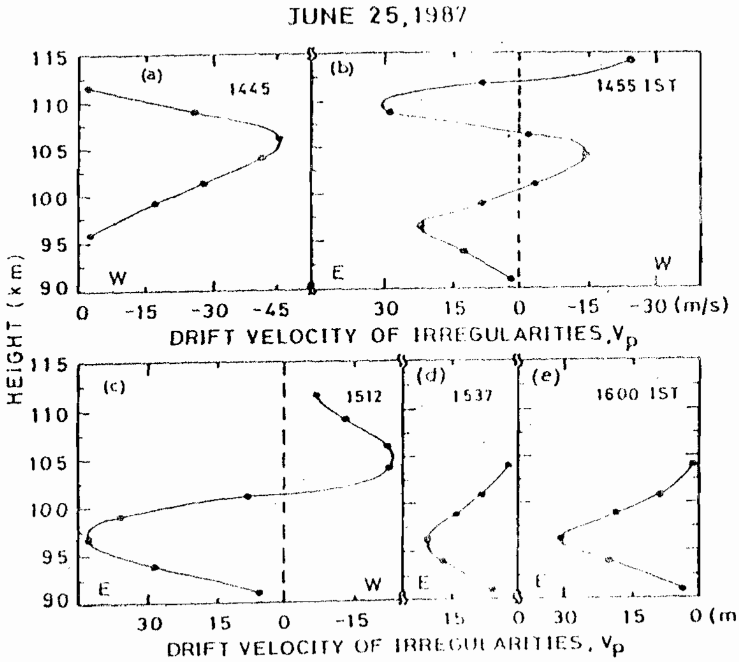


Fig. 4 Height structure of the drift velocity of the ionization irregularities in the equatorial electrojet at Trivandrum as measured with a VHF backscatter radar on 25 June 1987. E and W indicate the drift of the irregularities in the eastward and westward direction respectively. W is normal direction and E is reversed direction. After Somayajulu et al. (1994).

region because of the reversal of the vertical polarization electric field. This is CEJ by definition as well as by its driving electric field. The meridional current is also reversed. The westward current of the CEJ is confined within + 3° magnetic latitude at 110 km altitude and within about ±4° magnetic latitude at about 95 km altitude. The eastward global Sq electric field E_y is not reversed globally. Even in normal CEJ, it is not necessary for E_y to reverse because local vertical winds can reverse E_Z and cause CEJ without the reversal of E_y (Raghavarao and Anandarao 1980,1987). The report in this paragraph fully agrees with VIEW 1.

From RJS95 the explanation of VIEW 2 is as follows. "However, the superposition of a current system associated with an appropriate semidiurnal tide can produce the changes observed both in the electrojet and elsewhere. There may be a reversal of the vertical electrostatic field near 110km, (shown in his Fig. 8); which can explain both the partial CEJ and the E_S disappearance since the equatorial E_S occurs at the lower altitudes where the electric field is reversed".

The ΔH Latitudinal Profiles on 6 June and 15 July 1969 at the Transition Between EEJ and CEJ in Central Africa.

RJS95 drew attention to and called for the explanation of the ΔH latitudinal profiles in Fig. 5 on 6 June and 15 July 1969 at the transition between EEJ and CEJ observed in Central Africa. (a) AT 1030 L.T. on 6 June the EEJ peak was absent and the profile was fairly flat as the CEJ at 0930 L.T. was changing to the normal EEJ seen at 1230 L.T. (b) At 1230 L.T. on 15 July 1969 three humps or small peaks appeared at the dip equator and the edge of EEJ zone as the EEJ at 1130 L.T. was changing to the CEJ seen at 1430 L.T. How do VIEW 1 and VIEW 2 explain these observations?

The VIEW 1 has easy and natural explanation of these two profiles. (a) At 1080 L.T. on 6 June 1969 the upper current layer produced the background WSq ΔH_w = 70nT. That was the peak or range of the intense WSq for that day as is evident from the given backgrounds at the other hours of that day. After 0930 L.T. the CEJ began to disappear and the profile began to recover towards normal EEJ. This means that altitudes of the lower current layer at which eastward currents flow began to increase relative to altitudes at which westward currents flow. See Fig. 4. At 1030 L.T. the positive ΔH from the portions with eastward currents equaled and annulled the negative ΔH from the portions with westward current, making ΔH = 0. From Eq. (3) the observed ΔH_1 = ΔH_W = 70nT then comes from the upper current layer, and the profile is consequently flat. As the recovery continued, positive ΔH from eastward portions exceeded negative ΔH from westward portions and positive EEJ peak increased from 1130 L.T. to 1230 L.T. before the daily decline in intensity set in later as observed.

The VIEW 1 explains (b) on the same principles as (a) but the EEJ and WSq vary from day to day. At 1230 L.T. on 15 July 1969, the upper current layer produced the WSq background $\Delta H_W = 30$ nT plus the smooth background curve that may be continued by joining the two outside peaks at the edges of EEJ zone. Fig. 4 and another case suggest that shortly after the commencement of the CEJ process, westward current consolidates at lowest altitudes of the lower current layer. Thereafter, it spreads to higher altitudes through the layer. Rocket measurements find that the altitude extent of the lower current layer is as expected thinner at the edges and thicker at the axis of the lower current layer (Onwumechili 1992c). Therefore, as the reversal of the lower current layer continued after 1130 L.T., a point was reached at 1230 L.T. when all the current near the thin edges had reversed to westwards. But around the ticker axis, some remnant eastward current still flowed at higher altitudes of the layer. Near the edges, the negative ΔH of westward currents depressed ΔH_T below the background level ΔH_W curve. But near the axis at the dip equator, the positive ΔH of the remnant eastward currents cushioned the negative ΔH and caused the middle peak where $\Delta H_T \approx \Delta H_W$. Accordingly, three peaks occurred at the center and the edges as observed. As the westward current spread further to higher altitudes, the remnant eastward currents gradually disappeared and the central peak progressively turned into a trough as observed from 1330 L.T. to 1430 L.T.

Following RJS95 VIEW 2 explains the (a) and (b) observations as follows: "With suitable tidal modes, such as (2, 3) or (2, 4) it is possible to produce both the above mentioned ~~changes in~~ the electroject, with little change just outside it but noticeable changes at higher latitudes".

As comment we note that the claim of "noticeable changes at higher latitudes" is flawed. RJS95

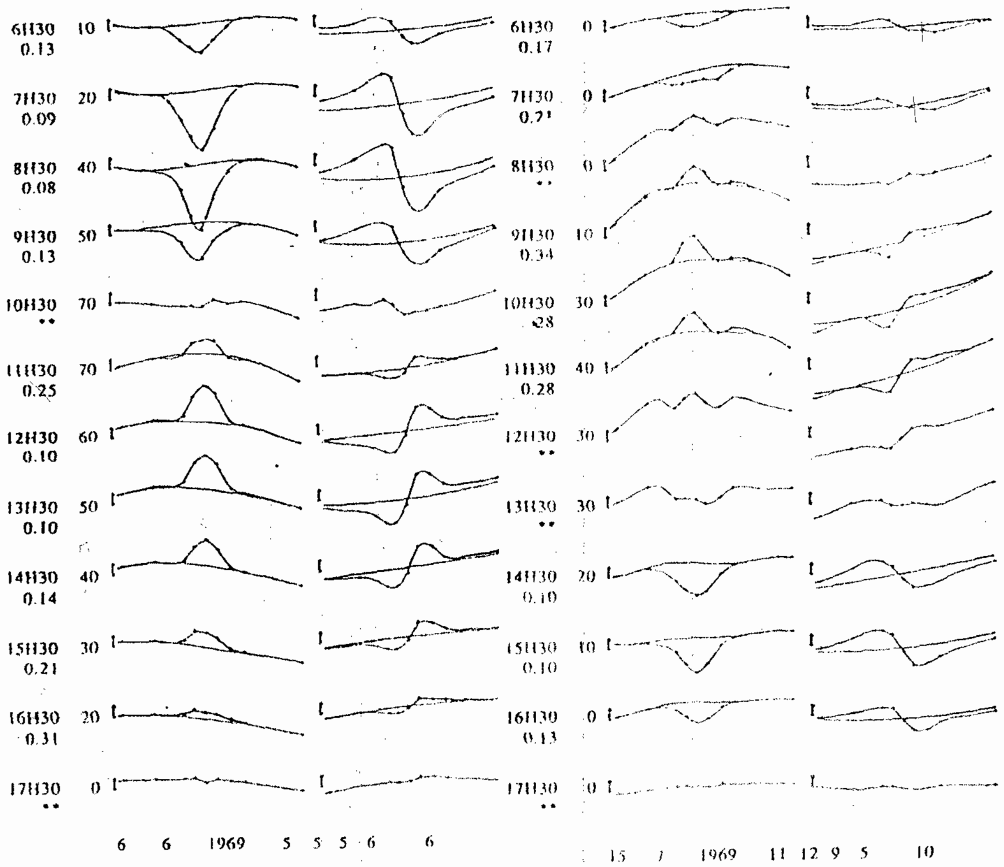
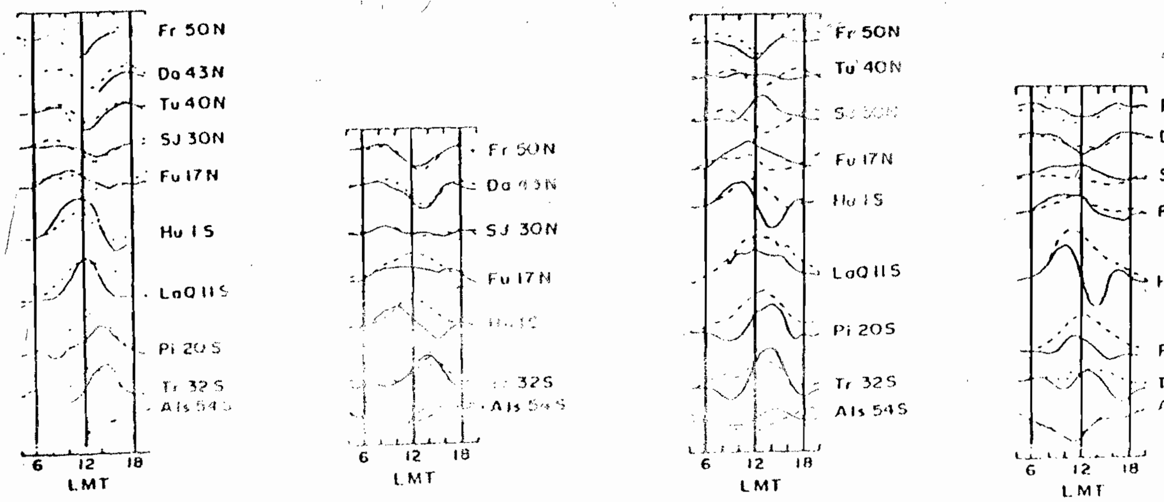


Fig 5 Hourly latitudinal profiles of ΔH and ΔZ from a chain of stations in Central Africa spanning 27.18° latitude from North to South, with the dip equator close to the center of the chain. Profiles for 6 June 1969 (left) and profiles for 15 July 1969 (right). The number below the time is the relative size of the residuals when it is less than 0.4 otherwise asterisk is shown. The smooth curve without points represents the worldwide part of Sq (WSq) background and the curve with points is the equatorial electrojet plus the WSq. The vertical bar is the scale for 10 nT. The horizontal mark at the bar represents the baseline for Z but for H it represents the value 0, 10,20 nT.... above the baseline as indicated on the left. After Fambitakoye and Mayaud (1976).



14-01-64 29-01-65 13-01-64 07-12-65

Fig 6. Diurnal variations of geomagnetic horizontal field ΔH at certain American sector stations on 14 January 1964, 29 January 1965, 13 January 1964 and 7 December 1965, being days with counter-equatorial electrojet (solid curves). In the same order, their control days (broken curves) are 22 January 1964, mean of 5 quiet days of January 1965, 22 January 1964 and 5 quiet days of December 1965 respectively. Selected from Stening (1977).

claimed that Stening (1977,1992) found evidence of the return current of CEJ at higher latitudes around WSq focus. The reader who is not familiar with diurnal features of ΔH around WSq focus is referred to Fig. 7 and Fig. 8 of Matsushita (1967) and Fig. 18 of Campbell (1989). They show that ΔH is somewhat semidiurnal close to the focus and reverses phase across the focus. Fig 6 here is a selection of 4 of the days on which the claim of RJS95 relies. We first concentrate on the diurnal variations on CEJ days (solid curves). On 29 January 1965 the WSq focus was almost directly at San Juan (SJ) making its ΔH almost zero. On 14 January 1964 the WSq focus was slightly north of SJ and ΔH was very slightly positive at SJ. On 13 January 1964 the WSq focus was clearly at Tucson (TU) north of SJ and ΔH at SJ was clearly positive as expected at stations south of the focus. On 7 December 1965, WSq focus was between SJ and Dallas (Da) and accordingly ΔH was positive at SJ as expected. It is the classical positive swing of ΔH at SJ when the WSq focus is north of SJ that Stening (1977, 1992) interpreted as evidence of the additional field from the return current of CEJ. It appears that the error of Stening arose from his use of control days (broken curves) to predict both amplitude and phase. When ΔH amplitude at SJ is higher on CEJ day than on the control day he considers that the additional field comes from the CEJ. This is fundamentally unreliable because such a difference can occur between any two days with or without CEJ, depending only on the respective locations of the focus on the two days.

Latitudinal Spread of Counter Equatorial Electrojet

The use of magnetic perturbations to determine latitudinal spread of the source current has two major problems. (a) The magnetic field of a current spreads much wider beyond the confines of the current. Therefore, magnetometers sense currents flowing over a wide range of altitude and latitude. Unless the other known sources are removed, there is no certainty that the perturbations arise from counter equatorial electrojet (CEJ) source. (b) Many researchers use control days to represent what the Sq would have been on the day if the CEJ had not occurred. This is fundamentally unreliable because Sq varies unpredictably but significantly from day to day. Indeed, it is impossible to retrieve what Sq would have been on the day if the CEJ had not occurred. If the control day is changed, the result may change because no two quiet days are exactly the same. The result of Bhargava and Sastri(1977) implies that when daily range of ΔH on control days is subtracted from the range on CEJ days, the difference is largest at the dip equator and decreases sharply with latitude. But on the contrary, Sastri et al (1982), using another set of control days from another data set, find that the daily range of ΔH is about equal on CEJ and control days in the equatorial electrojet (EEJ) zone. But north of EEJ zone, the difference increases gradually with latitude. Also the differencing method of Bhargava and Sastri (1977) would produce negative result throughout daytime from dip equator to 60^{0}N for

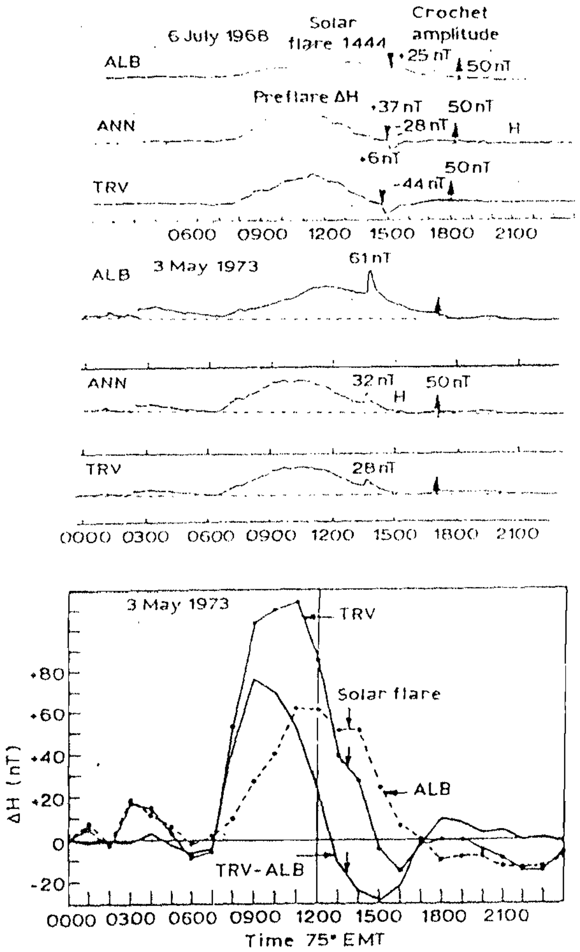


Figure 7 Solar-flare effects (SFE) in H at the Indian observatories Trivandrum (TRV), Annamalainagar (ANN) and Alibag (ALB) on a distinct counter-electrojet day (6 July 1968) and on a partial counter-electrojet day 3 May 1973. On a clear counter-electrojet day SFE in H near the equator is negative, while on a partial counter-electrojet day SFE is positive at the equator but lower in magnitude compared with that at stations outside the electrojet. (After Rastogi *et al.* (1975b).)

the two days used by Hanuise et al (1983). This contradicts the semidiurnal and latitude dependence nature of Bhargava and Sastri (1977). These demonstrate the fundamental unreliability of using control days. Similarly, the use of a different set of control days would contradict the claim of Stening(1977, 1992) even if his method had not been fundamentally erroneous as shown in section 2.5

In the circumstance, the best available observational evidence, to be explained on the latitudinal spread of CEJ comes from solar flare effect (SFE), as in Fig. 7 from Rastogi (1989). The solar flare releases a burst of ionizing radiations that suddenly increases ionization density in the ionosphere. The resulting sudden increase in conductivity and current take place virtually under the same conditions of wind and electric field as for the currently existing Sq current. The very sudden step change in H known as solar flare effect in H or SFE (H) is therefore a good indicator of the direction in which the zonal Sq current was flowing at the onset of the event, before the additional heating alters the wind and the electric field.

Forbush and Casaverde (1961) clearly showed that the amplitude of SFE (H) is maximum at the dip equator and decreases with latitude like EEJ ΔH

The SFE(H) in Fig. 7 during full CEJ is remarkably different from the expectation from the result of Forbush and Casaverde (1961) pertaining to the equatorial zone. In case (a) during a full afternoon CEJ on 6 July 1968, SFE(H) was negative at Trivandum(TRV), and Annamalainagar(ANN) in EEJ zone but positive at Alibag(ALB) and Hyderabad(not shown) outside EEJ zone The magnitude was greatest at TRV at the dip equator and decreased with latitude (Rastogi et al. 1975, Rastogi 1996) The result was the same during full morning CEJ on 21 June 1980(Rangarajan and Rastogi 1981). This indicates that in the EEJ zone the current was flowing westwards during the CEJ event. This westward current of the CEJ did not extend as far as Hyderabad (HYD) at about 9.3^0 north from the dip equator. In case (b) during a partial afternoon CEJ on 3 May 1973, SFE(H) was positive but lower at TRV and ANN in EEJ zone than at HYD and ALB outside EEJ. The magnitude was smallest at the dip equator and increased with latitude contrary to the result of Forbush and Casaverde(1961). Indeed, its magnitude at HYD and ALB was double the magnitude in EEJ zone (Srivastava 1974 and Rastogi 1996). This indicates that the westward current of the partial CEJ effectively reduced the magnitude of SFE(H) in the EEJ zone, but its effectiveness did not extend as far as Hyderabad at about 9.3^0 north from the dip equator.

The following results based on observational data are in support of and may be added to the solar flare results above. (i) The direct derivation from observational data by Ezema et al (1996) in which the westward CEJ current is confined to (-3.2^0 to 3.2^0) $\pm 0.04^0$ and its eastward return current is confined to (-14.1 to -3.2^0 and 3.2^0 to 14.1^0) $\pm 0.3^0$ dip latitude. (ii) The calculations of Raghavarao and Anandarao (1987) with observed winds and measured ionospheric parameters in which the westward CEJ current is confined to about -2.2^0 to 2.2^0 magnetic latitude and its eastward return current from about -7.1^0 to -2.2^0 and 2.2^0 to 7.1^0 magnetic latitude. (iii) Latitudinal profile of observed ΔH_T in Fig. 5 which is depressed below the background ΔHw from about -6.8^0 to 6.8^0 by the westward current of CEJ.

The VIEW 1 and VIEW 2 should explain the very clear result on the latitudinal spread of CEJ current from solar flare effect on H in Fig. 7, which is fully supported by the results based on observational data in the immediate paragraph above.

The VIEW 1 explains the observations in Fig. 7 as follows. As explained in section 2.4, the WSq(upper) current layer is not affected by the partial or full reversal of the EEJ(lower) current layer during a CEJ event. In case (a) on 6 July 1968, the upper current layer produced positive ΔH_w and SFE(H)$_w$ of +25nT at ALB and comparable positive ΔH_w and SFE (H)$_w$ at TRV and ANN. Just before the onset of SFE, the reversed lower current layer had produced negative ΔH_E at TRV. The SFE(H)$_E$ at TRV was also negative because the lower current layer was flowing westwards. The magnitude of SFE(H)$_E$ at TRV was much larger than the SFE(H)w at ALB as expected from Forbush and Casaverde (1961). Similar to Eq. (3) the resultant observed ΔH_T and FSE(H)$_T$ are

$$\Delta H_T = \Delta H_E + SFE(H)_E + \Delta H_w + SFE(H)_w \quad (5a)$$

$$FSE(H)_T = SFE(H)_E + SFE(H)_w \quad (5b)$$

At TRV, these resultant observed values are negative because the component contributions from the CEJ(lower) current layer are negative and greater in magnitude than the component contributions from the WSq(upper) current layer. The explanation for ANN is the same as for TRV. The resultant observed values are greater in magnitude at TRV than at ANN because Cowling conductivity and polarization electric field Ez are greater at Trivandrum than at Annamalainagar. But at HYD and ALB the resultant observed values are positive because the negative contributions from the westward CEJ(lower) current layer are feeble, if any, because the westward CEJ (lower) current layer does not extend to them and may indeed be confined to the EEJ zone.

In case (b) during the partial CEJ on 3 May 1973, the explanation is similar to that for (a) above. But following the explanation of partial CEJ in section 2.4,

$$\Delta H_E + \Delta H_w < \Delta H_w > 0 \text{ and } SFE(H)_E + SFE(H)_w < SFE(H)_w > 0 \quad (6)$$

Inserting Eq. (6) in Eqs. (5a) and (5b), it becomes clear that the resultant observed values of ΔHT and FSE(H)$_T$ are positive at all the stations but greater in magnitude at Alibag than at Trivandum and Annamalainagar as observed. Again ΔH_E and SFE(H)$_E$ are greater in magnitude at TRV than ANN because of greater Cowling conductivity and vertical electric field Ez at TRV than at ANN. Consequently, because ΔH_E and SFE(H)$_E$ are negative, the resultant observed value of FSE(H)$_T$ is smaller at Trivandrum than at Annamalainagar as observed. Thus cases (a) and (b) suggest that the westward CEJ(lower) current layer was probably confined to EEJ zone of about -4^0 to $4.^0$ dip latitude like the case encountered in the numerical model calculations of Takeda and Maeda (1980a).

From RJS95 we cite the stand of VIEW 2 on the latitudinal spread of CEJ current. "Early studies of the morphology of the CEJ showed that the reversal is confined to a narrow latitude range around the dip equator, again suggesting a separate current system."…. "However, the detection of changes at higher latitudes, associated with the CEJ, argues against the idea of a separate current system. Rather, the addition of another current system, possibly associated with a semidiurnal tide can explain both the CEJ and the higher latitude changes accompanying it (Stening 1977, Rastogi 1993)".

To complete the picture from VIEW 2, we also cite its reference to Stening(1977). "On coming to examine the geomagnetic data, the author brought with him a conviction that the reverse jet effects were caused by an additional current system in the dynamo region generated by some thermo-tidal mode. Such current system would produce effects at other latitudes and these should be searched for. The afore-mentioned conviction is not entirely substantiated by the following data, but it provided a framework for considering the results"

As comment, the preceding paragraph gives the clue how Stening (1977) misinterpreted Sq focus movement effects which in the end "did not entirely substantiate" his conviction. However, the claim of "the detection of changes at higher latitudes, associated with CEJ" has already been flawed in the last paragraph of section 2.5

The Focus of Counter Equatorial Electrojet Current.

The latitude of the focus of CEJ current systems estimated by various researchers is given in Table 1. Arora B.R (1994). is private communication. The first 9 and the last are derived from observational data while Nos. 10 and 11 are from numerical model calculations. Some methods of the derivations are not satisfactory. For example, Nos. 1 and 2 are based on misinterpretation of Sq focus movement effects, and those based on comparison of CEJ and control days are questionable. But even if they were all acceptable, they all agree on one thing. They all place the focus of CEJ between the dip equator and the Sq focus, and in most cases much closer to the dip equator than to the Sq focus. It implies that at least the greater part of CEJ currents return between its focus and the Sq focus. The VIEW 1 and VIEW 2 should explain how the Sq current systems have two foci in the same hemisphere and how the current vortices with these foci circulate.

The VIEW 1 has an easy explanation of the observed feature. The WSq(upper) current layer has the higher latitude focus in the midlatitude region, given as >40^0 in Table 1, in the cases that analyzed the data globally. This is not affected by the reversal during the CEJ. It is the EEJ(lower) current layer that reverses during the CEJ event as explained in section 2.4. The CEJ focus is not far from the edge of the EEJ zone as can be judged from Fig 7 and section 2.6. The CEJ returned at its own altitude range largely between its focus and the latitude of the Sq focus.

The VIEW 1 has an easy explanation of the observed feature. The WSq(upper) current layer has the higher latitude focus in the mid latitude region, given as >40^0 in Table 1, in the cases that analyzed the data globally. This is not

Table 1.
Latitude of the focus of afternoon counter equatorial electrojet currents. The last two are estimated values from the numerical models of the authors. The dip latitudes and geographic latitudes of CEJ focus refer to the same location

	Source	CEJ Focus Dip Latitude Degree N.	CEJ Focus Geographic Latitude Degree N.	Sq Focus Geographic Latitude Degree N.	Sector
1	Stening (1977)	-7.5	-22		America
2	Stening (1977)	-15.5	-32		America
3	Sastri and Bhargava (1980)	13-27	19-30		India
4	Sastri et al (1982)	23	27	44	India
5	Hanuise et al. (1983)	21	25	50	India
6	Hanuise et al. (1983)	13	19	50	India
7	Arora (1994)	10	16		India
8	From 2 SFE(II)	3-10			India
9	Ezema et al. (1996)	4	12	40	India
10	Takeda and Maeda (1980b)	10	20		
11	Takeda and Maeda (1980a)	3.5			Global
12	Raghavarao and Anandarao(1987)	2-3.5			India

affected by the reversal during the CEJ. It is the EEJ(lower) current layer that reverses during the CEJ event as explained in section 2.4. The CEJ focus is not far from the edge of the EEJ zone as can be judged from Fig. 7 and section 2.6. The CEJ returned at its own altitude range largely between its focus and the latitude of the Sq focus.

We now cite the relevant statements of VIEW 2 on the subject. "Rather the addition of another current system, possibly associated with a semidiurnal tide, can explain the CEJ and the higher latitude changes accompanying it (RJS95)". And Stening(1977) elaborated the expected outcome of this hypothesis as follows. "At the start of this investigation it was hoped that deviations from normal Sq pattern could be identified as current systems generated by a traveling semidiurnal tidal mode. In this case one would expect to see, (i) an increase in ΔH in the morning when there is a decrease in the afternoon, (ii) evidence of a focus of the perturbing current system with deviations of ΔH from the normal pattern in opposite directions above and below this 'perturbing focus', and (iii) similar deviations at similar local times in different longitude zones. Examination shows that the only days which fit this pattern are 13 and 14 January 1964 although a few other days not shown were found"

As comment we note that Fig. 6 and section 2.5 show that he misinterpreted the effects of Sq focus movements on 13 and 14 January 1964.

Therefore, his hypothesis failed, as he also appeared to admit as cited in section 2.6.

There are no direct experimental measurements on the focus of the EEJ. It has therefore not been listed. But the focus of CEJ provides some indication because CEJ is regarded as reversed EEJ. The nearest to experimental results are the direct derivations of the latitude of EEJ focus from observed magnetic data. Onwumechili and Ezema (1992) got 2.8^0 dip latitude from POGO satellite data, and Oko et al. (1996) got 2.9^0 dip latitude from Indian observatories data. Calculations of Rahavarao and Anandarao (1987) with observed winds and observed ionospheric parameters give 3^0 dip latitude

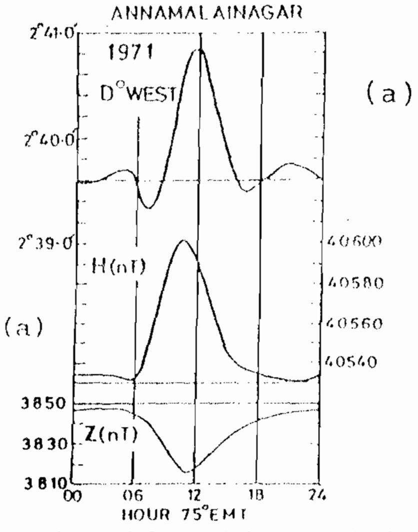


Fig. 8a. **Annual average daily variations of declination (*D*), horizontal (*H*) and vertical (*Z*) components of the geomagnetic field at Annamalainagar.** After Rastogi (1996).

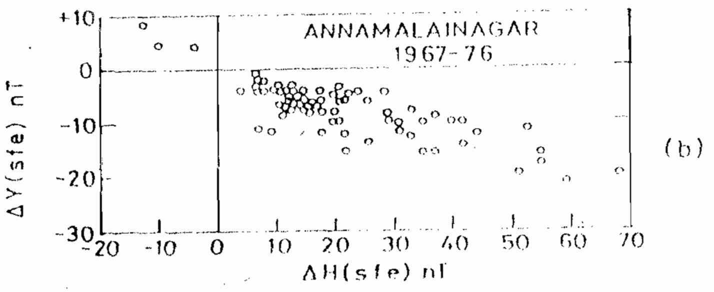


Fig. 8b. Relationship between the effects of individual solar flares on Y and H components of geomagnetic field at Annamalainagar. After Rastogi (1996).

North-South Currents of Equatorial Electrojet and Counter Electrojet

Rastogi (1996) used solar flare effects (SFE) on H, D, and Z to study the association between the east-west and north-south components of equatorial electrojet(EEJ) and counter equatorial electrojet (CEJ) currents. He analyzed 1967-1976 magnetic data of Annamalainagar (ANN) at dip latitude 2.7^{0}N supported by nearby Indian observatories' data. His results include Fig. 8a and Fig 8b. From quiet days without SFE, he found, "that on normal quiet days, an increase of H field (= eastward current) is associated with increase of D(westward) component (= poleward meridional current). In other words the meridional current over the magnetic equator seems to be an integral part of the zonal electrojet current".

From SFE on CEJ days he found; "These data strongly suggest that, at the time of solar flare. there existed an eastward Sq current and a westward counter electrojet current over Annamalainagar. It is important to note that, at the time of the partial counter electrojet, when a westward current is superimposed over a stronger Sq current over the equatorial latitudes, the solar flare effect on theY (north-south) field was negligible in spite of a strong effect on the H and Z fields. This suggests that the meridional current over the equatorial latitudes during partial electrojet conditions are a mixture of Sq associated currents in opposite directions".

Rastogi (1996) concluded: "The close relationship between SFE on horizontal and eastward fields at equatorial latitudes indicate that there is a component of the meridional current that is an integral part of the zonal EEJ current. Any temporary increase of the eastward electrojet current is associated with an increase in the poleward meridional current, and an increase of the westward electrojet current is associated with an increase in the equatorward meridional current"...

"Just as the zonal electrojet current is composed of an Sq-associated eastward current at 107km and another electrojet current eastward or westward at 100km level, the observed effect on the H field over the equator is a combined effect of these currents. Similarly, the meridional current at low latitudes consists of a component associated with the global Sq current and another component directly related to the electrojet current which is very sensitive to the changes in the conductivities or the electrojet at the dynamo level"s.

In effect, the above citations from Rastogi (1996) say in words that

$$SFE(Y)_T = SFE(Y)_E + SFE(Y)_W \text{ or } SFE(D)_T = SFE(D)_E + SFE(D)_W \qquad (7)$$

$$J_{\phi T} = J_{\phi E} + J_{\phi W} \text{ and } \Delta Y_T = \Delta Y_E + \Delta Y_W \text{ or } \Delta D_T = \Delta D_E + \Delta D_W \qquad (8)$$

$$J_{\phi T} = J_{\phi E} + J_{\phi W} \quad \text{and} \quad \Delta H_T = \Delta H_E + \Delta H_W \qquad (9)$$

$J_{\phi E}$ and $J_{\theta E}$ are integral parts of each other and similarly for $J_{\phi W}$ and $J_{\theta W}$ (10)

Where the subscript $_\phi$ denotes east-west (zonal) and $_\theta$ denotes north-south(meridional)

The VIEW 1 and VIEW 2 should explain these important findings of Rastogi (1996) on the structure of ionospheric currents.

The VIEW 1 is completely vindicated by the observations of Rastogi(1996). His paper describes a structure of ionospheric currents consisting of an EEJ(lower) current layer and a WSq or global Sq(upper) current layer in the dip equatorial latitudes. But sometimes the eastward EEJ reverses into westward CEJ, while the WSq continues to flow eastwards. It discusses the respective contributions of the two current layers: ΔH_E and ΔH_W to the horizontal field, ΔY_E and ΔY_W to the north-south field or declination field ΔD_E and ΔD_W, and ΔZ_E and ΔZ_W to the vertical Z field. Rastogi (1996) gives observational evidence of the poleward meridional component of the return current of EEJ, and the equatorward meridional component of the return current of CEJ. The paper also reported that the meridional current(= ΔY_E) due to EEJ or CEJ is very low at Trivandrum(TRV, dip latitude δ = 0.2^{0}N) is observable but small at Kodaikanal(KOD, δ =2.1^{0}N),is large at Annamalainagar(ANN, δ =3.3^{0}N) but is not detectable at Hyderabad(HYD, δ=9.3^{0}N) and at Alibag(ALB, δ =10.5^{0}N) It is noted that ΔY_E and meridional current of EEJ and CEJ are greatest at their focus and ANN is nearer that focus than the other stations.

Rastogi (1996) observed as in Eq (10) that the eastward and poleward currents of EEJ are integral parts of each other and similarly for the westward and equatorward currents of CEJ, and also for the eastward and poleward currents of WSq currents. This means that the east-west and north-south components of the lower current layer flow in the same circuit or vortex confined to the altitude range of the layer and similarly for the upper current layer. Therefore the observations of Rastogi(1996) are in full agreement with the EEJ circuit of Onwumechili(1996a, b) in Fig. 9, derived from the 1986 data of 8 Indian stations. When the directions are reversed in Fig. 9, we get the circuit of CEJ. The EEJ and CEJ flow in the lower current layer. Onwumechili (1996a,b) has produced the complementary circuit of WSq(upper) current layer from the same data. The present stage is as follows: The eastward component of Fig. 9 has been observed by rockets (Onwumechili1992b,c). The north-south component of Fig. 9 has been evidenced by the observed data by Rastogi (1996). The westward component of Fig. 9 has been observed by rockets.. The entire Fig. 9 has been derived from

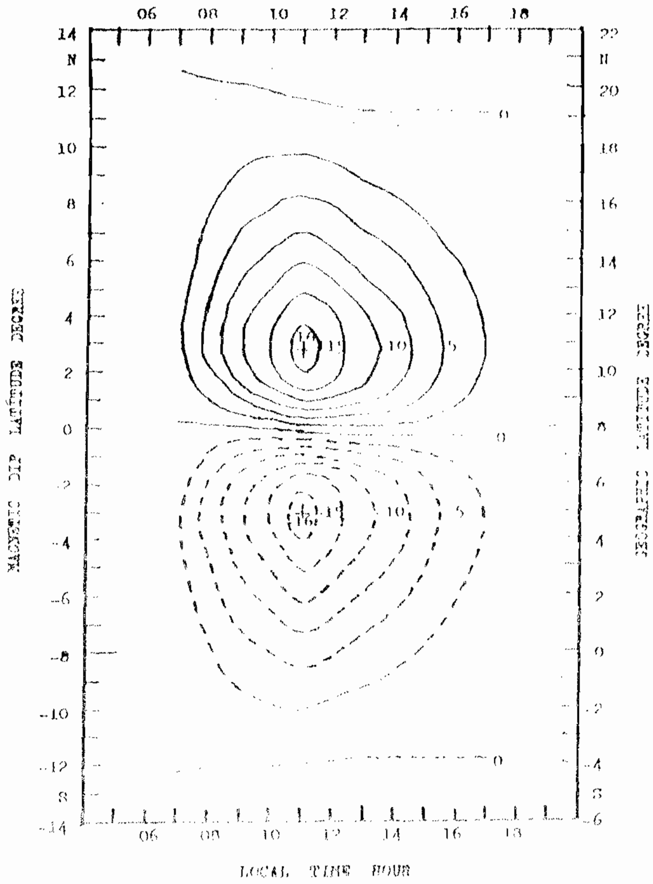


Fig 9 Subsolar elevation of equatorial electrojet current system in the style of Sq equivalent ionospheric current, derived from Indian observatories data of 1986. Continuous curves indicate counter clockwise current, broken curves indicate clockwise current, and 2500 Amperes flow between two consecutive curves. Symmetry about the dip equator is assumed. *The longer bar on each vertical axis is the zero level on the opposite axis.* After Onwumechili (1996a, 1997)
Rastogi (1996) believes that the lower current layer flows at *100km altitude and the upper* current layer flows at 107 km. The VIEW 1 believes that the two current layers are the *regular ones observed* by rockets at the altitudes of 106±1 km and 136±8 km respectively in the dip equatorial *zone*. There is no need for an ad hoc superposed current layer at 100km altitude. Fig. 1 support VIEW 1 because the lower current layer reversal during CEJ can occur from about 90km to 113km altitude. Beyond Rastogi upper current layers?

observational data. And Onwumechili (1996a,b) has given the electric fields, which combine to drive the EEJ current circuit in

From RJS95 we cite the stand of VIEW 2 appropriate to this subject. "But these winds, and the currents they generate, are only weakly linked to electrojet which is mostly driven by emfs poleward of the Sq focus. Thus the eastward and westward currents are largely driven by different sources and so it is hard to understand how one can be the return current of the other... It is not necessary to regard the westward currents as 'return currents' of the electrojet... Here we prefer to take a global point of view which does not assume the electrojet is a separate current system...A picture is suggested where there is a relatively constant current system, including both electrojet and Sq, with other superposed current systems mostly driven by semidiurnal tides....Indeed most of the currents equatorward of the Sq focus, including electrojet, might be considered as 'return current' of these higher latitude emfs".

As comment we ask what exactly is a superposed current system? Is it collocated in the same place with the constant current system? If so, only the resultant current system exists while both the constant current system and the semidiurnal current system become conjectures that have no physical reality. On the other hand, if the superposed current system flows at a different height apart from the constant current system, then each of them must have its own return paths. Their return paths need to be demonstrated as the return circuits of the upper and lower current layers are being discussed and evidenced above

Intensification During Contraction of Ionospheric Current Systems.

Maynard and Cahill (1965) noted that the more intense EEJ during their descent leg in Fig. 2 was thinner than the EEJ on the ascent. The peak current density increased by about 38% and the thickness at half peak value decreased by about 39%. Similarly, Sastry (1970) noted that his more intense rocket-measured EEJ at 1045 L.T. was thinner than the weaker EEJ measured at 1352 L..T. .at the same location on the same day. The peak current density decreased by about 51% while the thickness increased by 15%
Onwumechili (1996b) measured the peak current density and thickness of 18 rocket profiles of EEJ current. He confirmed that intensity varies inversely with thickness Also, Onwumechili and Agu (1981) found from the analysis of geomagnetic data that the latitudinal width of EEJ varies inversely with its peak current intensity and total forward current. The phenomenon is more pronounced in EEJ but is also noticeable in CEJ and WSq current systems. As the current system contracts, it intensifies relatively greater at a farther than at a nearer distance to the current center and vice versa. The phenomenon is sufficiently frequent for its effect to be noticeable in seasonal and annual averages (Onwumechili et al. 1996, Oko et al. 1996 and Ezema et al. 1996).

Using observed winds and measured electron density, Raghavarao and Anandarao (1987) found the same phenomenon from numerical calculations. Their results from zonal wind with positive shear are as follows: (a)That as the peak eastward current density increased by 5%, the latitudinal width of the contour of 0.5A/km decreased by 50% and the width at half of the peak density decreased by 19% in accord with the phenomenon of relative contraction. (b) That as the peak upward current density of the meridional current increased by about 74%, the boundary between the upward and downward currents moved several degrees farther away from the dip equator. (c) That as the peak current density of the lower part of north-south meridional current increased by about 57% and the upper part increased by about 121%, the thickness between them decreased by about 50%. The authors believe that wind with negative shear would produce results opposite the above. Even a table of intensities versus widths in the numerical model simulation of Reddy and Devasia (1981) supports the above phenomenon seen in rocket profiles and derived from observational data.

The VIEW 1 and VIEW 2 should comment on these observed results.

The VIEW 1 accepts the above results from observational data. The conductivities are smaller at the WSq(upper) current layer and at the off-noontime period of CEJ than at the noontime EEJ(lower) current layer. That is why the phenomenon is weaker in WSq and CEJ than in EEJ. If zonal local winds varying with height are the origin of the phenomenon, it should be noted that these winds are frequent. Commenting on their perturbations of magnetic profiles in EEJ zone, Fambitakoye et al. (1976) wrote." we conclude that thermospheric winds are variable not only during the course of a day but also from day to day and month to month. Nevertheless there seem to be average winds present through the year which make their presence known by their characteristic effects on the H and Z profiles averaged for the year".

From RJS95 we cite the comment of VIEW 2 on the above observational results. "Onwumechili (1992a) also attributes the negative correlations between the intensity of the EEJ and its half width to be the presence of westward currents on its flanks. This correlation was found in POGO satellite data. It is hard to understand why the ground-based data of Fambitakoye et al. (1976) do not yield a similar result. They found virtually no correlation".

As comment we note that the denial of the existence of this rocket-observed phenomenon by VIEW 2 is quite surprising. Westward currents cause depressions on ΔH profiles on the flanks of the eastward EEJ current. Fambitakoye et al. (1976) believed that zonal local winds varying with height caused the westward currents that frequently depressed the profiles. Their simulation including local zonal winds showed in their Fig 3 that when the westward currents and their attendant depression of the latitudinal profile of EEJ current intensity occurred, the width of the profile was greatly reduced.

2.9 Abnormal Phase Quiet Days

The abnormal phase quiet days (APQDs) are very quiet days on which the diurnal peak of Sq(H) occurs much earlier than the normal interval of the diurnal peak. Extensive studies have well established that these are also days of small amplitude Sq(H). The studies find that the characteristics and incidence of APQDs are very different in the dip equatorial zone and mid

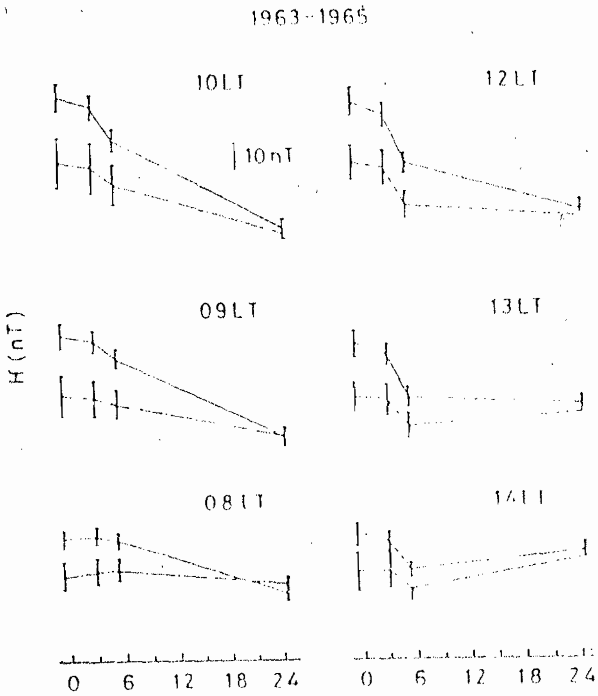


Fig. 10.Mean latitudinal profiles of the Sq (H) amplitudes at selected hours, LT from the Indian observatories in the equatorial region: Trivandrum (dip angle I = -0.6°), Kodaikanal (I = 3.0°), Annamalainagar (I = 5.4°), and Alibag (I = 24.5°). Solid lines (———) for normal quiet days on which the diurnal maximum of Sq(H) occurred at Trivandrum in the interval 1030-1130 LT and broken lines for abnormal phase quiet days (APQDS) on which the diurnal maximum of Sq(H) occurred at Trivandrum in the interval 0930-1030LT (-----) or in the interval 1130 LT-1230 LT (-.-.-). during the years (1963-1965) of low sunspot activity. The difference between the solid and broken lines represents the superposed magnetic field, SPMF (H), on APQDs tending to zero at Alibag. The vertical bars represent 99% confidence intervals of the mean values. After Sastri (1982).

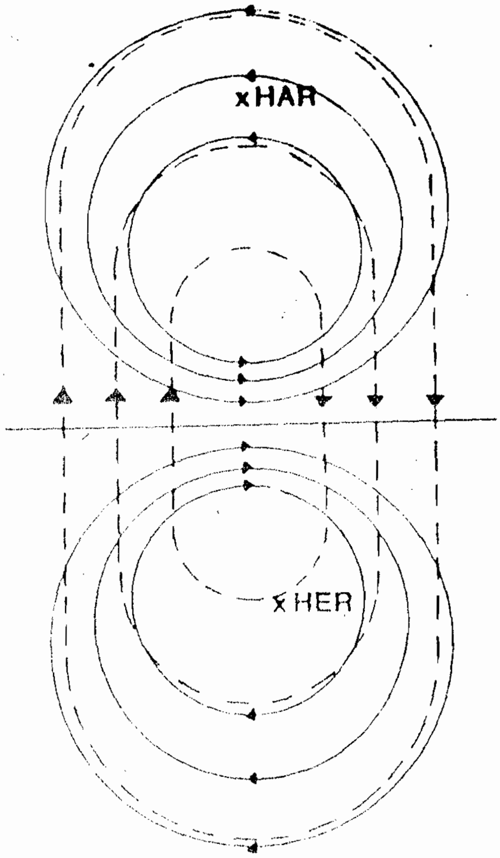
latitudes. In particular, APQDs do not occur on the same days in the equatorial and midlatitude regions(Sasatri1981, 1982, Butcher 1982, 1987). In Fig 10, Sastri,(1982) shows that in the Indian sector the small amplitude of Sq(H) on APQDs is confined to EEJ zone and does not extend to Alibag. On APQDs identified in midlatitudes, the perturbing magnetic field is present at all latitudes in northern and southern hemispheres. However, its northward component is greatest in midlatitude and decreases to insignificance at the equator (Butcher 1982, 1987). It is shown that the perturbing current flows in the ionosphere. Accordingly, Fig. 11 sketches the equivalent perturbing ionospheric single vortex current(SVC) system in relation to the Sq vortices. The SVC system of Schlapp et al. (!988) spans both hemispheres and its focus is close to the equator where the northward perturbing magnetic field is zero around local noon. The zonal component of the SVC system flows effectively at latitudes in the range of about 14^0-60^0 latitude.

The VIEW 1 and VIEW 2 should explain the structure of ionospheric currents that is consistent with the observed APQDs.

In VIEW 1, the intensity of the WSq(upper) current layer during midlatitude APQDs changes greater at midlatitudes than in equatorial zone. This is largely independent of the intensity of the EEJ(lower) current layer. Consequently, the midlatitude APQD event is not easily noticeable in the EEJ zone as observed. On the other hand the change in intensity of the EEJ (lower) current layer during APQD event at the equator is largely confined to the EEJ zone. Consequently, its reduction of the amplitude of Sq(H) does not extend far beyond the EEJ zone as observed. Thus changes in the intensities of the current layers can be mostly independent.

For the VIEW 2 we cite from the papers of Stening. The EEJ is "an enhancement of the Sq current at the magnetic dip equator with its variations linked to the changes at higher latitudes",(RJS95). The features of the ionospheric current flow due to the S(2, 3) tidal mode, "may be possible explanations of (1) the meridional current pattern observed at Saint-Santin, (2) current flows on abnormal (phase) quiet days (APQDs), (3) the reverse EEJ, (4) the seasonal phase anomaly in the lunar geomagnetic tide, and (5) the "invasion" of one hemisphere's current pattern by that from the opposite hemisphere" Stening(1989)

Comments may now be made on the statements of VIEW 2. Even if Stening's arbitrary changes of the phase of S(2, 3) tidal mode are ignored, at least claims numbers (2) and (3) fail. Claim (3) fails because VIEW 2 was unable to explain the experimental results discussed in sections 2.4. 2.5, 2.6, 2.7. and 2.8 concerning CEJ i.e. reverse EEJ. Indeed, the citations at the end of section 2.6 show that Stening (1977) virtually admitted that the expected outcome of his hypothesis concerning claim (3) was not substantiated. Similarly, claim (2) fails for the following reasons (a) His current system from S(2. 3) has two vortices contrary to the single vortex current system from APQDs in Fig. 11. (b) The north-south component of his S(2, 3) current system does not flow across the equator contrary to the SVC from APQDs. (c) The east-west component of his S(2, 3) current is largest at the equator and therefore it produces its largest ΔH perturbation at the equator contrary to the SVC from APQDs whose ΔH perturbation is zero at the equator. (d) The S(2, 3) current system is semidiurnal contrary to the SVC from APQDs which is largely diurnal. More generally, it is even more important that contrary to the basis of VIEW 2, the changes in Sq current intensity at higher latitudes that cause the midlatitude APQDs are not linked to the EEJ as VIEW 2 stated. Also, the changes in EEJ current intensity in Fig. 10 that cause the APQDs in the EEJ zone are not linked to the Sq currents far from the EEJ zone.



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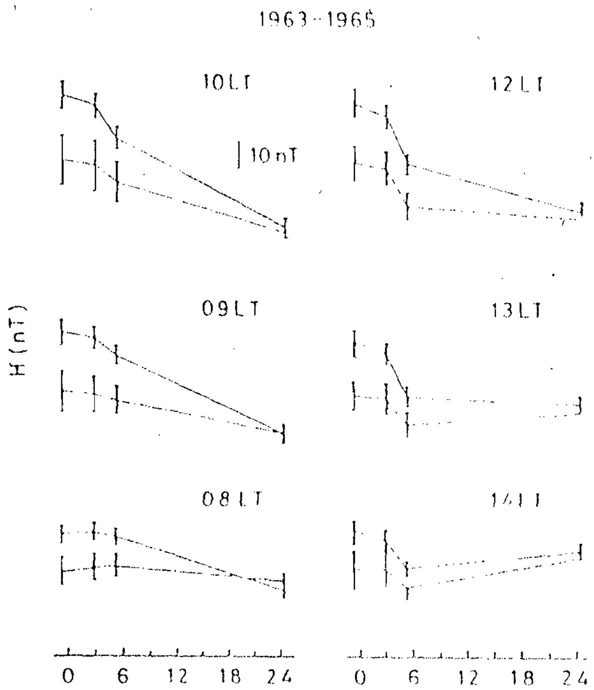
2.10 Correlation and Related Case Studies of Day to Day Variabilities of Sq Ionospheric Currents.

Since Forbush and Casaverde (1961), there have been very many studies on the correlation of geomagnetic day to day variabilities in the equatorial and midlatitude regions. It is not practicable to list all of them because of space. To save space we call a station in EEJ zone an E station and call a station in low latitudes outside EEJ zone an L station. Forbush and Casaverde found that magnetic variations at E-E pair of stations as well as L-L pair of stations correlate very well but E-L pair of stations do not correlate. An overwhelming majority of all the studies confirmed the results of Forbush and Casaverde(1961). We select only three of the most important aspects of the correlation studies.

(a) To present the basic element, we represent all the studies by the hardly surpassable works of Schlapp, Mann and Greener. In several papers, they collaboratively considered and or took into account a number of factors, even if remotely likely to affect the study. These factors included residual disturbance and Dst type effects, non-cyclic variation, great circle distance separating the two stations, seasonal variation, 27-day variation, movement of Sq focus effects, effect of CEJ, and spatial coherence properties of the correlations. Finally, using very large data of solar activity minimum and a large number of stations pairs, Mann and Schlapp (1988) concluded that for the same distance of separation, the difference in the correlation coefficients for L-L station pairs and E-L station pairs is highly significant at better than 1% level, the E-L pairs being less well correlated than the L-L pairs. The result was then confirmed with data from solar activity maximum period. It was also tested to ensure that the result represents a real phenomenon.

(b) The study of the correlations of ΔH at all hours at 7 stations in a narrow longitude sector in the equatorial region by Onwumechili and Ezema (2000a) has shown that the diurnal variations of the correlation coefficients depend on the locations of the two stations whose data are being correlated as in Fig. 12a and Fig.12b When the



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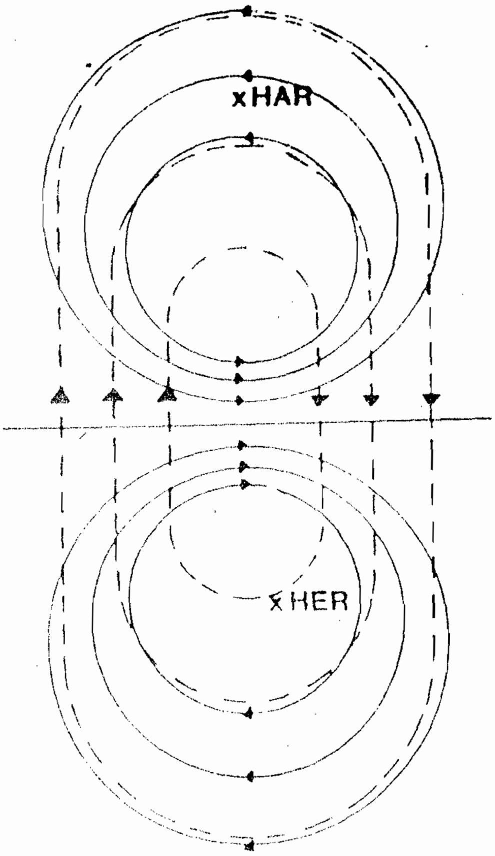

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(b) The study of the correlations of ΔH at all hours at 7 stations in a narrow longitude sector in the equatorial region by Onwumechili and Ezema (2000a) has shown that the diurnal variations of the correlation coefficients depend on the locations of the two stations whose data are being correlated as in Fig. 12a and Fig.12b When the

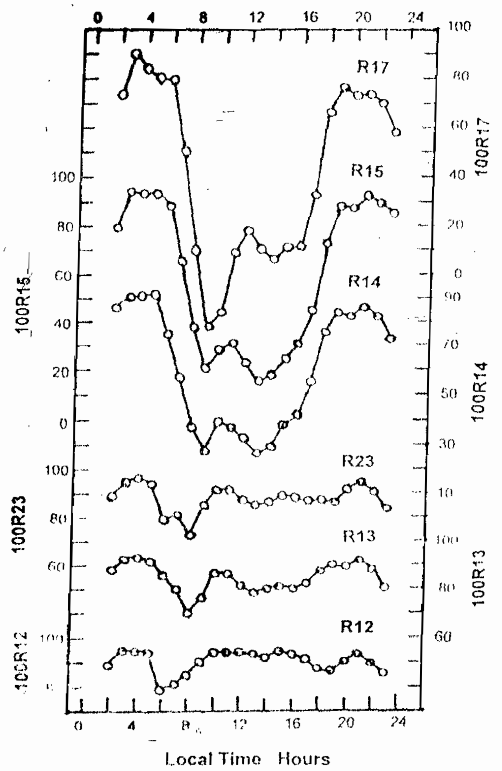

Fig 12a. The diurnal variation of correlation coefficients Rmm **between ΔH on quiet days** at station m and station n, referring to the stations: 1 *Trivandrum* **(dip** latitude $\delta = 0.20^0$), 2 *Kodaikandal* ($\delta = 2.14^0$), 3 Annamalainagar **($\delta = 3.28^0$), 4** *Hyderabad* ($\delta = 9.33^0$), 5 Alibag ($\delta = 10.54^0$), 6 Ujjain (δ = **15.09⁰), and 7 Jaipur (δ** = 18 83⁰). The correlation coefficients are multiplied by 100. **After Onwumechili** and Ezema (2000a).

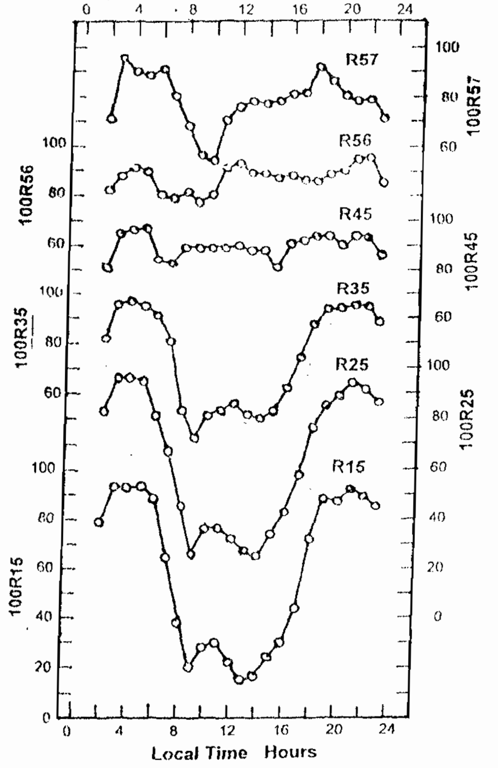

Fig. 12b. The diurnal variation of the correlation coefficients between Aliibag and six other stations. The correlation *coefficients Rmm* between ΔH on quite days at *station m* and station n, referring to the stations: 1 Trivandrum (dip latitude $\delta = 0.20^0$), 2 Kodaikandal ($\delta = 2.14^0$), 3 Annamalainagar ($\delta = 3.28^0$), 4 Hyderabad ($\delta = 9.33^0$), 5 Alibag ($\delta = 10.54^0$), 6 Ujjain ($\delta = 15.09^0$), and 7 *Jaipur* ($\delta = 18.83^0$). The correlation coefficients are multiplied by 100. After Onwumechili and Ezema (2000a).

two stations are in the equatorial electrojet (EEJ) **zone** (E-E stations) and when both are in the **worldwide** part of Sq(WSq) zone (L-L stations), the correlation coefficients are steadily very high and positive at all hours. When one station is in the EEJ zone and the other station is in the WSq zone (E-L stations), the correlation coefficients remain very high and positive in nighttime, but fall drastically to low and often insignificant or even slightly negative values in daytime. In Figs. 12a and 12b, the E-E pairs of stations are represented by R12, R13 and R23, the E-L pairs of stations are represented by R14, R15, R17, R25, and R35, and L-L pairs of stations are represented by R45, R56 and R57.

(c) Horizontal magnetic field, SPMF(H), superposed on the monthly mean Sq(H) to compose the diurnal profile of Sq(H) on a given quiet day, has been found to be complex. In effect, the SPMF(H) is a sequence of the differences, hour by hour, between the diurnal profile of ΔH on a given quiet day and the profile of mean ΔH on the five quietest days of the month. The SPMF(H) is therefore relative to the monthly mean ΔH. Its complex diurnal pattern varies from day to day and can be different at two stations on the same longitude. However, the pattern in a narrow longitude sector, on a given quiet day has been found to be very similar at all the stations in the EEJ zone and very similar at all the stations in the WSq zone outside the influence of the EEJ (Onwumechili and Ezema 2000b). All the 9 possible categories of the patterns of SPMF(H) in the EEJ zone vis-à-vis the SPMF(H) in WSq zone have been found with their occurrence frequencies listed in Table 2. It shows that the intensities of the EEJ and the WSq currents systems vary independently. In particular, variations of the intensities of the EEJ and the WSq current systems in phase and in antiphase respectively, as in Fig. 13a, Fig. 13b and Fig. 13c, are found to occur with about equal frequency.

The VIEW 1 and VIEW 2 should explain these results based on observational data in (a), (b), and (c).

The explanations of VIEW 1 are as follows. Whatever the winds of whatever origins or changes in conductivity that cause hour to hour and day to day changes in the environment of Sq current systems, there are two ionospheric current layers as found by rockets in the dip equatorial zone. The determinants of ionospheric current intensity like the wind W, the ambient magnetic field B, the magnetic dip angle I, the plasma density N, the temperature T, the gyrofrequency ω, the collision frequency ν, and the height h km of the current layer are different at the two current layers. This is because the two current layers are separated in altitude and latitude, and their latitude extents are also different. Therefore the changes in the current intensities of the two current layers can also be different and even independent.

From section 2.3 and Eq. 3, the horizontal magnetic perturbation caused by current intensity changes in the two current layers are $\Delta H_E+\Delta H_w$ at an E station in EEJ zone but only ΔH_w at an L station in WSq zone. Thus, E-E pair of stations correlate very well because both record $\Delta H_E + \Delta H_w$ and an L-L pair of stations correlate very well because both record ΔH_w. But for E-L pair of stations, we are correlating $\Delta H_E + \Delta H_w$ with ΔH_w. There is some small correlation because of the element of ΔH_w recorded at both stations. However, the correlation is poor because changes in ΔH_E are recorded at the E station but not at the L station. Therefore, E-L pairs of stations are significantly less correlated than E-E and L-L pairs of stations as established by correlation studies in part (a) above.

In part (b) we face the diurnal profiles of the correlation coefficients of 124 quiet days with Ap ≤ 6. The correlation coefficients for E-E and L-L pairs of stations are positive and steadily very high at all hours because both stations are under the same current layers and record the same changes in current intensities and resultant ΔH. In nighttime, the correlation coefficients of E-L pairs of stations are positive and steadily very high because very small if any currents flow in the dynamo altitudes at night and the EEJ(lower)current layer is absent. Thus at night. both stations are under the same currents of mainly magnetospheric origin and therefore they record the same changes in resultant ΔH and correlate very highly. But in daytime when ionospheric currents dominate, the E station is under both the EEJ(lower) current layer occasionally modulated by the CEJ, and the WSq (upper) current layer. Whereas the L station is only under the WSq(upper) current layer occasionally modulated by the single vortex current (SVC) system arising from midlatitude abnormal phase quiet days (APQDs). Therefore the correlation coefficient for E-L pairs of stations drastically falls in daytime to mostly insignificant and even slightly negative values because of the mismatch of current intensity changes in the lower and upper current layers.

In part © we face case studies of patterns of changes of current intensities on 135 quiet days with Ap ≤ 6, as seen from SPMF(H); being the sequence of hourly differences between the ΔH on a given quiet day and the mean ΔH from the 5

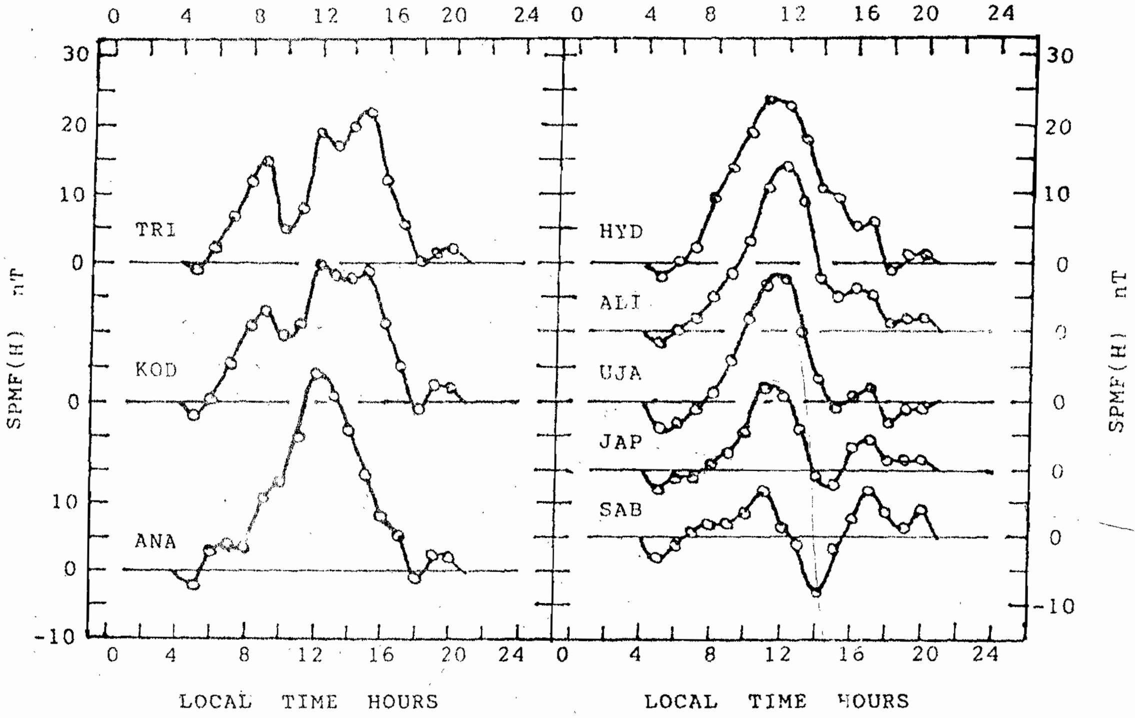

Fig.13a Diurnal variation of the horizontal magnetic field, SPMF (H), superposed on the monthly mean Sq(H), on the quiet day, 2 February 1986 Ap ≤ 6, at 8 observatories: 1 Trivandrum (TRI, dip latitude $\delta = 0.20^0$), 2 Kodaikanal(KCD), $\delta = 2.14^0$), 3 Annmalainagar (ANA, $\delta = 3.28^0$), 4 Hyderabad (HYD, $\delta = 9.33$), 5 Alibag (ALI, $\delta = 10.54^0$), 6 Ujjain(UJA, $\delta = 15.09^0$), 7 Juipur(JAP, $\delta = 18.83^0$) and Sabhawala(SAB, $\delta = 22.28^0$) After Onwumechili and Ezema (2000b)

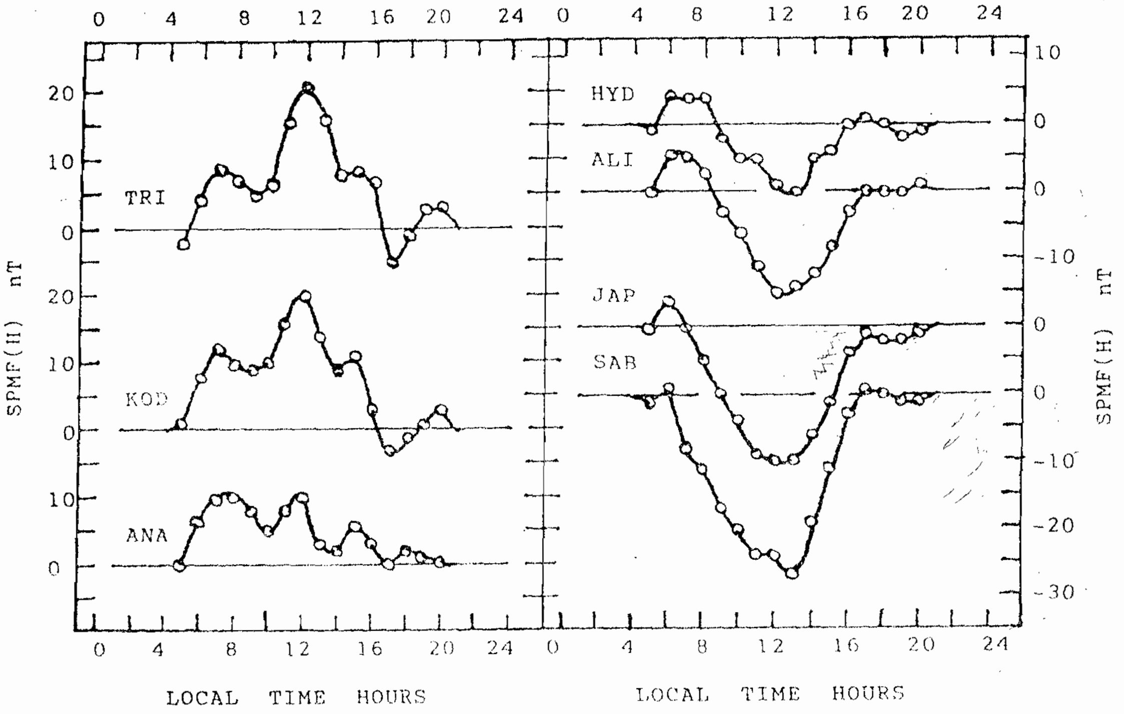

Fig. 13b. Same as for Fig. 13a but for 10 July 1986 Ap 6. Note missing Ujjain data.

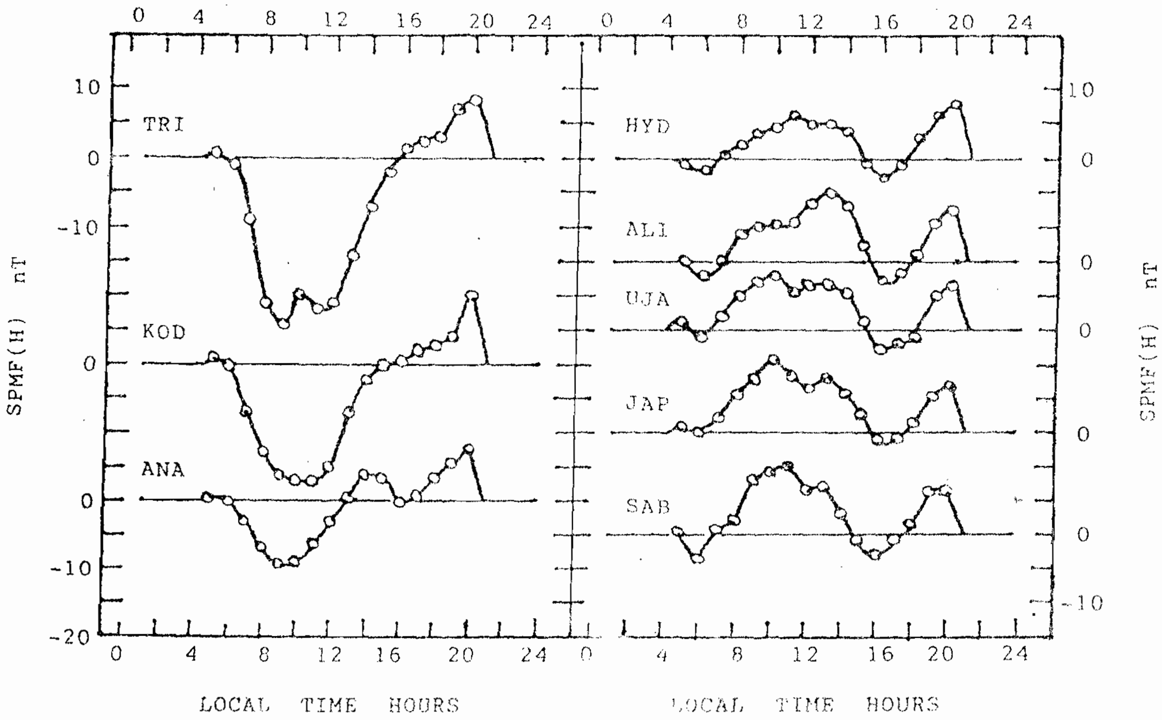

Fig. 13c. Same as for Fig. 13a but for 26 October 1986, Ap 3

quietest days of each month. The station in the EEJ zone are under both the EEJ (lower) current layer occasionally modulated by the CEJ, and the WSq (upper) current layer.

Whereas the stations in the WSq zone are only under the WSq (upper) current layer occasionally modulated by the single vortex current (SVC) system arising from midlatitude abnormal phase quiet days (APQDs). Therefore the patterns of SPMF(H) are similar at the stations in EEJ zone because these E stations are all under the same current layers. In the same way the patterns of SPMF are the same at the stations in WSq zone because these L stations are under the same

Table 2: Nine categories of superposed magnetic field (SPMF) status.

Category	Symbols	Meaning	Percentage Occurrence
1	EEJE with WsqE	Enhanced EEJ with Enhanced WSq	7
2	EEJE with WSqM	Enhanced EEJ with Mean WSq	17
3	EEJE with WSqR	Enhanced EEJ with Reduced WSq	7
4	EEJM with WSqE	Mean EEJ with Enhanced WSq	10
5	EEJM with WSqM	Mean EEJ with Mean WSq	28
6	EEJM with WSqR	Mean EEJ with Reduced WSq	6
7	EEJR with WSqE	Reduced EEJ with Enhanced WSq	6
8	EEJR with WSqM	Reduced EEJ with Mean WSq	12
9	EEJR with WSqR	Reduced EEJ with Reduced WSq	7

current layers. But the patterns of SPMF are different between the stations in the EEJ zone and the stations in the WSq zone because of the mismatch of current intensity changes in the lower current layer at the E stations and in the upper current layer at the L stations. The status of the SPMF(H) pattern can be Enhanced relative to the monthly mean Sq(H) and this is symbolized as EEJE in EEJ zone and WSqE in WSq zone. When the status of SPMF(H) pattern is Reduced relative to the monthly mean Sq(H) it is symbolized as EEJR in the EEJ zone and WSqR in the WSq zone. But if the SPMF(H) is neither Enhanced nor Reduced relative to the monthly mean Sq(H), its status is symbolized as EEJM in the EEJ zone and WSqM in the WSq zone. There are only 9 possible ways of associating one of the three statuses in EEJ zone with one of the three statuses in WSq zone. The percentage occurrence frequencies of these 9 categories in Table 2 are interesting.

Only four of the five categories involving the Mean status of SPMF(H) have occurrence frequencies greater than the others. This is because the condition for classifying the Sq(H) on a quiet day as different from the monthly mean Sq(H) was purposely made stringent to ensure that the Enhanced and Reduced statuses are clearly different from the Mean status. Consequently, many days fell into the Mean status. All the four categories not involving the Mean status have about equal percentage occurrence frequencies. These are (1) EEJE with WSqE 7%, (3) EEJ with WSqR 7%, (7) EEJR with WSqE 6%, and (9) EEJR with WSqR 7%. Therefore there is no evidence that any category naturally occurs preferentially. It is concluded that the current intensity of the EEJ(lower) current layer and the current intensity of the WSq(upper) current layer change independently.

We now illustrate the case studies with three categories. (i) The Fig. 13a shows category 1 in which the SPMF(H) is enhanced in both EEJ zone and WSq zone on 2 February 1986, Ap=6. This would be expected by conventional wisdom. We however note that the sudden drop in current intensity of the EEJ(lower) current layer about 10 L.T. and 11 L.T. did not occur in the WSq (upper) current layer. Its perturbation of ΔH was therefore confined to the EEJ zone. The magnitude of the perturbation decreased with latitude from Trivandrum to Annamalainagar in the same way as ΔH_E. (ii) The Fig. 13b shows the case of a category 3 diurnal profile of SPMF(H) on 10 July 1986 Ap=6, when the SPMF(H) was enhanced in EEJ zone but was reduced in WSq zone relative to the monthly mean Sq(H). Here the current intensity changes in the EEJ (lower) current layer and the WSq (upper) current layer in midlatitudes occurred in anti-phase. Such a case would not have been observed if changes in the WSq current system in midlatitudes were linked to the changes in EEJ current system at the equator, but we have seen that they are independent. (iii) The fig. 13c for 26 October 1986, Ap=3, illustrates the case of category 7 which is the opposite of category 3. Here, the reduction in the current intensity of EEJ (lower) current layer occurs in anti-phase with the enhancement of the WSq(upper) current layer.

We cite the explanations of VIEW 2 from RJS95. The EEJ is "an enhancement of the Sq current at the magnetic dip equator with its variations linked to the changes at higher latitudes". However, "A 'random component' system represents day to day variations in the EEJ with the lunar component removed. The (random component) current system 'focus' is near 10^0 to 15^0 latitude and the strength is about 1/3 that of the Sq system.. So the local emfs at low latitudes are driving currents in the opposite direction to the EEJ. These emfs, which may be quite variable if the (2, 2) mode plays a big part,...may also be the cause of the poor correlations often found between geomagnetic variations at stations under the EEJ and those at low latitudes outside it. ..While statistically the correlation coefficients quoted in the figure are 'highly significant', the plots show a large scatter".

We make the following comments on the explanations of VIEW 2. On the premise that ionospheric currents flow in one current layer, VIEW 2 states that current intensity changes in higher latitudes are linked to EEJ at the dip equator and vice versa. Since VIEW 2 does not admit the existence of two current layers at different altitudes, we assume that the random component collocates with the main Sq current system of VIEW 2. In which case, both the main Sq current system and the random component circulate in the same current loops to create a resultant Sq current system. So if the local emfs were to drive currents opposing the EEJ current, this would reduce the current in the part of the loops in the EEJ zone. And since the loops are the same for the resultant Sq current system, the current intensity reduction would be linked to higher latitudes through the same loops as is in fact stated in the first sentence of the explanations. If this were correct, the diurnal profile of the correlation coefficients for E-L pairs of stations would not have been as observed.

Also, in the case studies, only categories 1, 5, and 9 would be seen. The other 6 categories would not have existed, especially categories 3 and 7 in which the current intensities vary in anti-phase in the dip equatorial and midlatitude regions.

DISCUSSIONS

The two views on the structure of ionospheric currents agree that atmospheric winds can generate electric field. But electric fields in the ionosphere are of tidal, gravity wave or magnetospheric origins. They both agree that ionospheric current flows where there is conductivity, and such currents must have return paths. Their major difference is whether the ionospheric currents in the dip equatorial zone flow in one or two layers. This difference has implications on the distribution of ionospheric currents including on where and how the currents return. The two views have attempted explanations of 11 experimental results, in section 2, relevant to the structure of ionospheric currents. We now discuss their performances therein starting with VIEW 1.

The View 1 has no problem in demonstrating its viability because it is based on experimental and observational results. The ionosphere is pervaded by electric fields. All the electric fields at a point from local, regional, and global winds and from any other sources combine into a resultant electric field. There is only one current density at that point driven by the resultant electric field and supported by the conductivity at that point. As the inputs supporting that current density at that point change the current density varies from hour to hour and day to day. The conductivity, resultant electric field and therefore the current density also vary principally with altitude and latitude. Because of the peculiar altitude distribution of conductivity, resultant electric field and current density in the dip equatorial region, two current layers exist in the region at two altitude ranges as observed by rockets. Following this scenario, VIEW 1 has given simple and consistent explanations regarding all the 11 experimental and observational results in section 2 without quibbling and or ad hoc revisions of its core tenets.

We now discuss the performance of VIEW 2. A core tenet of VIEW 2 is that there is only one relatively constant current system in one current layer, including both the EEJ and Sq, with other superposed current systems mostly driven by semidiurnal tides. The constant current system idea probably comes from MacDougall (1979b) who suggested a current system constant in form and amplitude throughout the year. A current system constant in form, amplitude and phase is difficult to imagine. What winds constant in form amplitude and phase can generate the electric fields constant in form, amplitude and phase that drive the constant current system? It does not appear feasible. But even if it were, it would raise a fundamental question. The current function from which Sq current systems are derived is a potential whose constant is indeterminate. Consequently, Sq currents have no unique baseline. How then can the constant current system be distinguished from the indeterminate baseline of Sq currents?

In section 2.1, VIEW 2 has no explanation but simply denies the existence of two ionospheric current layers in the dip equatorial zone. However, most rockets have measured the two layers and numerical model calculations have successfully simulated them. In section 2.9, VIEW 2 similarly denies the existence of intensification during contraction of EEJ. However, rockets have observed the phenomenon. It has been confirmed by calculations with observed winds and electron density, and by simulations with model winds. Therefore, VIEW 2 has completely failed with regard to these two experimental results.

All the conjectured explanations of the 9 other experimental results by VIEW 2 are based on semidiurnal tides namely, (2, 2), (2, 3) and (2, 4). It is difficult to accept these conjectures for a number of reasons. (i) The amplitudes of semidiurnal oscillations are less dependent on latitude than the amplitudes of diurnal oscillations (Forbes 1981). Semidiurnal winds are therefore not suitable for the explanation of the short range changes of current and other events confined to the narrow EEJ zone of about -4^0 to 4^0 dip latitude.

(ii) Perhaps the most comprehensive diagnostic study is the three-dimensional calculations of the diurnal, latitudinal and vertical variations of Sq EEJ and polarization electric field by Forbes and Lindzen (1976ab, 1977). They obtained good reproductions of the mean and harmonic components of ground magnetic Sq and EEJ with the combination of (1, -2) + (1, 1) + (2, 2) + (2, 4) modes, sometimes including prevailing and local winds. Forbes and Lindzen (1976a) stated, "Although the (1, -2)mode accounts for most of the observed variation at the equator, it is evident that the addition of semidiurnal winds produces a better fit to the data, particularly the terdiurnal component. Semidiurnal winds have relatively little effect on the amplitudes of the diurnal and mean magnetic components. The inefficiency of (2, 2) and (2, 4) to produce low-harmonic current is primarily attributable to weak coupling with low-order harmonics of the conductivity." The (1, 1) mode improves particularly the fitting of vertical structures. Forbes and Lindzen (1877) added, "The theoretical electric field consists of about equal and semidiurnal components, whereas the observed field is almost entirely diurnal(amplitude of 0.50mV/m) with small (≈0.06mV/m) mean and semidiurnal harmonics. It is therefore extremely doubtful that the semidiurnal modes can muster large enough magnitude to account for the explanations VIEW 2 attributes to them.

(iii) Perhaps VIEW 2 sticks to the upward propagating tides because of their variability. But the observed mean and diurnal winds are similarly variable (Glass et al 1978). In particular, after removing semidiurnal oscillations from observed winds Salah(1994) found large day to day variability of E region winds from about 100km to 120 km altitude. The most outstanding features of observed diurnal tide are their day to day variabilities (Forbes 1982a). The day to day variability is about 100% of the mean oscillation in the altitude range of 100-120 km and at least 50% at other altitudes. The diurnal dominates the semidiurnal up to the altitudes of about 120 km. The day to day variabilities of observed diurnal winds have been reported by Harper (1981) and Manson et al. (1991). Importantly, Manson et al. (1991) reported that equatorial model calculations differ substantially from observations. In the light of all the above, how can VIEW 2 demonstrate (a) that the dynamo effects of diurnal wind variabilities do not dominate those of semidiurnal winds; and (b) that its model calculations do not differ substantially from equatorial realities?

(iv) It is noted that virtually all the explanations of VIEW 2 are tentative and vague phrases like,"easy to conceive local wind structure", 'is likely to yield", there may or may not be," 'may be quite variable if the (2, 2) plays a big part"; "an alternative explanation may be," "with suitable tidal modes", "possibly associated with a semidiurnal tide", and so on. These hedging phrases are borne out of deep-seated uncertainties surrounding the explanations. Indeed, Stening (1981) conceded, "After many years of research we are still not certain which tidal modes are mainly responsible for the winds which drive Sq current system". He also conceded that the use of simple tidal modes to describe winds in dynamo region is questionable. Similarly, Forbes and Lindzen (1976a) stated, "these diagnostic studies are not definitive since the chosen wind models are shown to be unrealistic by recent experimental data and theoretical advancements in dissipative tidal theory.' Since recent experimental data and advances in tidal theory show that its chosen wind models are unrealistic, how can VIEW 2 demonstrate that the results of its calculations from the unrealistic wind models are also not unrealistic?

(v) It is important to note that in the real thermosphere, the variables of Laplace's tidal equation are not separable as assumed by classical tidal theory leading to the modes. Consequently, the Hough tidal modes cease to be distinct and are said to be coupled together (Lindzen et al. 1977, Forbes and Hagan 1982, Forbes 1984). Forbes (1982b) summarizes that the real (ie coupled) semidiurnal component, (a) between 90 km to 120 km altitude is mostly (2, 4) with some contributions from (2, 5) and (2, 2) modes, and (b) above 140 km altitude is predominantly (2, 2) with secondary contributions from (2, 3) and (2, 5) modes. Thus in the essential altitude range of Sq currents, the tidal modes conjectured by View 2 cannot exist as distinct modes and are dominated by (2, 4) mode Therefore the explanations of VIEW 2 based on these non-distinct modes are not tenable in reality.

(vi) The key changes in the quiet time intensity of EEJ and CEJ have been attributed to the presence of gravity waves in the measured winds by a number of authors. Anandarao (1976) concluded that gravity waves are mostly present in the 90 km to 110 km region of winds measured by Rees et al. (1976) at Thumba. Raghavarao and Anadarao (1987) conclude: "It is shown that local winds alter the structure of EEJ currents in the zonal and meridional directions by as much as 70 to 100%. As the measured winds are irregular revealing winds of gravity wave origin, the EEJ current structure in latitude and height, is expected to undergo dynamic changes on even magnetically quiet days".

Gravity waves are also involved in the zonal winds that distort and reverse the height structure of EEJ (Somayajulu et al, 1994), and in the vertical winds that reverse the EEJ (Raghavarao and Anandarao 1980) during the formation of CEJ. Other citings of the influence of gravity waves in EEJ zone include Forbes(1981) at Huancayo, Gonzales et al. (1983) at Jamaica. Somayajulu et al. (1980) at Thumba and Pandey et al.(1982) at Thumba. Similar changes outside EEJ zone include Harper (1981) and Gonzales et al. (1983) for day to day and shorter period variations of the electric field at Arecibo, while Manson et al. (1991) declare generally that gravity wave distortions of tides has now been well demonstrated. These two paragraphs of (vi) show that gravity waves are more likely to explain the key current intensity changes in EEJ zone than any semidiurnal tidal mode. Yet VIEW 2 relies on semidiurnal tidal mode winds excluding gravity wave winds.

(vii) Wind studies have amply shown that the mean and diurnal components of measured winds exhibit large changes from hour to hour, day to day and season to season. Therefore, there are no real winds that can produce the constant electric field that will drive the constant current system proposed as the basis of VIEW 2

(viii) Earle and Kelly(1987) established that the source for changes of zonal electric field E_y at Jicamarca in the period range of 1 to 10 hours, is magnetospheric when Kp>3 but atmospheric when Kp<3. They find that on disturbed days, 11 October 1980, Ap = 40, and 23 October, Ap=44, fluctuations in E, in this period range at Jicamarca (12^0S, dip latitude 1.0^0) and Arecibo(18.3^0N, dip latitude 32.1^0) are highly correlated. But on quiet day 16 October 1980, Ap = 3 the fluctuations have very low correlation. They conclude that the fluctuations on 16 October 1980 are of atmospheric gravity wave origin. Therefore, on a quiet day, changes in zonal electric field inside and outside the EEJ zone can be independent as in this case.

The observation of Earle and Kelly (1987) on the quiet day 16 October 1980 is an important test for the VIEW 1 and VIEW 2. Fluctuations in the period range of 1 to 10 hours are in the same range as the perturbations in Figs. 13a, 13b, and 13c. The perturbations in the eastward current density and horizontal magnetic field ΔH at Jicamarca in EEJ zone: and the perturbations at Arecibo in WSq zone, on the quiet day 16 October 1980, would be independent like the fluctuations in the zonal electric field that caused them. This would fully agree with the correlation results discussed in section 2.11 as shown in Figs. 12a, 12b. It would also agree with VIEW 1 on the conclusion from the case studies that current intensity changes in the EEJ and WSq current layers are independent. See the outcome of the independence in Table 2 but only 3 of the 9 categories are illustrated in Figs. 13a, 13b and 13c. But if VIEW 2 were correct, the perturbations in eastward current intensity and ΔH at Jicamarca in EEJ zone and at Arecibo in WSq zone caused by the zonal electric field fluctuations would be linked through the only current loop of its single current system. The results in Figs 12a and 12b and in Table 2 would not have existed and only categories 1, 5 and 9 would be observed. It is clear that VIEW 2 fails.

(ix) As cited in section 2.7, Stening (1977) listed 4 expected outcomes to test his hypothesis that CEJ current returns poleward of Sq focus. He claimed that only 2 out of 8 days presented showed the expected outcomes Surprisingly, he still concluded that the hypothesis was correct. However, even the two days, 13 and 14 January 1964, also failed because what he interpreted as the expected outcomes were the effects of Sq focus movements. Therefore the hypothesis failed completely. Once more, the linkage VIEW 2 expects between EEJ and CEJ with perturbations in higher latitudes has not been observed.

(x) There are not many attempts to directly link the variabilities of wind and ΔH perturbations Philips and Briggs, (1991) made a comprehensive attempt to correlate ionospheric winds recorded at Buckland Park (35°S, 138°E) with ΔH recorded at Camberra (35°S, 149°E) and Port Moresby(9°S, 147°E). Cross correlation functions were computed for lags of ±60days for the following pairs; (u_1, v_1) the diurnal components of zonal and meridional winds, (u_2, v_2) the semidiurnal components of zonal and meridional winds, (u_1, u_2), (v_1, v_2), (ΔH, u_1),(ΔH, v_1),(ΔH, u_2) and (ΔH, v_2) None of the last 6 pairs revealed any correlation. Stening et al. (1996) found that CEJ at Trivandum in India, and the minimum of eastward mean wind at Saskatoon in Canada, occurred within 2 days of each other for most of the cases selected in winter. On the other hand, no such connection was found between them in summer, when the CEJ is most frequent at Trivandum. Also there was no consistent behavior between the winds at Adelaide in Australia, and CEJ in Trivandum. They therefore remarked; 'It is the authors' belief that the CEJs are driven by a global tide; probably semidiurnal, which has amplitude and/or phase which differs from the normal during CEJ. The data presented have not proven this idea". Therefore one to one correspondence between changes in the wind and ΔH perturbations has not been observed. Also there is no proof that day-to-day changes in winds at higher latitudes and ΔH perturbations at the equator are correlated. Therefore, all the attempts of VIEW 2 to link ΔH perturbations at the equator with tidal mode winds have not been observed. It remains conventional wisdom.

It emerges that VIEW 2 has serious feasibility problems. To raise its vague and tentative suggestions from the level of conjectures to acceptable explanations, it needs to: (a) Demonstrate that real winds exist and have been observed which are constant in amplitude and phase that produce the electric fields; constant in amplitude and phase all through the year, which drive the constant current system it relies on. (b) Demonstrate that a real wind can exist and has been observed which is made up of only one distinct semidiurnal tidal mode. (c) Demonstrate that in a real wind, one semidiurnal tidal mode that is normally of little or no consequence to Sq and is mode-coupled with other semidiurnal modes, can incredibly generate large Sq currents that will dominate the currents due to the mean, the diurnal and the gravity wave components of the real wind. The same remark applies to variations in the wind components and the currents due to them, especially as the (2, 4) is the dominant partner in the coupled semidiurnal mode in Sq dynamo altitudes. (d) Demonstrate that contrary to the observations and views in (vi) above, the key changes in local winds and magnetic fields of EEJ and CEJ found by the authors are not due to gravity wave winds but to a semidiurnal tidal mode wind. (e) Demonstrate or cite direct linkage based on observed data, between day to day or hour to hour perturbations of quiet time ΔB and semidiurnal tidal mode.

CONCLUSIONS.

The differing views on the structure of ionospheric currents symbolized as VIEW 1 and VIEW 2 are given in section 1. Such differing scientific views are assessed by the extent to which they elucidate experimental results. Accordingly, the explanations of 11 experimental results by VIEW 1 and VIEW 2 have been presented side by side in section 2.

The explanations and discussions of the performances of VIEW 1 and VIEW 2 led to the review of quite a number of papers, turning out interesting results. What emerges is that feasibility of the bases and vague explanations of VIEW 2 are doubtful. Furthermore, VIEW 2 merely denied the existence of two out of the 11 experimental results, despite their having been observed by rockets.

RJS95 suggested at least three hypothetical ways of separating ionospheric currents into components. They are all based on conjectures and are different from View 1. Again, some of them face feasibility problems like View 2. We prefer VIEW 1, which is firmly based on experimental measurements, and offers natural and simple explanations of experimental results so far

REFERENCES

Anandarao, B.G., 1979. Effects of gravity wave winds and wind shears on equatorial ect. Geophys. Res. Lett., 3: 545-548.

Anaandarao, B.G. and Raghavarao, R. 1979. Effects of vertical shears in the zonal winds on the electrojet. Space Res. XIX: 283-286.

Bhargava, B.N.and Sastri, N.S. 1977. A comparison of days with and without occurrence of counter electrojet afternoon events in the Indian region, Ann. Geophys. 33: 329 – 332.

Butcher, E.C. 1982, An investigation of the causes of abnormal quiet days in Sq (H) Geophys. J.R. astr. Soc. 69: 101-111.

Cahill, L.J. 1959. Investigation of the equatorial electrojet by rocket magnetometer, J. Geophys. Res. 64: 489-503.

Cain, J.C. and Sweeney, R.E. 1973. The POGO data. J.Atmos. Terr. Phys. 35 1231-1247.

Campbell, W.H. 1989. The Regular Geomagnetic Field Variations During Quiet Solar Conditions. Vol. 3, Chap 3: 285-460, in Geomagnetism ed.J.A. Jacobs. Academic Press, London.

Champion, K.S.W. and Forbes, J.M. 1978. Some recent mesospheric and lower thermospheric data and models, Ann. Geophys. 34: 285.

Earle, G.D. and Kelley, M.C. Spectral studies of ionospheric electric fields, J. Geophys. Res. 92 212-224.

Ezema, P.O. Onwumechili, C.A. and Oko, S.O. 1996. Geomagnetically quiet day ionospheric currents over the Indian sector-III. Counter equatorial electrojet currents, J. Atmos. Terr. Phys., 38: 1 17.

Fambitakoye, O. Mayaud, P.N. and Richmond, A.D, 1976. Equatorial electrojet and regular daily variation SR I.A determination of the equatorial electrojet parameters, J. Atoms. Terr. Phys. 38: 1-17.

Fambitakoye, O. Mayaud, P.N. and Richmond, A.D., 1976. Equatorial electrojet and regular daily variation SR III Comparison of observations with a physical model, J. Atoms. Terr., 38: 113 121.

Forbes, J.M., 1981. The equatorial electrojet, Rev. Geophys. Space Phys., 19: 469-504.

Forbes, J.M. 1982a. Atmospheric tides-1. Model description and results for the Solar diurnal component, J. Geophys. Res. 87: 5222-5240.

Forbes, J.M. 1982b. Atmospheric tides-2. The Solar and lunar semidiurnal components, J.Geophys. Res. 87: 5241-5252.

Forbes J.M. 1984. Moddle atmosphere tides. J. Atmos. Terr. Phys. 46:1049-1067.

Forbes, J.M and Hagan, M.E. 1982. Thermospheric extensions of the classical expansion functions for semidiurnal tides, J. Geophys. Res. 87: 5253-5259

Forbes, J.M. and Lindzen, R.S. 1976a. Atmospheric solar tides and their electrodynamic effects-1. The Equatorial Electrojet, J. Atmos. Terr. Phys. 38: 897-910.

Forbes, J.M. and Lindzen, R.S., 1977. Atmospheric tides and their electrodynamic effects-II. The polarization electric field, J. Atmos. Terr. Phys.,39: 1369-1377.

Forbush, S.E. and Casaverde, M., 1961. The Equatorial Electrojet in Peru, Carnegie Institution of Washington Publication No.620: 135pp.

Glass, M., Bernard, R., Fellous, J.L. and Massebeuf, M., 1978. The French meteor radar facility, J. Atmos. Terr. Phys.; 40: 923-931.

Gonzales, C.A., Kelley, M.C., Behnke, R.A., Vickery, J.F., Wand, R. and Holt, J., 1983. On the latitudinal variations of ionospheric electric field during magnetospheric disturbances. J. Geophys Res., 88: 9135-9144.

Hanuise, C., Mazaudier, C., Villa, P., Blane, M. and Crochet, M., 1983. Global dynamo simulation of ionospheric currents and their connection with the equatorial electrojet and counter electrojet: a case study, J. Geophys. Res., 88: 253-270

Harper, R.M. 1977. A comparison of ionospheric currents, magnetic variations and electric fields at Arecibo, J. Geophys. Res., 82: 3233-3242.

Harper, R.M., 1981. Some results of mean tidal structure and day to day variability over Arecibo, J. Atmos. Terr. Phys., 43: 255-262.

Hesse, D., 1982. An investigation of the equatorial electrojet by means of ground-based magnetic measurements. Ann. Geophys., 38: 315-32.

Hutton, R., 1967. Sq currents in the American equatorial zone during the IGY-I. Seasonal effects. J, Atmos. Terr. Phys., 29: 1411-1427.

Kane, R.P., 1971. Relationship between H ranges at equatorial and middle latitudes, J. Atmos Terr. Phys., 33, 319-327.

Kane, R.P., 1976. Dilema of the equatorial counter electrojet and the disappearance of I sq., Indian J. Rad. Space Phys., 5: 6-12.

Lindzen, R.S., Hong, S.S. and Forbes, J.M., 1977. Semidiurnal Hough mode extension into the thermosphere and their application. Menso. Rep. 3442, Naval Res. Lab., Washington D.C.

MacDougall, J.W., 1969. The equatorial ionospheric anomaly and the equatorial electrojet Radio Science, 4, 805-810.

MacDougall, J.W., 1979a. Equatorial electorjet and Sq current system – Part I, J. Geomag. Geoelectr., 31: 341-357.

MacDougall, J.W., 1979b. Equatorial electrojet and Sq current system – Part II, J. Geomag. Geoelectr., 31: 359-372.

Maeda, H., 1955. Horizontal wind systems in the ionospheric E region deduced from the dynamo theory of the geomagnetic Sq variation – I, J. Geomag. Geoelectr., 7: 121-132.

Mann, R.J. and Schlapp, D.M., 1985. The equatorial electrojet and the day-to-day variability of Sq, J. R. astr. Soc., 80: 535-540.

Mann, R.J. and Schlapp, D.M., 1988. The equatorial electrojet and the day-to-day variability of Sq, J. Atmos. Terr. Phys., 50: 57-62.

Manson, A.H., Meek, C.E., Avery, S.K., Fraser, G.J., Vincent, R.A., Philips, A., Clerk, R.R., Schminder, R., Kurschner, D. and Kazimirovsky, E.S., 1991. Tidal winds form the mesosphere, lower thermosphere global radar network during the second LTCS campaign: December 1988, J. Geophys. Res.: 1117-1127.

Marriot, R.T., Richmond, A.D. and Venkateswaram, S.V., 1979. The quiet time equatorial electrojet and counter electrojet, J. Geomag. Geoelectr., 31: 311-340.

Matsushita, S., 1967. Solar quiet and lunar daily variation fields, Vol. I, Chap. III-1: 301-424 in Physics of Geomagnetic Phenomena, ed. Matsushita S. and Campbell W.H., Academic Press, New York.

Maynard, N.C., 1967. Measurement of ionospheric currents off the coast of Peru, J. Geophys. Res., 72: 1863-1875.

Maynard, N.C. and Cahill, L.J. Jr., 1965. Measurement of the equatorial electrojet over India, J. Geophys. Res., 70: 5923-5936.

Musmann, G. and Seiler, E., 1978. Detection of meridional currents in the equatorial ionosphere, J. Geophys., 44: 357-372.

Oko, S.O., Onwumechili, C.A. and Ezema, P.O., 1996. Geomagnetically quiet day ionospheric currents over the Indian sector-II. Equatorial electrojet currents, J . Atmos. Terr. Phys., 58: 555-564.

Oldenburgh, D.W., 1976. Ionospheric current structure as determined from ground-based magnetometer data, Geophys. J. R. astr. Soc., 46: 41-66.

Onwumechili, C.A., 1992a. Study of the return current of the equatorial electrojet, J. Geomag. Geoelectr., 44: 1-42.

Sastri, N.S. and Bhargava, B.N., 1980. Geomagnetic effects of the equatorial counter electrojet and their extension to non-equatorial latitudes, J. Geomag., Geoelectr., 32: 333-340.

Sastri, N.S., Arora, B.R. and Rao, D.K.R., 1982. Effect of the equatorial counter electrojet in the Indian region on the geomagnetic solar and lunar daily variations, Ann. Geophys., 38: 321-325.

Sastry, T.S.G., 1970. Diurnal change in the parameters of the equatorial electrojet as observed by rocket borne magnetometers, Space Res., X: 778-785.

Schlapp, D.M., Mann, R.J. and Butcher, E.C., 1988. On the relation between days of small amplitude of Sq(H) and abnormal quiet days, Geophys.J.R. astr. Soc., 95: 633-639.

Shumann, B.M., 1970. Rocket measurement of the equatorial electrojet, J. Geophys. Res., 75: 3889-3901.

Singh, A. and Cole, K.D., 1987. A numerical model of the ionospheric dynamo-II. Electrostatic field at equatorial and low latitudes, J. Atmos. Terr. Phys., 49: 529-537.

Somayajulu, V.V., Reddy, C.A. and Viswanathan, K.S., 1980. Low latitude Aeronomical processes (Advances in Space Exploration), Vol. 8, p.25, Ed. A.P. Mitra, Pergamon Press, Oxford.

Somayajulu, V.V., Cherian, L., Ramakumar, G. and Reddi, C.R., 1993. Mean winds and tidal components at the equator during counter electrojet events, Revista Brasileira., 11(3): Especial, 319-333.

Somayajulu, V.V., Viswanathan, K.S., Subbarao, K.S.V. and Cherian, L., 1994. Distortions in the height structure of equatorial electorjet during counter electrojet events J. Atmos. Terr. Phys., 56: 51-58.

Srivastava, B.J., 1974. The geomagnetic solar flare effect on 3 May 1973 at Indian stations and its dependence on the counter electrojet, J. Atmos. Terr. Phys., 36: 1571-1575.

Stening, R.J., 1968. Calculation of electric currents in the ionosphere by equivalent circuit method, Planet. Space Sci., 16: 717-728.

Stening, R.J., 1969. An assessment of the contributions of various tidal winds to the Sq current system. Planet. Space Sci., 17: 889-908.

Stening, R.J., 1977. Magnetic variations at other latitudes during reverse equatorial electrojet. J. Atmos. Terr Phys., 39: 1071-1077.

Stening, R.J., 1981. A two-layer ionospheric dynamo calculation. J. Geophys. Res., 86: 3543-3550.

Stening, R.J., 1985. Modeling the equatorial electorjet. J. Geophys. Res., 90: 1705-1719.

Stening, R.J., 1989. A calculation of ionospheric currents due to semidiurnal antisymmetric tides. J. Geophys. Res., 94: 1525-1531.

Stening, R.J., 1992. The enigma of the counter equatorial electrojet and lunar tidal influences in the equatorial region. Advances in Space Research 12: (6)23-(6)32.

Stening, R.J., 1995. What drives the equatorial electrojet? J. Atmos. Terr. Phys., 57: 1117-1128.

Stening, R.J., Meek, C.E. and Manson, A.H., 1996. Upper atmosphere wind systems during reverse equatorial electrojet events. Geophys. Res. Lett., 23: 3243-3246.

Suguira, M. and Poros, D.J., 1969. An improved model equatorial electrojet with a meridional current system. J. Geophys. Res., 74: 4025-4034.

Suzuki, A., 1973. Returning flow of the equatorial electrojet currents. J. Geomag. Geoelectr., 25: 249-258.

Takeda, M. and Maeda, H., 1980a. Three-dimensional structure of ionospheric currents – I. J. Geophys. Res., 85: 6895-6899.

Takeda, M. and Maeda, H., 1980b. Equatorial Sq. current system at occasions of the equatorial counter electrojet. J. Geomag. Geoelectr., 32: 297-301.

Takeda, M. and Maeda, H., 1983. F-region dynamo in the evening – Interpretation of equatorial ΔD anomaly found by MAGSAT. J. Atmos. Terr. Phys.. 45: 401-408.

Tarpley, J.D., 1970. The ionospheric wind dynamo II. Solar tides. Planet. Space Sci., 18: 1091-1103.

Onwumechili, C.A., 1992b. A study of rocket measurements of ionospheric currents- III. Ionospheric currents at the magnetic dip equator, Geophys. J. Int., 108: 647-659.

Onwumechili, C.A., 1992c. A study of rocket measurements of ionospheric currents – IV. Ionospheric currents in the transition zone and the overview of the study, Geophys. J Int., 108: 660-672.

Onwumechili, C.A., 1996a. Spatial and temporal distribution of ionospheric currents in subsolar elevations, J. Atmos. Terr. Phys.. in press.

Onwumechili, C.A.., 1997. The equatorial Electrojet, pp. 627. Gordon and Breach Sci. Publ., Amsterdam.

Onwumechili, C.A. and Agu, C.E., 1981. The relationship between the current and the width of the equatorial electrojet. J. Atmos. Terr. Phys., 43: 573-578.

Onwumechili, C.A. and Ezema, P.O., 1992. Latitudinal and vertical parameters of the equatorial electrojet from an autonomous data set, J. Atmos. Terr. Phys., 54: 1535-1544.

Onwumechili, C.A. and Ezema, P.O., 2000a. Local time dependence of ionospheric current correlations in low latitudes. In Press.

Onwumechili, C.A. and Ezema, P.O., 2000b. On the complexities of ionospheric current systems equatorward of Sq current focus. In press.

Onwumechili, C.A. and Oguehi, P.O., 1996. Analysis of the magnetic field of the equatorial electrojet, J. Atmos. Terr. Phys., 29: 533-566.

Onwumechili, C.A., Oko, S.O. and Ezema, P.O., 1996. Geomagnetically quiet day ionospheric currents over the Indian sector-I. Worldwide part of Sq currents, J. Atmos. Terr. Phys., 58: 541-553.

Pandey, R., Prakash, S. and Sinha, H.S.S., 1992. Formation of ionization layers responsible for blanketing Es during daytime counter-electrojet over magnetic equator, J. Atmos. Terr. Phys., 54: 54-63.

Philips, A. and Briggs, B.H., 1991. The day to day variability of upper atmosphere tidal winds and dynamo currents, J. Atmos. Terr. Phys., 53: 39-47.

Raghavarao, R. and Anandarao, B.G., 1980. Vertical winds as a plausible cause for equatorial counter electrojet, Geophys. Res. Lett., 7: 357-360.

Baghavarao, R. and Anandarao, B.G., 1987. Equatorial electrojet, Indian J. Rad. Space Phys., 16: 54-75.

Rangarajan, G.K. and Rastogi, R.G., 1981. Solar flare effect in equatorial magnetic field during morning counter electrojet, Indian J. Rad. Space Phys., 10: 190-192.

Rastogi, R.G., 1975. On the simultaneous existence of eastward and westward flowing equatorial electrojet currents, Proc. Indian Acad. Sci., 81A. 80-92.

Rastogi, R.G. 1989. The equatorial electrojet: Magnetic and ionospheric effects, Volume 3, Chapter 7: 461-[illegible] in Geomagnetism, ed. J. A. Jacobs. Academic Press, London.

Rastogi, R.G., 1993. The ionospheric current system associated with the equatorial counter electrojet. J. Geophys. Res., in press.

Rastogi, R.G., 1996. Solar flare on zonal and meridional currents at the equatorial electrojet station, Annamalaingar, J. Atmos. Terr. Phys., 58: 1413-1420.

Rastogi, R.G., Desphande M.R. and Sastri, N.S., 1975. Solar flare effects in equatorial counter electorjet currents, nature, 258: 218-219.

Ravat. D. and Hinze, W.J., 1993. Considerations of variations in ionospheric field effects in mapping equatorial lithosphere Magsat magnetic anomalies. Geophys. J. Int., 113: 387-398.

Reddy, C.A. and Devasia, C.A., 1981. Height and latitude structure of electric fields and currents due to local east-west winds in the equatorial electorjet, J. Geophys. Res., 86: 5751-5767.

Rees, D., 1979. Mid-latitude winds and electric fields in the lower thermoshere and their relationship with the global Sq ionospheric current system. J. Geomag., Geoelectr., 31: 267-285.

Rees, D., Bhavsar, P.D., Desai, J.N., Gupta. S.P., Farmer. A.D. and Rounce, P., 1976. Preliminary report on the Commonwealth collaborative rocket programme from Thumba equatorial rocket launching station for investigation of atmospheric and ionospheric processes, Space Res., 16: 407-412.

Salah, J.E., 1994. Variability of winds and temperatures in the lower thermosphere, J.Atmos. Terr. Phys., 56: 1327-1337.

Sartiel, J. 1977. Champs electriques dan la region l'electrojet equatorial. Ph.D. Thesis, Universit Paris VI, France.

Sastri, J.H., 1981. Occurrence of abnormal Sq(H) phas the equatorial electrojet region. Planet. Space. 29: 741-745.

Sastri, J.H., 1982. Phase variability of Sq(H) on normal q days in the equatorial region, Geophys. J. R. Soc., 71: 187-197.