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Resumo: Development of equatorial Ionization Anomaly (EIA) under quiescent and disturbed ionospheric conditions are investigated using the data collected from the low-latitude network of ionosondes and magnetometers operated at different longitude sectors of the globe as a part of the SUNDIAL 86 campaign (22 September to 3 October, 1986). Based on case studies of EIA developments, attention is focused on identifying the EIA response to changes in the electric fields associated with the equatorial electrojet and counter electrojet events. The response time of the EIA to electric field changes is found to vary from 2.5 to 4 h. An anomalous EIA development observed in the morning sector on September 23 suggested possible electric field penetration to low latitude during a substorm energy storage/Dst development phase. The analysis also shows that the afternoon EIA could be inhibited due to equatorward blowing disturbed neutral winds. The results of the present analysis emphasize the need for pursuing further investigations for the response of EIA to magnetosphere-induced disturbances.

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the case of the EIA inhibition during CEJ events a clear response time is observed. These response characteristics should be studied with additional data and through modelling by global, or low latitude, ionospheric models, which will be a continuing objective within the SUNDIAL program.

In the immediate vicinity of the equator, the *F*-layer height dependence on the EEJ variations does not appear to involve any noticeable response time. Generally good correlation is seen, as expected, between h_pF_2 and the EEJ strength for a major part of the day as well as on a day-to-day basis. However, the effect of the EEJ electric field (through vertical ionization drift) on the h_pF_2 is not necessarily straightforward. This is due to the importance of the ion production at lower heights and its subsequent ambipolar diffusion coupled with the fountain associated diffusion processes in establishing the equilibrium layer peak height. Thus, the correlation between the time variation of h_pF_2 (in gross features) with those in the EEJ electric field observed here for the daytime conditions, contrasts with the good correlation, observed during evening and night hours, between the $d(h'F)/dt$ and the electric field (vertical ion drift velocity) of the *F*-layer when $h'F \gtrsim 300$ km (Abdu *et al.*, 1981 ; Bittencourt and Abdu, 1981).

The EIA development could get enhanced or inhibited under disturbed conditions. The case studies presented here represent periods of weak disturbances. The EIA effects could occur through (a) the action of a direct penetration electric field associated with magnetospheric convection changes, or (b) intensification or inhibition of the EEJ electric field by local dynamic processes or by the processes in (a). Distinction between these two aspects would require more elaborate analysis of appropriate data sets. The observation of the morning EIA development on 23rd September, though represents only one event, does seem to originate from an eastward directed penetration electric field in the early morning hours, perhaps related to a brief duration *B* southward change that occurred around 1930 UT on 22 September.

Previous studies have indicated that, statistically, the EIA development tends to be inhibited during magnetic disturbances due to weakening of the EEJ electric field. In the present data set we have observed two cases of EIA inhibition in the Asian sector, on the 24th and on the 25th of September, that were preceded by weak counter electrojets. Also the two days were magnetically quieter than the 23rd, on which no EIA inhibition was observed. Perhaps larger magnetic disturbances might be required to produce the afternoon EIA inhibition process discussed by others (see some case studies reported by Walker, 1973). A case of EIA inhibition in the afternoon hours was observed in our analysis for a weakly disturbed condition. The indications are that it was most likely produced by the action of equatorward blowing disturbance neutral winds.

There is a need to undertake a more elaborate study of the EIA development, focusing attention on the dependence of the effect on the degree of the magnetic disturbances. Attention should also be given to possible longitude asymmetries of the EIA development under varying conditions of magnetic activity. Such analysis should necessarily involve detailed data on the IMF, *AE* indices or high latitude magnetograms, and possibly wider coverages of ionosonde, magnetometer and TEC data than it has been possible to include in the present study.

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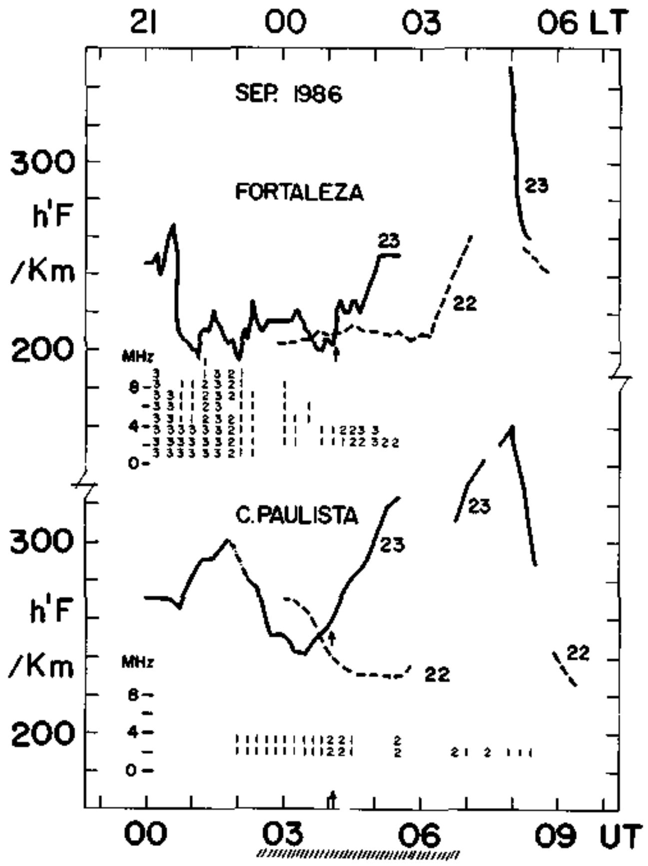

Figure 9

h'F variations over Fortaleza and Cachoeira Paulista during the magnetospheric disturbances of 23rd September compared with the h'F values for 22nd September. The spread F development on the night of 23rd is shown by the index numbers as function of frequency and local time. The index numbers 1, 2 *and* 3 *represent spread F ranges* < 100 km, > 100 km, < 200 km, > 200 km *respectively (see Abdu* et al., 1988 *also). The shaded line at the bottom of the figure from* 0230-0650 UT *corresponds to the substorm duration from Kiruna and Syowa magnetograms and riometer data. The arrows at* 0410 UT *coincides with a temporary substorm recovery (see the text).*

bay disturbances (near 0650, shaded line below Fig. 9) which seems to agree with the beginning of the *Dst* recovery phase (Fig. 5). Electric field penetration to low latitude associated with this event seems to be responsible for the observed rise of $h'F$ near this time over Cachoeira Paulista as shown in Figure 9. (Due to very low f_oF_2 values at these hours the *F*-layer height over Fortaleza was not deducible from Fortaleza ionograms). Besides the $h'F$ variations over Fortaleza and Cachoeira Paulista, Figure 9 shows also the range type spread *F* indices plotted as functions of frequency and local time (see Abdu *et al.*, 1988) for these two stations. The normal spread *F* (namely, the spread *F* produced by the regular *F*-layer dynamo) that was present on the night of 22 September was in its decay phase when the $h'F$ over both Fortaleza and Cachoeira Paulista registered a rise (indicated by arrows) near 0110 LT (0410 UT) (at the latter station the $h'F$ rise onset was probably superimposed over an already varying $h'F$). This vertical rise of the layer agrees in time with a temporary substorm recovery in the high latitude magnetograms and riometer absorption (as seen for example at Syowa Station, Antarctic) (there was loss of B_z data during this period). This *F*-layer rise did trigger a plasma bubble irregularity event over Fortaleza as seen in the intensification of index number from 1 to 2 or 3 (used in the same way as in Abdu *et al.*, 1988). Such spread *F* triggering seems to have occurred simultaneously, in regions several degrees west of the Fortaleza such that the effect of the vertically rising bubbles is seen over Cachoeira Paulista with a time delay of approximately 2.5 h, representing a vertical rise velocity of the order of 45 m s^{-1} (see Abdu *et al.*, 1983). A possible spread *F* triggering by the 0620 UT rise of $h'F$ was not registered over Fortaleza due to missing data, and the spread *F* was not observed over C. Paulista due probably to the sunrise transition that set in soon. (However, see Aarons and Das Gupta, 1984, on *Dst* recovery and eastward electric field in post midnight sector).

DISCUSSION AND CONCLUSIONS REMARKS

The SUNDIAL 86 data from latitudinally distributed ionosonde and magnetometer stations in the Asian and American longitude sectors have permitted an investigation of the development of the EIA in the two sectors. Due to the limit of the data no attempt has been made to study possible longitude asymmetry in the EIA development. The focus of the present analysis has been to identify the processes that control the EIA development under quiet and disturbed conditions, namely, the equatorial electric field, originating from the ionospheric dynamo as well as from magnetospheric processes, on one hand, and the meridional wind on the other. Before evaluating some of these important results it may be pointed out that the use of h_pF_2 to represent the *F*-layer height could introduce errors depending upon the local time and shape of the layer since h_pF_2 is reduced from ionograms assuming a parabolic fit near the peak (URSI Ionogram manual, 1972). A statistical comparison was made between the h_pF_2 and the h_mF_2 parameters obtained from true height analysis using Titheridge POLAN code (Titheridge, 1985), which showed that good agreement existed, within 10 km, between the two parameters in the absence of the *E* layer or under sunset-to-pre-sunrise conditions. During daytime the difference could vary mostly from 20 to 40 km. However, since our study focuses attention on the relative features of the h_pF_2 time variations, any difference between the h_pF_2 and h_mF_2 is not likely to be significant enough to modify its main conclusions.

An important finding from the present study is the observation of a response time for the EIA development with respect to changes in the EEJ electric field. The results suggest that this time varies from 2.5 to 4 h. Although varying degrees of correlation of the electrojet and EIA strength have been brought out by previous studies (for example, Rush and Richmond, 1973; Raghava Rao *et al.*, 1978; Alex *et al.*, 1988) these studies did not take into account the response time which is a very important aspect of the fountain effect. The effect of a reverse, or counter, electrojet (a temporary electric field reversal to westward), is to inhibit the EIA development, the same effect being observed even when a weakening of the normal electrojet occurs. It is important to note that also for

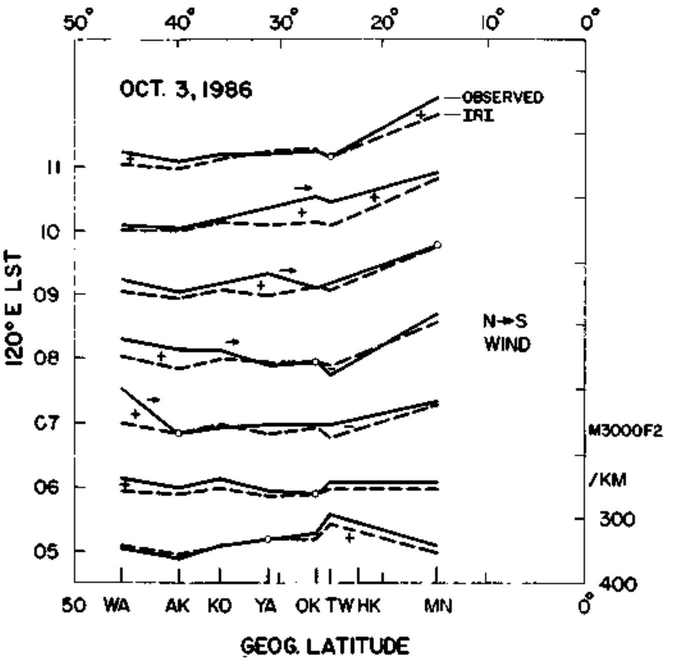

Figure 7

Latitude plots of F-layer height (h_mF_2) presented as M3000F2 *plotted in inverted scale (since h_mF_2) is related inversely to* M3000F2 *as $h_mF_2 = -176 + 1490/M$ (3000F2). The dashed lines represented the mean behaviour and therefore the positive departures in the h_mF (solid line) of 3 October, that shifts to lower latitude with increasing local time from 07 to 11 LT, indicate presence of equatorward blowing neutral winds.*

values during the hours when the wind was present. This modification, however, does not affect appreciably the EIA latitude profile (the higher crest amplitude at 15 LT on this day was produced by higher EEJ intensity (Fig. 4*b*) as discussed before and not by winds).

A very likely case of a neutral wind effect on the EIA development is presented in Figure 8. Variations in h_pF_2 over Fortaleza and f_oF_2 over Cachoeira Paulista are compared in the right half of Figure 8 for 26 and 27 October 1985, which were magnetically very quiet (the ΣK_p being 8 and 7 respectively on the two days). As discussed earlier the relative h_pF_2 variation over Fortaleza can be used as an indicator of the relative changes in the electrojet intensity for a major part of the day. Thus, the anomaly peaks over Cachoeira Paulista on both days were equally well developed, but displaced in local time (namely, 3 h later on 27th than on 26th) which must be produced by corresponding local time displacements in the EEJ intensities as indicated by the rapid decrease in h_pF_2 near 13 LT on the 26th and not on the 27th. In the left half of this figure we have compared the same parameters for 25th and 26th October, the 25th being magnetically more disturbed ($\Sigma K_p = 8$) compared to the 26th. A comparison of the h_pF_2 values over Fortaleza on 25th with those of 27th (that were very similar between 10 and 18 LT) indicates that the EEJ intensities on these two days were very similar in as far as their role in the anomaly development is concerned. However the EIA peak is almost totally inhibited on 25th as compared to its amplitudes on 26th and 27th. This can be best explained as due to the process of inhibition of fountain associated diffusion by equatorward meriodional winds.

During the disturbances of 23 September a spread *F* event was triggered in the Brazilian longitude postmidnight sector. Northward turning of B_z at 0620 UT marked the end of high latitude magnetic

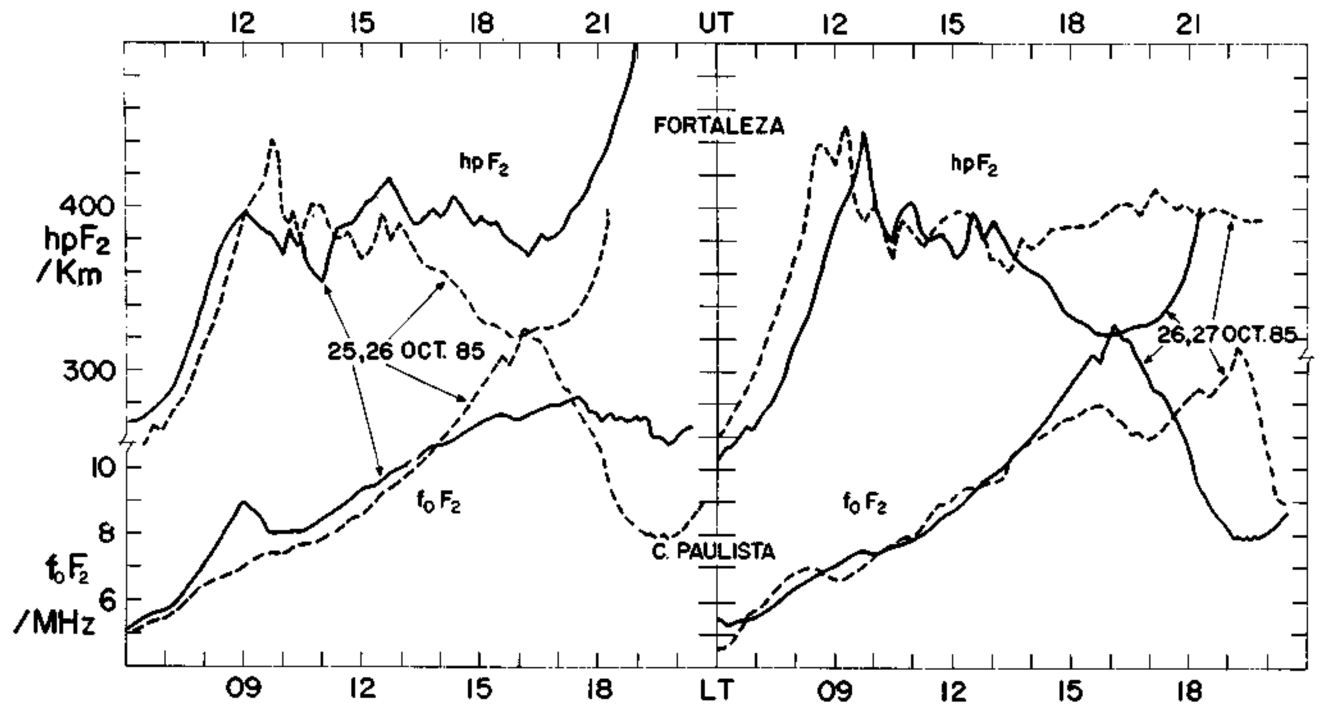

Figure 8

Comparison of F-layer heights over Fortaleza on pairs of days, 25 and 26, and 26 and 27 October 1985, with f_oF_2 values over Cachoeira Paulista to illustrate the inhibition of EIA *due to equatorward blowing wind as explained in the text.*

the horizontal line) near the Lunping magnetic data. The f_oF_2 latitude plot of Figure 6 shows the LT development of this anomaly (right half of the Fig.), the peak density occurring almost exactly at the same latitude as that of the normal afternoon EIA. We have no data to see if there was present also a southern hemisphere EIA crest. Nevertheless, we could assume that this observed latitudinal feature might well be produced by an anomalous fountain effect. The operation of the associated fountain would require an eastward F-region electric field to be present (as per the response time previously discussed) some 2-4 h prior to the anomaly development, namely, during the interval approximately from 19-21 UT. The effect of magnetospheric compression, namely, the positive H variations marking the storm commencement, might be responsible for the generation of low latitude electric field, although the electric field associated with $\partial B/\partial t$ is expected to be small due to the slow storm onset. It may be noted, however, that the IMF B_z showed, during this period, intensity enhancement (10-12 nT) with a brief southward turning that lasted only for about 30 min centered around 1930 UT. This B_z southward event might not be long enough to produce any substorm event. Its effect in generating low latitude electric field, the suspected cause of the observed EIA enhancement, needs to be investigated. During the growth phase, namely, during the energy storage phase, prior to a substorm that occurred on 22 March 1979, eastward electric field penetration in EEJ has been reported by Somayajulu *et al.* (1987). During the same event Tanaka (1986) has reported low latitude F-region response over Japan. Both effects were observed in the afternoon-evening sector and the magnetospheric disturbances were significantly more severe than the 23 September event.

The midday enhancement of the EIA strength on 23 September must be produced by an enhancement in the EEJ intensity in the morning hours (09 LT) based on the EIA response time discussed earlier (though Davao magnetogram data over this period were missing). EIA enhancements took place also on the two quietest days of the SUNDIAL 86 campaign, 22 and 30 September, as shown in Figure 6 (left half). These enhancements were clearly controlled by EEJ intensity as observed before.

The effect of a disturbed meridional wind on the EIA development is examined below using a case available during the SUNDIAL 86 campaign, which is complemented by data in October 1985 that had similar magnetic activity conditions. Figure 7 presents a latitude plot of h_mF_2 (here represented by M3000F2 plotted on inverted scale) in the Asian longitude sector during the forenoon period of October 3 that was immediately preceded by moderately disturbed K_p values (the K_p values during the four preceding 3-h intervals being 3+, 4−, 5+ and 4+). In this figure the solid lines which are the observed values, are compared with a mean value used as reference. Starting from the plot at 07 LT, positive deviation in h_mF_2 is seen displaced systematically towards the equator with increasing time till 1100 LT. This feature is a clear manifestation of the equatorward winds generated under disturbance conditions. Its effect, as seen in the f_oF_2 latitude plot of October 3 in Figure 4*a*, is to increase the peak densities above their quiet day

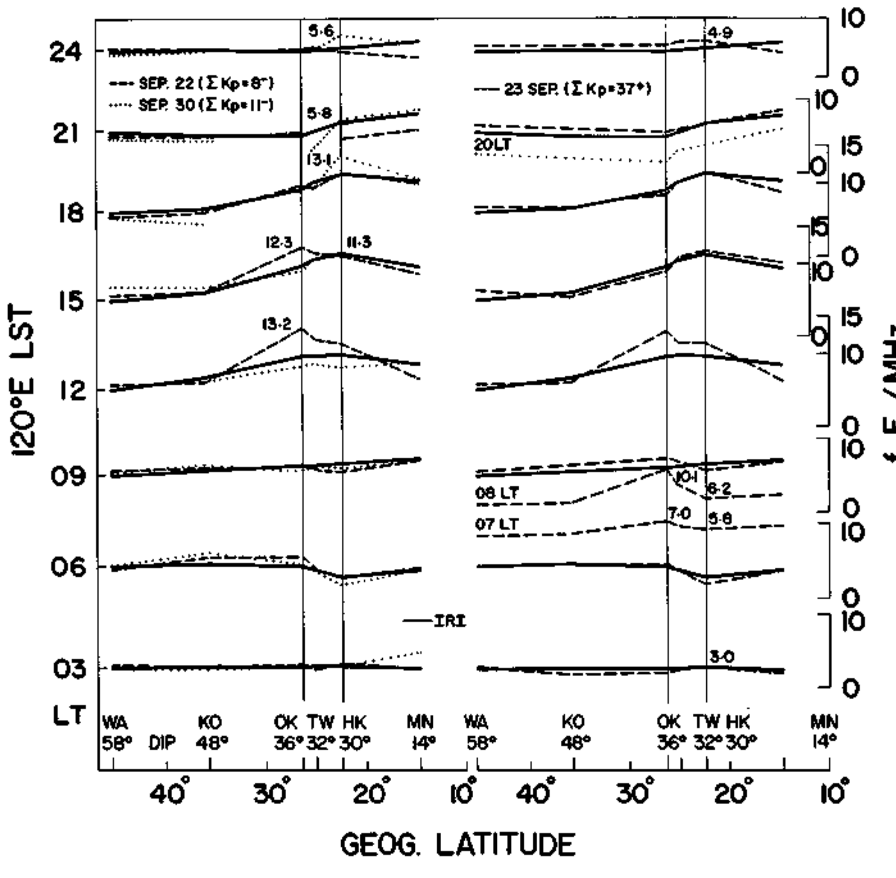

Figure 6

Latitude plots of f_oF_2 in the Asian longitude sector (as in Fig. 4a), for the quietest days of the SUNDIAL-86 campaign, 22 and 30 September (left half) and for 23 September (right half) the most disturbed day. The morning EIA development on 23rd is seen well developed in the plot at 08 LT.

EQUATORIAL IONOSPHERIC RESPONSE TO MAGNETIC DISTURBANCES: EIA AND SPREAD *F*

During the SUNDIAL 86 campaign, 22 and 23 September represented the quietest ($\Sigma K_p = 8$) and most disturbed ($\Sigma K_p = 37$) days of the campaign, respectively. The magnetic activity of the 23rd was associated with southward IMF portion of a solar wind blob that was characterized by enhanced density and magnetic field intensity (J. A. Joselyn, private communication). Solar wind density and velocity from IMP-8 plotted in Figure 5 together with magnetic *H* component at low latitude stations show commencement of magnetic disturbances near 1800 UT on the 22nd, the positive changes in *H* (and in *Dst* shown at the bottom of the figure) maximizing nearly at the same time as that of solar wind density. This solar wind density enhancement was in fact sitting at the leading edge of a brief southward excursion of the IMF at 1920 UT (indicated in the figure). However the high latitude magnetograms (over Kiruna and Syowa, Antarctic) registered substorm events only from 0230 to 0650 UT, and they were consistent with the B_z polarity variations, (namely, a decrease (increase) in the substorm intensity being associated with B_z changes from southward (northward) to northward (southward) sense), during the period for which B_z data were available (from 0020 till 0450 UT there was loss in the B_z data). A detailed description of the solar-interplanetary changes during this period is given in a companion paper by Szuszczewicz *et al.* (1990).

The EIA as well as the spread *F* developments under magnetospherically disturbed conditions are controlled by cross field uplift and $B\|$ transport of ionization under the processes operating in the enhanced coupling of the global electrodynamic system. They include, as discussed before, electric field penetration to low latitude associated with substorm onset and recovery depending upon the magnetospheric convection growth and decay phases (Gonzales *et al.*, 1979; Fejer, 1986; Spiro *et al.*, 1988; Foster and Aarons, 1988), partial closure of ring current on the dusk side (Gonzales *et al.*, 1979; Tanaka, 1986); disturbance dynamo electric field associated with equatorward blowing thermospheric winds driven by enhanced auroral heating at high latitude (Blanc and Richmond, 1980; Fejer *et al.*, 1983; Salah *et al.*, 1988) and ionization transport under the action of the meridional component of the disturbance winds (Rishbeth, 1975; Abdu *et al.*, 1988).

During the early part of the event (Fig. 5) longitude was in the morning sector and anomalous development of EIA was registered from 07 to 0930 LT (23 UT of 22nd to 0130 UT of 23rd), as indicated (by

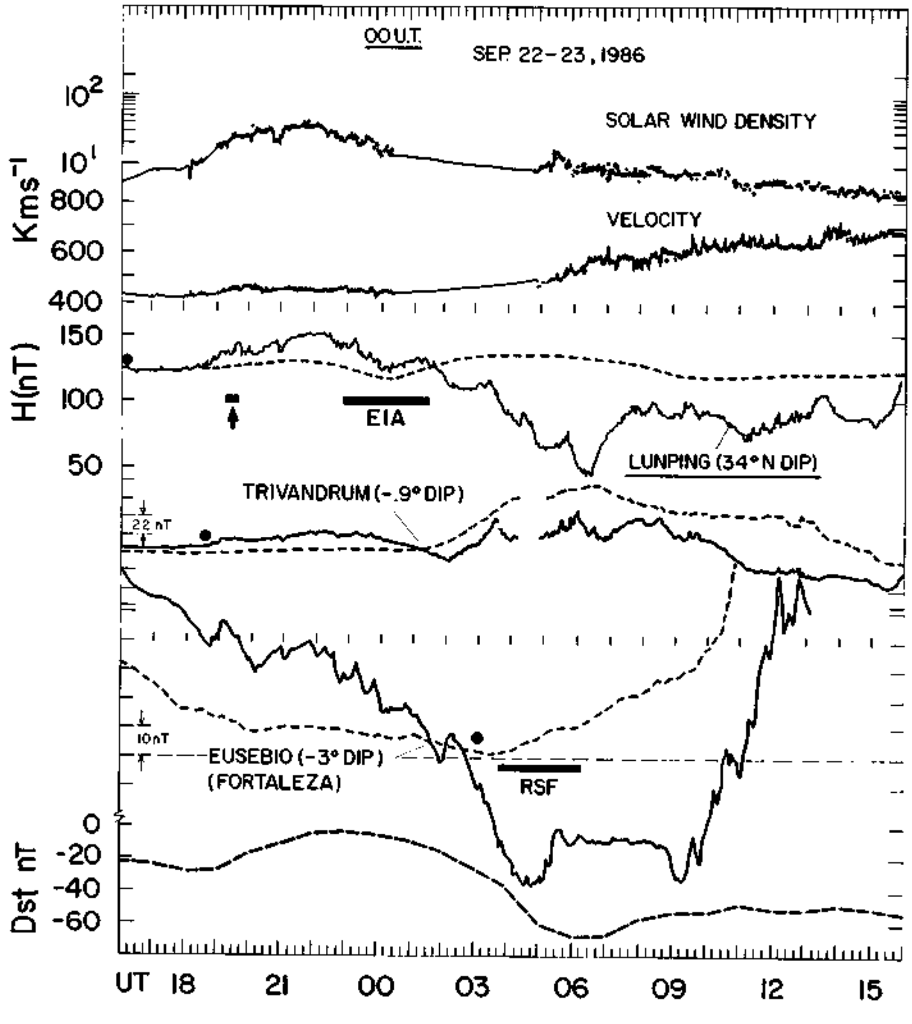

Figure 5

The magnetospheric disturbance of 22-23 September 86 showing UT variations in solar wind density and velocity (upper two sections), and magnetic field H component variations over Lunping (34° dip, 12° E), Trivandrum (− 9° dip, 82.5° E) and Eusebio, Fortaleza (− 6° dip, 38° W). Magnetograms for 30 September-01 October were used as the quiet day reference (dotted) curves. Development of EIA in the Asian morning sector and that of range type spread F, RSF, in American post midnight sector are marked. A brief southward turning of B_z starting at 1920 UT is indicated. Filled dots represent local midnight.

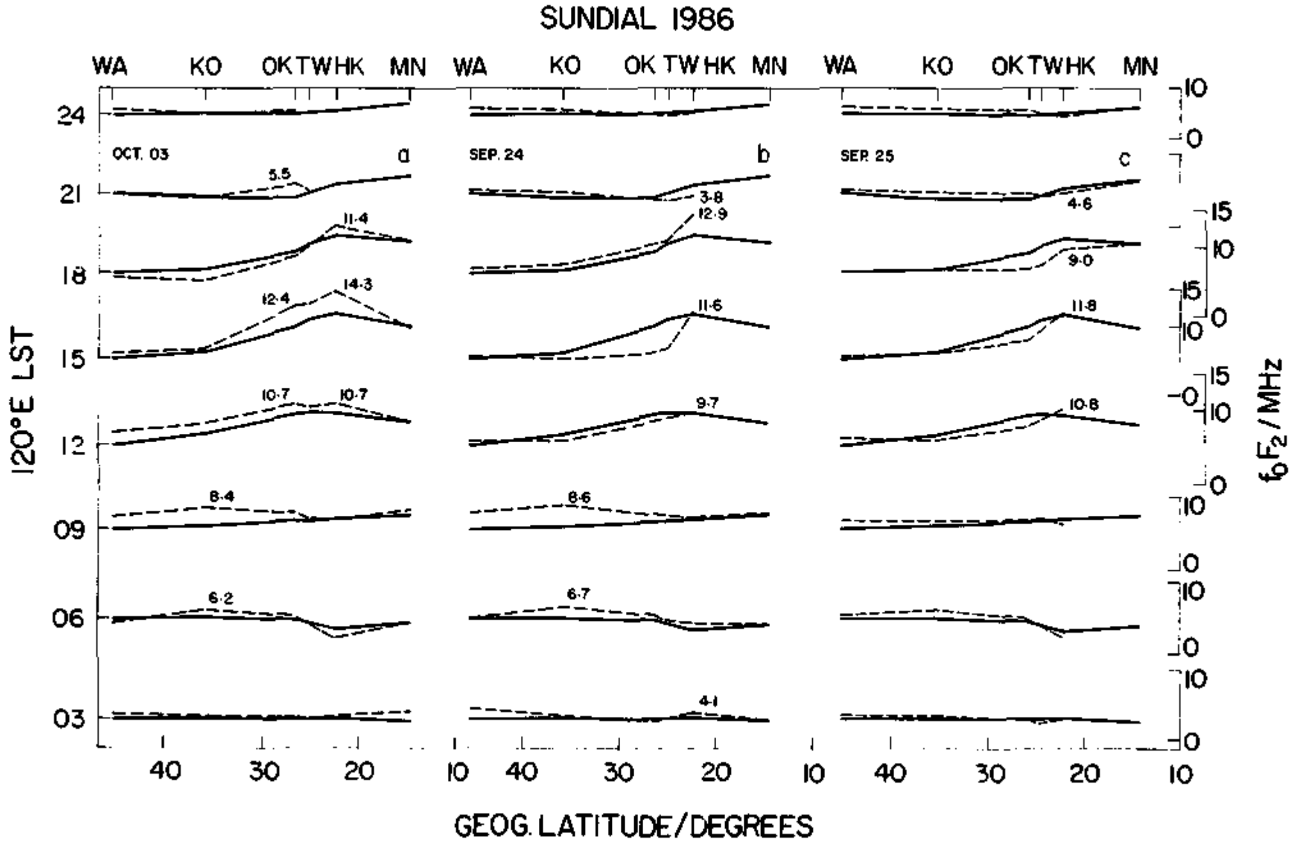

Figure 4*a*

Latitude plots of f_oF_2 in the Asian longitude sector, using data from Manila, Hong Kong, Taiwan, Okinawa, Kokubunji and Wakanai, for local times at 3 h intervals. The plots are for 3 October, 24 and 25 September representing different electrojet and counter electrojet local time-intensity variation.

In order to examine the effect of the electrojet electric field on the anomaly development we have plotted in Figure 4*b* the electrojet magnetic field *H* component diurnal variations represented by ΔH(DA-LU), namely, the difference between the diurnal range of *H* variations over Davao (−2° dip) and Lunping (34° N dip), for the same days as those of the data in Figure 4*a*. These days are : 3 October, 24 and 25 September. On 3 October the electrojet intensity (Fig. 4*b*) was significantly higher than the reference value (the dashed curve representative of the mean conditions for this period of study), especially in the prenoon hours. Correspondingly, the anomaly crest amplitude at 15 LT (Fig. 4*a*) is also significantly higher than the mean behaviour. Although accentuated EIA distribution on this day was evident even at midday the largest amplitude of enhancement occurred around 15 LT. In this case, a certain time delay (of the order of 2-3 h) is evident with respect to the maximum in the electrojet intensity difference which occurred near 1100 LT or before. On 24 September (Fig. 4*b*) the electrojet intensity was higher than normal during the morning hours and a counter electrojet occurred close to 1400 LT. The anomaly amplitude is correspondingly inhibited in the curve at 1500 LT (Fig. 4*a*). The data on 25 September also shows EEJ enhancement similar to that of 24 September, and an afternoon CEJ somewhat later than on 24 September. Correspondingly the anomaly inhibition has largest amplitude near 1800 LT (see Fig. 4*a*). Thus the inhibition of the EIA produced by the CEJ occurs with systematic delay with respect to the maximum strength of the CEJ. This systematic response time of the anomaly to the CEJ intensity variations represents a new aspect of observational evidence on the electric field control on the EIA (see also Walker, 1973).

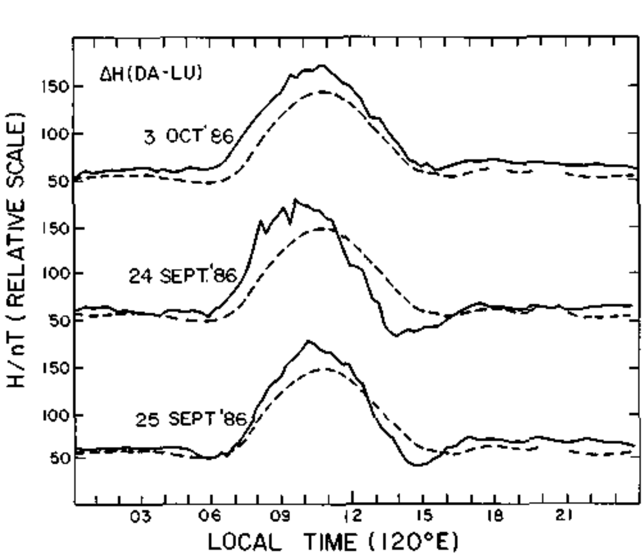

Figure 4*b*

The variations in ΔH between Davao (DA) *and Lunping* (LU) *representing the electrojet intensities corresponding to the f_oF_2 plots of Figure 4a.*

required for detecting an f_oF_2 change over sub-equatorial latitude corresponding to a change in the equatorial electric field (through the height parameter in our case) imposed on an ambient ionization distribution that is non or weakly anomalous as is normally the case in the morning-noon hours. If, however, a rapid change in the electric field should occur due to penetration of magnetospheric electric fields this response time will depend very much also on the existing degree of the anomaly development. For example if an eastward electric field penetration occurs in the dusk sector where the anomaly is either fully developed, or is retreating after the peak development, the $\mathbf{E} \times \mathbf{B}$ plasma drift (upward and poleward) could produce enhancement or expansion of the anomaly such that the f_oF_2 over a location on, or in the immediate vicinity of, the equator would decrease while it could get enhanced over a low latitude station which at that phase of the event was immediately poleward of the anomaly. In other words simultaneous decrease and increase of f_oF_2 over a pair of stations (equatorial and sub-equatorial) could be observed as in the example over Manila and Okinawa presented in the interesting study by Tanaka (1981, see also 1986), on the evening ionosphere response to ring current developments.

Simultaneous f_oF_2 variations over Fortaleza and Cachoeira Paulista for 4 days of the SUNDIAL campaign (those of Fig. 2*a*) are plotted in Figure 2*b* ; A comparison of the two sets of curves shows that : *a*) The so-called noon bite-out (midday minimum) in f_oF_2 over the equatorial station associated with the development of the fountain (occurring around 1030 LT in the present case) is absent at the low latitude site. This equatorial f_oF_2 variation is closely identical to that of the Indian station, Kodaikanal for similar low solar activity epoch discussed by Anderson (1973*b*) ; *b*) The anomaly peak in f_oF_2 over Cachoeira Paulista occurs anywhere between 13 and 19 LT after which the f_oF_2 falls steeply due to the collapse or retreat of the anomaly as suggested in the rather slower decrease of this parameter at these times over Fortaleza ; *c*) Although some predominant peaks in the afternoon f_oF_2 values at the two stations (on 2 and 4 October, for example) seem to be correlated occurring earlier at Fortaleza than at Cachoeira Paulista, the comparison of the f_oF_2 variations over these stations does not bring out, as to be expected, any clear anomaly response time as that demonstrated by the plots in Figure 2*a*.

An interesting example of the control of the anomaly f_oF_2 and the total electron content (TEC) by the equatorial electric field is presented in Figure 3. October 1 was a normal electrojet day and the fully developed anomaly is seen in the f_oF_2 and TEC peaks around 16 LT. A fairly strong reverse electrojet was present centered around 1300 LT on 30th September which produced total inhibition of the anomaly that should have occurred around 16 LT. In these results also, an anomaly response time can be inferred which is of the order of 2.5 to 3 h.

The diurnal development of the quiettime EIA in the Asian longitude sector is shown by the latitude plots of f_oF_2 at 3 h local time intervals presented in Figure 4*a*. The solid lines represent the anomaly latitude profile as modelled in the IRI, representative of solar minimum equinoctial conditions. The anomaly is completely absent until 09 LT, partially developed at midday and shows maximum growth around 15 LT.

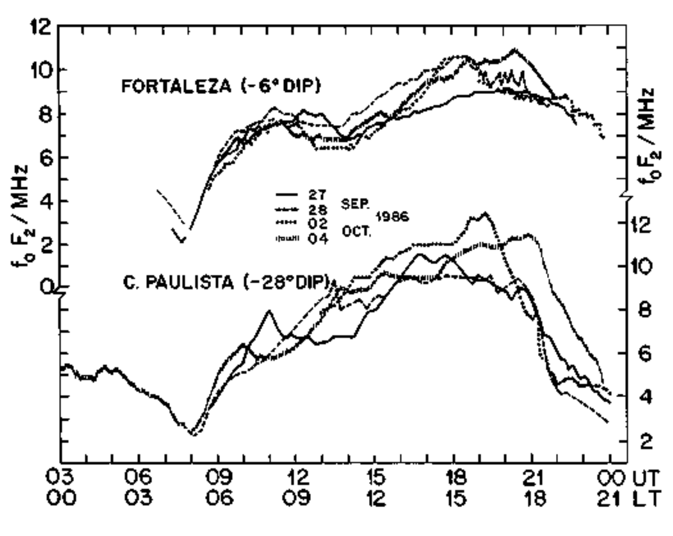

Figure 2*b*

Simultaneous f_oF_2 variations on 4 days (27, 28 September, 02, 04 October) over Fortaleza and Cachoeira Paulista.

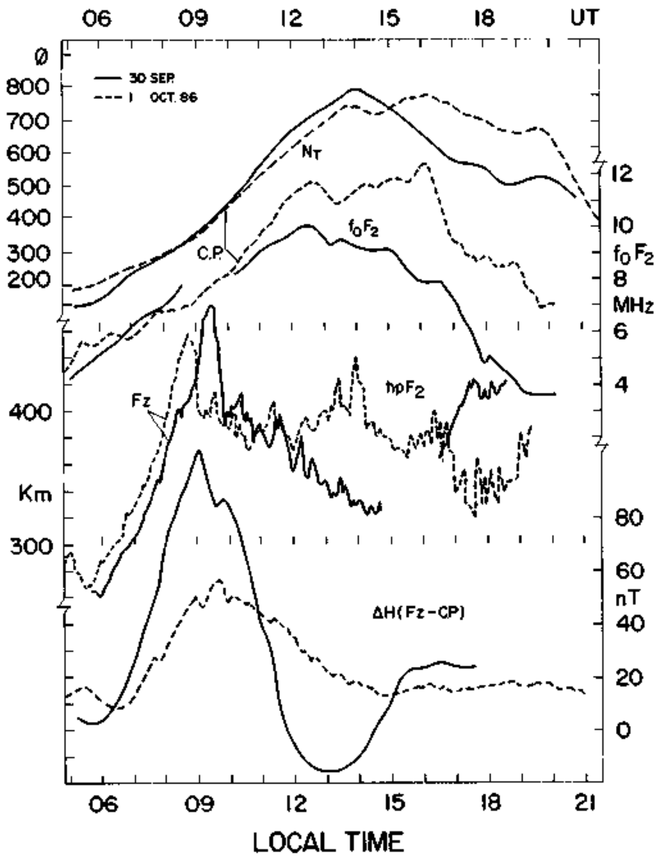

Figure 3

The total electron content relative variations over Cachoeira Paulista plotted together with the f_oF_2 over the same station, F-layer height and electrojet intensity over the equator. The effect of the counter electrojet around 13 LT was to inhibit the EIA near 16 LT, on 30 September.

altitude of its production, and the fountain associated diffusion which produces the low latitude ionization crests should, of course, control the F_2 peak height over the equator. Morning counter electrojet events (CEJ) that were present on two of these days, 24th and 27th September, have contributed to decrease the F_2 peak heights relative to those of the non counter electrojet days. The afternoon CEJ that was present on the 24th also had the effect of lowering the F peak heights. The ΔH variations after 16-17 LT seem to have no influence on the height as seen in the data of 22 and 27 September.

Some results on the association between equatorial h_pF_2 and anomaly crest f_oF_2 are presented in Figure 2*a*. Relative variation on two consecutive, or nearby, days are compared for the two parameters. Corresponding features such as cross over points, or other outstanding features in the relative variations of the two parameters are marked (by identical arrows) on these curves. There is a systematic delay in the crest latitude f_oF_2 variations relative to the corresponding equatorial F_2 peak height variations. This delay, which varied from 2.5 to 4 h, is the response time of the anomaly crest ionization to changes in the equatorial F-layer height, namely electrojet electric field. Such response time should be considered for the cases of F-layer height changes arising from magnetospheric electric field penetration events as well (to be discussed later in the paper). These results in fact offer experimental evidence for the anomaly response time suggested from the theoretical calculations such as those presented by Hanson and Moffet (1966). The variation in the response time, namely 2.5 to 4 h observed in Figure 2*a* would depend upon factors such as the vertical ionization drift velocity, the heights of the flux tubes involved in the anomaly formation (diffusion time), as well as on the meridional winds.

It is important to point out further that the response time obtained from our analysis is in fact the time

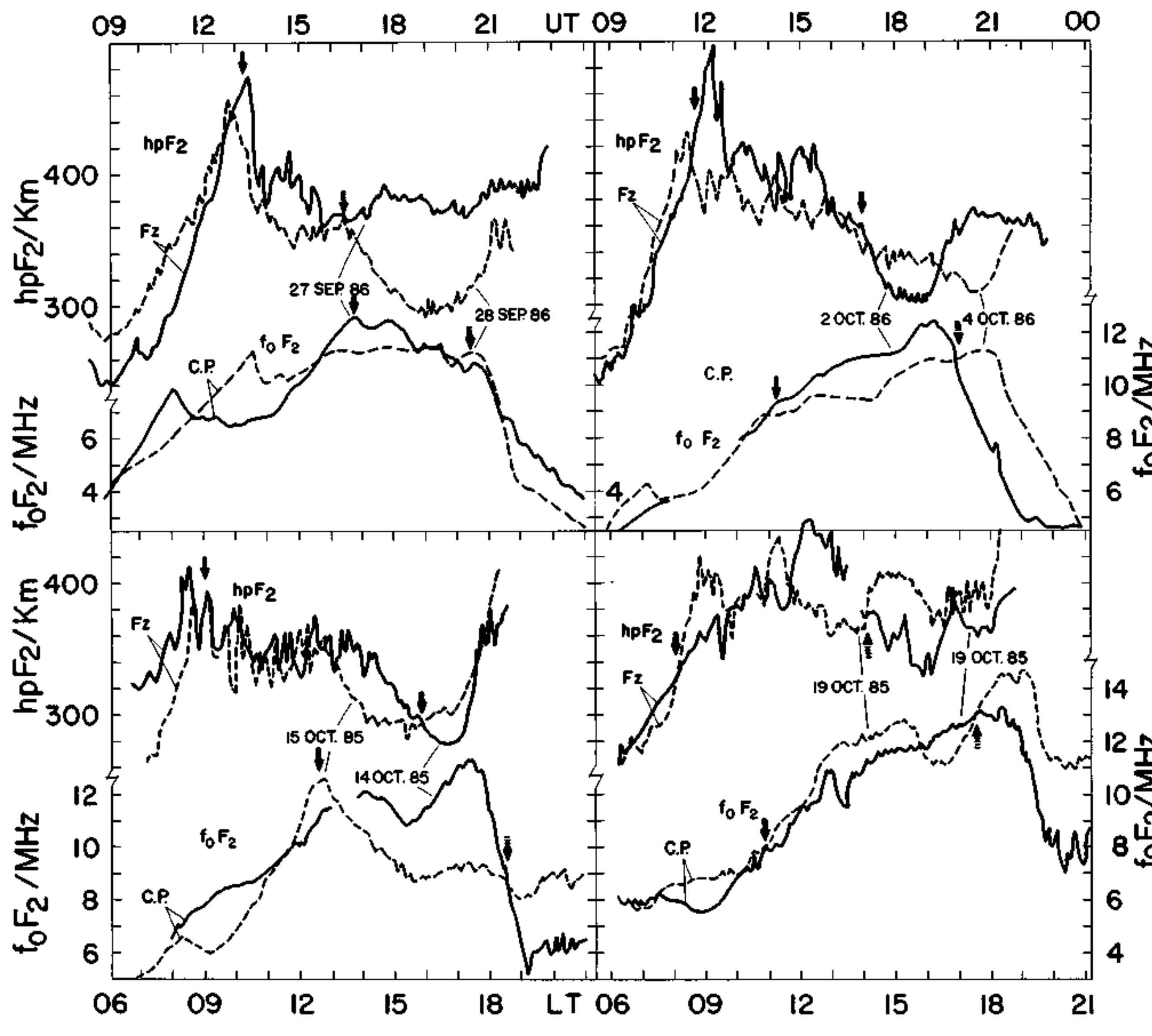

Figure 2*a*

Comparison of daytime variations in h_pF_2 over Fortaleza and Cachoeira Paulista for four pairs of days, to illustrate the response of the EIA *crest ionization to changes in the F-layer peak height over the equator. The corresponding feature in the two parameters, such as cross over points or dominant peaks, are indicated by identical arrows.*

in reponse to magnetospheric disturbances due largely to the complex interplay between the penetrating electric field and the disturbed neutral wind briefly mentioned above. Better understanding of these aspects could be achieved from the study of the anomaly parameters simultaneously with measurements of electric fields and neutral winds. Alternatively, significant conclusions on the relative roles of these latter parameters could be inferred from the response characteristics of the anomaly during specific events provided that data are available from coordinated measurements using a low latitude network of instruments deployed at widely separated longitude sectors. Some results of pursuing such an approach through the SUNDIAL project is presented here. Data from the ionosonde and magnetometer network operated in the American, Asian and Indian longitude sectors during the September-October 10-day SUNDIAL-86 campaign were analysed and the results discussed in this paper focus attention on the processes of the equatorial anomaly based on case studies of its development under quiet and magnetospherically disturbed conditions.

QUIETTIME EIA DEVELOPMENT

Numerous studies on the anomaly developments for different longitude sectors, solar activity phases and seasons have been carried out in the past. In general the anomaly development begins in the forenoon hours by 1000 LT during sunspot minimum and somewhat later (by 2-3 h) during sunspot maximum. The electric field control of the EIA can be examined by following the anomaly development as a function of the EEJ intensification. Two aspects of EEJ-EIA connection need to be considered, namely, (a) EEJ control of the equatorial F-layer peak heights (h_mF_2), and (b) association between the equatorial h_mF_2 and the F_2 peak densities (f_oF_2) of the anomaly crest. These two aspects are separately studied below for Brazilian longitude sector using the ionosonde and magnetometer data for Fortaleza (– 6° dip), a magnetic equatorial station, and for Cachoeira Paulista (– 28° dip) that represents the anomaly crest. In Figure 1 the daytime variations of h_pF_2 (which is an approximate measure of h_mF_2) over Fortaleza are compared with the electrojet intensity over the same station. The latter was determined as the difference between the magnetic field H component diurnal range for Fortaleza and for Cachoeira Paulista. In each set, data for two days are compared in order to bring out the correlation between the two parameters in their day-to-day variations as well. For most of the daytime, (from 07 till 15 LT), the electrojet intensity follows closely the east-west electric field variations, as measured by the Jicamarca radar (see Fejer *et al.*, 1979). Up to about 15-16 LT on all these days there is an excellent correlation between the general behaviour of the F-layer peak height and the electrojet intensity in the local time pattern as well as in the day-to-day variabilities. Although such behaviour is expected, the precise eastward electric field control of the F_2 peak height is not explicit in these results. For example, downward movement of the F_2 peak sets in around 10 LT, near the maximum and the decreasing phase of the EEJ variation, when the ionization drift is still upward. Such features clearly demonstrate the influence of other controlling processes. In particular, the ambipolar diffusion of ionization from lower

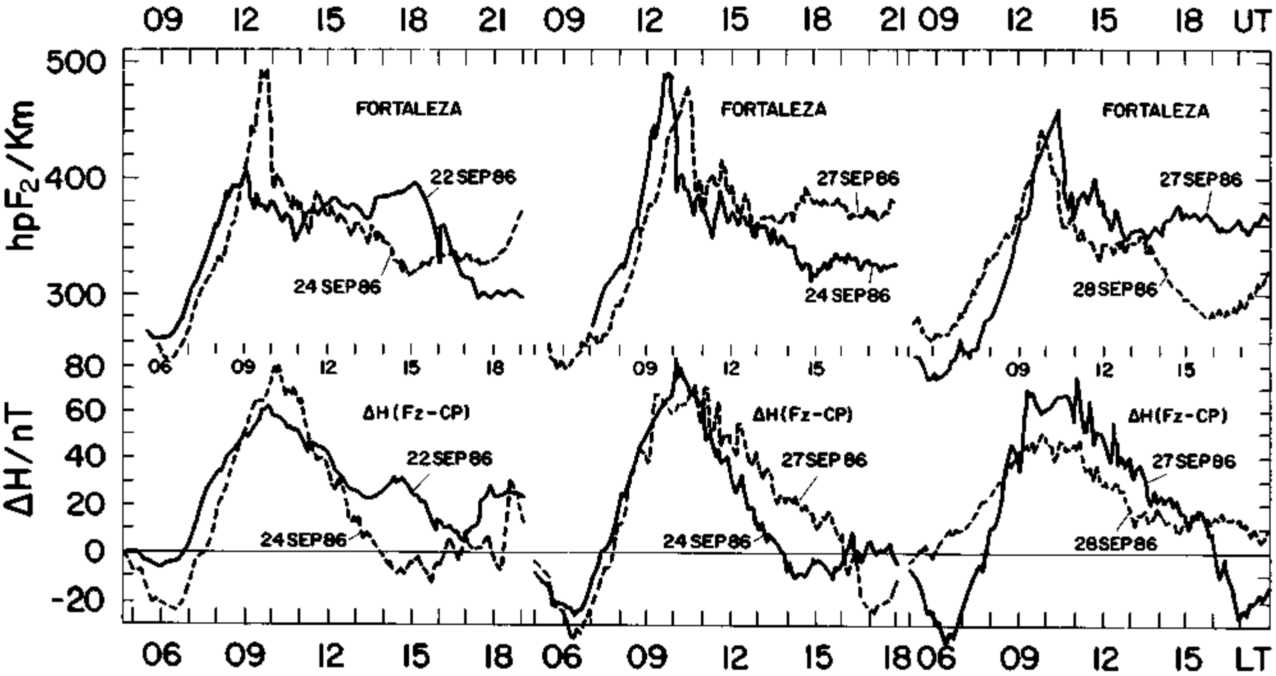

Figure 1

F-layer peak height (h_pF_2) *variations over the magnetic equatorial station, Fortaleza and the electrojet intensity represented by* ΔH(Fz-CP), *namely, the difference between the* ΔH *variation over Fortaleza and that over Cachoeira Paulista, plotted for three pairs of days. It may be noted that morning counter electrojets were present on 24 and 27 September 86.*

ture occur frequently, in the form of significant north-south asymmetry of crest, inhibition or enhancement of the anomaly development due to longitude and seasonal dependent processes, or in response to magnetospheric disturbances that involve equatorial ionosphere-magnetosphere coupling as part of the global electrodynamic system.

Lifting up of the ionization to higher altitude, due to the action of the daytime eastward equatorial electric field and subsequent deposition at higher latitude by diffusion along magnetic field line was suggested by Martyn (1955) as the fountain effect responsible for the development of the equatorial anomaly. Theoretical calculations by Hanson and Moffet (1966) and by Sterling *et al.* (1969) have verified the fountain hypothesis and have further brought out the important role of the meridional neutral winds in the anomaly development. Using the electric field values measured by the Jicamarca radar and assumed neutral winds, Anderson (1973*a*,*b*, 1981) has explained theoretically many important features of the N_{max} distribution, such as the noon bite-out over the equator and late night peak over the low latitudes. He has also explained the difference of local time variations in this parameter in the Asian and American longitude sectors for low and high activity periods. Further numerical calculations including coupled ion/neutral motions have been carried out by Chan and Walker (1984*a*,*b*) to explain the distribution of observed equinoctial f_oF_2 and h_mF_2 during low activity period at east Asian regions. Also many important features of the equatorial anomaly have been modelled and explained using the global ionospheric model by Sojka and Schunk (1985).

The eastward electric field which is responsible for the daytime equatorial anomaly is the tide induced *E*-layer dynamo field that is mapped by conducting field lines to *F*-layer heights. The same primary field drives the equatorial electrojet (EEJ). Therefore good correlation between the EEJ intensity and EIA magnitude is expected, subject of course to the independent control of the latter by the meridional winds. Statistical data analyses in search of such correlations have been carried out with varying degrees of success (see e.g., Dunford, 1967; Rush and Richmond, 1973; Raghava Rao *et al.*, 1978). An important factor that determines such correlation is the response time of the anomaly to an applied east-west electric field which theoretical models (Hanson and Moffet, 1966; Anderson 1973*b*) suggested to be of the order of 2-3 h. However, no observational evidence to this effect has been presented so far. The present study will provide explicit evidences in this respect based on some case studies of the EIA development. The response of the EIA to the electric field reversals, namely Counter Electrojet events, CEJ, has been recently investigated for topside electron densities by Alex *et al.* (1987).

The persistence of the anomaly during nighttime, a dominant feature around solar maximum, is caused, according to theoretical calculations, by enhanced (prereversal) eastward electric field (Anderson, 1973*a*,*b*) which arises from the *F*-region dynamo field that develops near sunset hours. The prereversal enhancement of eastward electric field has been extensively measured by the Jicamarca radar (Woodman, 1970; Fejer *et al.*, 1979). It is produced under the conditions of sunset decrease of the *E*-layer Pedersen conductivity in the presence of eastward blowing thermospheric winds (Rishbeth, 1971; Heelis *et al.*, 1974; Batista *et al.*, 1986) thus suggesting control by these parameters on the post-sunset EIA magnitudes.

During magnetospheric disturbances the EIA development can be modified by penetrating electric field of magnetospheric origin. This includes the direct penetration electric field during the energy storage, the substorm onset, and recovery phases, as well as the disturbance dynamo field that involve propagation time from high latitude to equatorial latitude of about 16-24 h (see Fejer, 1986; Blanc and Richmond, 1980; Tanaka, 1986). The expected effect on the EIA should, of course, depend upon the sense of these penetrating electric fields. A sudden decrease in the cross polar cap potential, often associated with a northward turning of B_z, causes westward and eastward electric field changes in the dayside and nightside of the equatorial ionosphere, respectively, while though less frequently, southward changes of B_z, namely increases of the polar cap potential, produce electric field changes of the same polarity as the ambient field. The penetrating electric field is eastward in duskside under the condition of developing asymmetric ring current (Tanaka, 1986). Thus, depending upon the local time and nature of the electric field penetration event the response of the EIA is seen as an inhibition or an enhancement in its development or as no detectable effect at all (see also Huang *et al.*, 1989). On the other hand, neutral wind associated with the disturbance dynamo (Rishbeth, 1975) will, in general, be directed equatorward so that the effect of this wind on the anomaly distribution could tend to be local time invariant. (An example of possible neutral wind effect on the EIA seen in the SUNDIAL-84 data was discussed by Abdu *et al.*, 1988). The disturbance thermospheric circulation associated composition changes could produce negative storm effects on the distribution of ionization (Prolss and von Zahn, 1977). However, severe magnetic disturbances are necessary to produce such effects over the equatorial and low-latitude regions.

Reasonable understanding of the gross features of the EIA behaviour has been obtained based mainly on statistical analyses of accumulated data supported by theoretical model studies. For example, north-south crest asymmetry has been explained as caused by trans-equatorial neutral winds favoured in solsticial seasons, or asymmetric meridional winds in equinoctial months brought about by the non coincidence of geographic and geomagnetic equators (Chan and Walker, 1984*b*; Sojka and Schunk, 1985). The longitudinal asymmetry which is significantly influenced by magnetic declination angle is only partly understood (Walker, 1981), since the nature of the longitude asymmetry in the *F*-region dynamo electric field itself is still not sufficiently understood on a global basis (see Batista *et al.*, 1986). Among the least understood aspects of the anomaly is its development or inhibition

Electric field *versus* neutral wind control of the equatorial anomaly under quiet and disturbed condition : A global perspective from SUNDIAL 86

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ABSTRACT. Developments of equatorial Ionization Anomaly (EIA) under quiescent and disturbed ionospheric conditions are investigated using the data collected from the low-latitude network of ionosondes and magnetometers operated at different longitude sectors of the globe as a part of the SUNDIAL 86 campaign (22 September to 3 October, 1986). Based on case studies of EIA developments, attention is focused on identifiying the EIA response to changes in the electric fields associated with the equatorial electrojet and counter electrojet events. The response time of the EIA to electric field changes is found to vary from 2.5 to 4 h. An anomalous EIA development observed in the morning sector on September 23 suggested possible electric field penetration to low latitude during a substorm energy storage/*Dst* development phase. The analysis also shows that the afternoon EIA could be inhibited due to equatorward blowing disturbed neutral winds. The results of the present analysis emphasize the need for pursuing further investigations for the response of EIA to magnetosphere-induced disturbances.

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INTRODUCTION

A major feature of the equatorial ionosphere is the anomalous latitudinal distribution of the *F*-region ionization that manifests itself as two low-latitude ionization crests, with a trough on the equator, seen clearly in the noon $N_mF_2(f_oF_2)$ at all longitude sectors of the globe. Widely known as Appleton anomaly or equatorial ionization anomaly (EIA) this feature has been the subject of extensive investigation by using ground-based ionosondes, satellite borne topside sounders and, to a limited degree, by the satellite beacon monitoring of the total electron content (TEC) of the ionosphere. Early observational studies have brought out many outstanding morphological features of the EIA (Appleton, 1946 ; Croom *et al.*, 1960 ; Ducan, 1960 ; Lyon and Thomas, 1963 ; Rastogi, 1959 ; Rao and Malhotra, 1964 ; see also, Walker and Ma, 1972 ; Anderson and Klobuchar, 1983). The morphological features and the physical and electrodynamical processes that control the EIA phenomenon have been reviewed by Moffet (1979).

Though predominantly a daytime phenomenon, the anomaly which can dominate the ionization distribution of the low latitude *F*-region extends well into the post-sunset and predawn hours depending upon the season and solar activity phase. Typically during equinoctial months, the anomaly first appears near 1000 LT, reaches its maximum in the afternoon hours and persists until the decay sets in around 2200 LT or later during the solar maximum and somewhat earlier (1800 LT) during the solar minimum phase (see Walker, 1981). In fully developed form the quiet time N_mF_2 crests are located, near 15° to 18° dip latitude (latitudinal extentions tend to spread during high solar activity phase and tend to shrink during disturbed magnetic conditions), and bear a ratio, with respect to the trough value, of the order of 2. However, substantial deviations from the above pic-

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MFN= 007096
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02 5684
03 INPE-5684-PRE/1841
04 CEA
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10 Walker, G.O.
10 Reddy, B.M.
10 Sobral, Jose Humberto Andrade
10 Fejer, B.G.
10 Kikuchi, T.
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87 IONOSONDA
87 ANOMALIA EQUATORIAL
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