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Post-Sunset Behaviour of the Equatorial Anomaly in the Indian Sector

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A detailed investigation is made of the relationship, in the post-sunset period, between the depth of the equatorial anomaly and the evening rise of F-region at the trough on a day-to-day basis, using published data of ionosonde stations in the Indian sector for a 2-yr period (1957-58) of high sunspot activity. The day-to-day changes in the post-sunset rise of F-region at the trough are found to show a significant positive correlation with those of the depth of the anomaly, and a significant negative correlation with those of f_0F2 at the trough during all seasons and on quiet as well as distrubed days The day-to-day variability of f_0F2 at the crest of the anomaly is also found to exhibit a significant positive correlation (with a delay of 2 hr) with that of the evening rise of F-region at the trough during disturbed days of all the three seasons and on quiet days of summer and equinoxes. The results of the present study are in accordance with the prevailing view that the post-sunset enhancement of the anomaly during periods of high sunspot activity is due to a renewal of the 'fountain effect' It is suggested that the conspicuous absence of a significant relationship of the day-to-day variability of f_0F2 at the crest of the anomaly with that of the post-sunset rise of F-region at the trough during quiet days of winter months is due to the effect of poleward neutral winds in the post-sunset period

1. Introduction

The Appleton or equatorial anomaly which refers to the existence of two crests around 16° dip latitude, one on either side of the dip equator, in the latitudinal distribution of the peak electron density of F-region is a well known feature of the equatorial ionosphere. The morphology of the anomaly has been extensively studied by several workers since its discovery by Appleton[1] and is well documented in the literature (Ref.2 and references therein). It is established from numerous theoretical studies[3-10] that the formation of the anomaly occurs primarily through the 'fountain effect', originally proposed by Martyn[11]. The ionization lifted vertically upwards by an eastward electric field of E-region origin around the dip equator diffuses downwards along the field lines under the influence of gravity and pressure gradient forces, resulting in crests of ionization in north and south of the dip equator and a trough at the dip equator. However, it is to be pointed out that although the formation and development of the anomaly is basically due to the vertically upward electromagnetic drift[3-5,9,10], some features of the anomaly behaviour like, for example, the interhemisphere asymmetry in the electron density at the anomaly crests can be accounted for only when the effects of thermospheric neutral air winds are taken into consideration[6-8,10].

It is known that in a rather narrow latitudinal belt centred on the dip equator, the F-region experiences an abnormal increase in height in the post-sunset hours during high sunspot activity periods[12]. The post-sunset increase of F-region height is now widely considered to be due to an enhancement of the eastward electric field that is responsible for the formation of the anomaly during daytime[13]. The F-region vertical drift measurements at Jicamarca, Peru, by using the incoherent scatter radar show the occurrence of a peak in the upward vertical drift in the post-sunset hours during years of high sunspot activity[14-16]. However, there is no agreed opinion among the workers as to the origin of the post-sunset enhancement of the electric field in the immediate vicinity of the dip equator[17,18]. It has been shown by several workers[19-23] that the post-sunset enhancement of the electric field is due to a build-up of polarization fields in the F-region due to the sudden decrease of E-region conductivity at sunset (F-region dynamo effect). On the other hand, the recent work of Walton and Bowhill[24] demonstrated that the post-sunset enhancement of electric field can be produced by a simple E-region dynamo acting in conjunction with a thermospheric neutral wind system consisting of the first evanescent diurnal mode and the semi-diurnal mode, and that external effects such as an F-region dynamo are not necessary.

One well established feature of the diurnal variation of the anomaly during high sunspot activity periods is its conspicuous enhancement in the post-sunset hours[25,26]. The post-sunset enhancement of the anomaly has been shown, for quiet days, to result from changes in ionization density both at the crest (increase) and trough (decrease) latitudes[25]. The physical picture that emerges from these considerations[13] is that the post-sunset enhancement of the anomaly owes its origin to an apparent renewal of the 'fountain-effect' due to an increase of the eastward electric field. The increase in the eastward electric field causes an increased outflow of ionization from the trough region, thereby increasing the ionization density at the crests at the expense of that at the trough, thus enhancing the crest-to-trough density ratio of the anomaly. The earlier work of Rao[27] indeed showed the occurrence of large evening enhancements of ionization density near the crests of the anomaly, about 2 hr after the peak heights are attained at dip equator in the African zone during the years of high sunspot activity.

A very consistent feature revealed by the F-region vertical drift measurements at Jicamarca is the presence of considerable day-to-day variability, even during quiet days, in the evening peak of the upward vertical drift[14]. It would, therefore, be instructive to examine, as pointed out by Rishbeth[13], if the day-to-day variability of the evening rise of the F-region in the vicinity of the dip equator correlates well with that of the depth of the equatorial trough of the anomaly. In this paper we present the salient results of a detailed study of the relationship between the day-to-day changes in F-region height near the dip equator and the parameters of the equatorial anomaly in the Indian zone for the post-sunset period (1900 hrs LT).

2. Data and Analysis

Published data of ionosonde stations (see Table 1) in the Indian equatorial regions pertaining to a 2-yr period of high sunspot activity (1957-58, mean $R_z = 187$) have been used for the present investigation. It is to be pointed out here that the geographical locations of the ionosonde network in the Indian sector permit a study of only the northern half of the equatorial anomaly. The analysis is attempted for geomagnetically quiet and disturbed days selected as follows. Days on which the planetary magnetic index $A_p < 15$ on the day, < 25 on the previous day and < 60 two days before are taken as quiet days, as was done earlier by Lyon and Thomas[25]. Days on which $A_p > 25$ are taken as disturbed days. For each of the quiet and disturbed days of the months over the 2-yr period, the latitudinal variation of f_0F2 has been scrutinized at 1900 hrs LT and the location of the crest of the anomaly ascertained. The depth of the equatorial trough (R) of the anomaly, defined as the ratio of f_0F2 at the crest to that at the trough (Kodaikanal) is then evaluated. The normalized depth (d) of the anomaly is also simultaneously evaluated from the relation

$$d = \frac{f_0\text{F2 (crest)} - f_0\text{F2 (Kodaikanal)}}{f_0\text{F2 (Kodaikanal)}} \times 100$$

Table 1—Details of Ionosonde Stations

Station	Geographic coordinates		Dip latitude
	Lat., N	Long., E	°N
Kodaikanal	10°14′	77°29′	1.75
Tiruchirapalli	10°49′	78°42′	2.4
Madras	13°05′	80°17′	5.3
Bombay	19°00′	72°50′	13.0
Ahmedabad	23°01′	72°36′	18.6
Delhi	28°38′	77°13′	24.8

Use of f_0F2 at Kodaikanal, instead of that at Trivandrum right on the dip equator, for the evaluation of R and d is found appropriate as the anomaly trough manifests in the Indian sector not exactly at the magnetic equator but slightly towards the north of it and close to Kodaikanal during periods of high sunspot activity[12,26]. Information on the F-region height at the trough is derived from h'F data at Kodaikanal. The data pertaining to quiet and disturbed days of h'F at Kodaikanal and anomaly parameters (R and d) over the 2-yr period are divided into three seasonal groups of months, and the relationship between the day-to-day variability of the post-sunset increase of h'F at the trough and anomaly parameters is studied through correlation analysis. The three seasonal groups of months adopted are: Equinoxes (Mar., Apr., Sept. and Oct.), Summer (May-Aug.) and Winter (Nov.-Feb.).

3. Results and Discussion

Figs.1 and 2 depict the relationship between R and h'F at the trough for quiet and disturbed days, respectively. The straight lines drawn through the scatter plots in Figs. 1 and 2 are the regression lines obtained by least square fitting. Table 2 gives the relevant statistical details of the relationship between the variates shown in Figs.1 and 2. It is quite evident from Fig.1 and Table 2 that, on quiet days, the day-to-day variability of the depth of the anomaly in the post-sunset period correlates very well with that of the evening rise of F-region at the trough during equinoctial and summer months. The correlation, although statistically significant, is less in winter months compared to that in equinoxes and summer. The seasonal trends in the correlation between R and h'F at the trough during disturbed days (see Fig.2 and Table 2) are more or less the opposite of the ones during quiet days. The correlation during disturbed days is highly significant in winter and is comparatively less in summer and equinoxes. The relationship of the day-to-day variability of h'F at the trough with the normalized depth of the anomaly (d) is found to be essentially the same in all its details as that with R (Table 2).

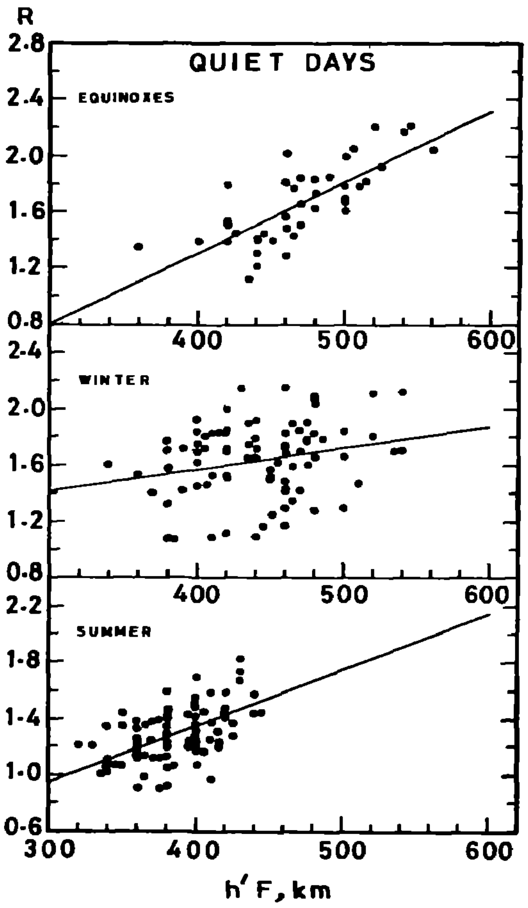

Fig. 1—Mass plots showing the relationship (at 1900 hrs LT) between the depth (*R*) of the equatorial anomaly and F-region height (*h*'F) at the trough on quiet days during the three seasonal groups of months

With a view to infer the relative role of the changes in ionization density at the crest and trough latitudes of the anomaly in the evidenced positive correlation between *h*'F at the trough and the anomaly parameters *R* and *d*, correlation coefficients between *h*'F at the trough and f_0F2 at the crest and trough latitudes have been evaluated for the various data sets. The results presented in Table 3 show that during both quiet and disturbed days changes in ionization density at the trough (decrease in f_0F2 with increase of *h*'F), more or less, play a predominant role in the noticed positive correlation of *h*'F with *R* and *d*. This is rather to be expected as the ionization density at the crests of the anomaly responds to changes in the eastward electric field in the trough region with a delay of about 2 hr corresponding to the time needed for the meridional transport of plasma from the trough to the crest latitudes[28]. Correlation coefficients between *h*'F at the trough (at 1900 hrs LT) and f_0F2 at the crest (at 2100 hrs LT) have, therefore, been evaluated for the different data sets. The results (Table 4) show that, except during quiet days of winter, the day-to-day variability

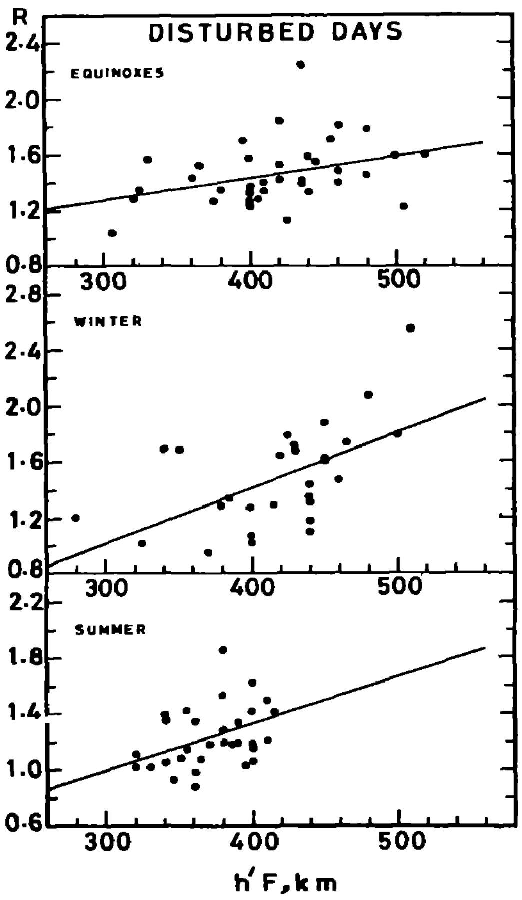

Fig. 2—Same as in Fig. 1 but for disturbed days

of the ionization density at the crest of the anomaly correlates very well (with a delay of 2 hr) with that of *h*'F at the trough in the post-sunset period.

Results of the present analysis demonstrate a positive correlation, in the post-sunset period, between the day-to-day changes in F-region height at the trough of the equatorial anomaly and the parameters representing the depth of the anomaly (*R* and *d*), during quiet as well as disturbed days of all seasons. Further, the day-to-day variability of the post-sunset height rise at the trough exhibits a negative correlation (with a delay of 2 hr) with that of f_0F2 at the crest of the anomaly, irrespective of season and during both quiet and disturbed days. The one major exception to these trends is the behaviour during the quiet days of winter months, when the ionization density at the crest of the anomaly is found to be more or less independent of the changes in the post-sunset height rise at the trough, even after allowing for the time needed for the meridional transport of ionization (see Table 4). This is an interesting behaviour of the equatorial anomaly in the Indian sector and does not seem to have been reported earlier. As already mentioned, it is now well established that meridional neutral winds affect the behaviour of the equatorial anomaly through their

Table 2—Statistical Data on the Relationship (at 1900 hrs LT) between h'F at the Trough and Parameters Representing the Depth of the Anomaly (R and d) during Different Seasons for Quiet and Disturbed Days

Season	Parameters compared	No. of points	Correlation coefficient (r)	Level of significance %	Slope of regression line
		Quiet days			
Equinoxes	h'F versus R	42	+ 0.759	>99.9	5.07×10^{-3}
	h'F -do- d	42	+ 0.758	>99.9	5.01×10^{-1}
Summer	h'F -do- R	82	+ 0.607	>99.9	3.99×10^{-3}
	h'F -do- d	82	+ 0.533	>99.9	3.53×10^{-1}
Winter	h'F -do- R	85	+ 0.254	$95 < r < 98$	1.56×10^{-3}
	h'F -do- d	85	+ 0.258	$95 < r < 98$	1.57×10^{-1}
		Disturbed days			
Equinoxes	h'F -do- R	37	+ 0.346	$95 < r < 98$	1.52×10^{-3}
	h'F -do- d	37	+ 0.344	$95 < r < 98$	1.50×10^{-1}
Summer	h'F -do- R	32	+ 0.407	$95 < r < 98$	3.34×10^{-3}
	h'F -do- d	32	+ 0.403	$95 < r < 98$	3.31×10^{-1}
Winter	h'F -do- R	28	+ 0.560	>99.0	3.87×10^{-3}
	h'F -do- d	28	+ 0.561	>99.0	3.87×10^{-1}

Table 3—Correlation Coefficients between h'F at the Trough and f_0F2 at the Crest and Trough Latitudes of the Anomaly during Different Seasons for Quiet and Disturbed Days

Season	Parameters compared	Correlation coefficient (r)	Level of significance %
	Quiet Days		
Equinoxes	h'F versus f_0F2 (T)	− 0.737	>99.9
	h'F -do- f_0F2 (C)	+ 0.312	$95 < r < 98$
Summer	h'F -do- f_0F2 (T)	− 0.526	>99.9
	h'F -do- f_0F2 (C)	+ 0.333	>99
Winter	h'F -do- f_0F2 (T)	− 0.259	$95 < r < 98$
	h'F -do- f_0F2 (C)	+ 0.029	—
	Disturbed Days		
Equinoxes	h'F -do- f_0F2 (T)	− 0.333	$95 < r < 98$
	h'F -do- f_0F2 (C)	− 0.115	—
Summer	h'F -do- f_0F2 (T)	− 0.508	>99
	h'F -do- f_0F2 (C)	+ 0.413	$98 < r < 99$
Winter	h'F -do- f_0F2 (T)	− 0.511	>99
	h'F -do- f_0F2 (C)	+ 0.386	$95 < r < 98$

Note: T-Trough, C-Crest

influence on the motions along the field lines produced by the mechanisms (electric fields and diffusion) responsible for the formation of the anomaly. East-west neutral winds may also influence the anomaly behaviour in the post-sunset period as pointed out very recently by Tsunoda *et al*[29]. The lack of a significant correlation between the height of F-region at the trough and f_0F2 at the crest of the anomaly during quiet days of winter months may be due to the presence of poleward neutral winds in the post-sunset hours in the Indian sector. A poleward wind (moderate or even weak) operating in association with, say, a large eastward electric field will enhance the poleward and downward diffusion of equatorial plasma into regions of enhanced loss rate, thereby, reducing f_0F2 (instead of increasing) at the crest of the anomaly. If this is to be the mechanism underlying the noticed behaviour during quiet days of winter months, the height of maximum electron density at the crest of the anomaly should be considerably lower in winter compared to that in summer and equinoctial months. Therefore, the behaviour of h_pF2 (height of maximum electron density based on a parabolic approximation of the layer) at the crest of the anomaly has been examined

Table 4—Correlation Coefficients between h'F (at 1900 hrs LT) at the Trough and f_0F2 (at 2100 hrs LT) at the Crest of the Anomaly during Different Seasons for Quiet and Disturbed Days

Season	No of points	Correlation coefficient (r)	Level of significance %
		Quiet Days	
Equinoxes	37	+ 0645	>99.9
Summer	82	+ 0 514	>99.9
Winter	79	+ 0.189	—
		Disturbed Days	
Equinoxes	29	+ 0.505	>99
Summer	28	+ 0.694	>99.9
Winter	26	+ 0.637	>99.9

Table 5—Seasonal Variation of the Height of Maximum Electron Density (h_pF2) at the Crest of Anomaly (at 2100 hrs LT) during Quiet Days

Season	Mean h_pF2 km	Standard deviation km
Equinoxes	398	44.5
Summer	434	35.4
Winter	345	30.2

during the three seasonal groups of months. The results presented in Table 5 clearly show that the mean value of h_pF2 is significantly lower in winter compared to that in equinoxes and summer, indicating a role of neutral wind effects during quiet days of winter months.

4. Conclusion

The present study lends substantial support to the prevailing understanding that the post-sunset enhancement of the equatorial anomaly during periods of high sunspot activity is due to an apparent strengthening of the 'fountain effect'. The study also suggests a definite possibility for the presence of poleward neutral winds in the post-sunset hours, on quiet days of winter months in the Indian equatorial region, during years of high sunspot activity.

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