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On the development of abnormally large postsunset upward drift of equatorial F region under quiet geomagnetic conditions

J. Hanumath Sastri

Indian Institute of Astrophysics, Bangalore, India

Abstract. The regular postsunset enhancement of upward drift of the equatorial *F* region is observed to be abnormally large on certain quiet days ($Ap \leq 5$) as manifested by an anomalous dusktime increase of *F* region height. We explored the origin of this extreme form of the quiet-time variability of postsunset vertical drift/height through case studies using data from the ionosonde and magnetometer networks in the Indian equatorial region. It is found that on the days with an unsually large postsunset increase of *F* region height near the magnetic equator, the diurnal profile of the equatorial electrojet (EEJ) strength is severly distorted (with a shift, in some cases, of *Sq*(H) phase from the usual time interval, charactersitic of the abnormal quiet days) with enhanced EEJ conditions in the postnoon period (1300-1600 LT). This is accompanied, near the magnetic equator, by higher values of *F* layer peak height (*hpF2*) and lower values of peak electron density (*f0F2*) in the early evening period (1600-1800 LT), compared with the monthly median/quiet day mean values. These changes in EEJ and *hpF2/f0F2* are consistently seen in all eight cases studied. It is suggested that the perturbations in plasma density distribution of equatorial *F* region increase the thermospheric zonal wind and its local time gradient and the ratio of flux-tube-integrated Pedersen conductivity of the *F* to *E* region. These modifications just prior to sunset of the properties of the equatorial thermosphere-ionosphere prompt an efficient *F* region dynamo action, resulting in the observed abnormally large dusktime increase of *F* region height.

1. Introduction

The global atmospheric dynamo is the dominant source of ionospheric electric fields at low latitudes during quiet geomagnetic conditions [e.g., *Richmond et al.*, 1976]. The interaction between the zonal component of the dynamo-generated electric field and the north-south geomagnetic field leads to **E**×**B** drift of *F* region plasma in the vicinity of the dip equator. The diurnal pattern of the electric field is such that the dip equatorial *F* region drifts upward by day and downward by night, with a conspicuous enhancement of the daytime upward drift after sunset before its reversal to downward direction [see *Fejer*, 1981]. The postsunset or prereversal enhancement is the dominant feature of the nighttime pattern of *F* region vertical drift (V_z), determined with ground-based diagnostics like the VHF incoherent scatter radar [see *Fejer*, 1981; 1991], HF Doppler radar [e.g., *Sastri et al.*, 1994], and HF ionosonde observations of *F* region height [e.g., *Batista et al.*, 1986; *Goel et al*, 1990] as well as with satellite measurements [e.g., *Fejer et al.*, 1995] . This feature is understood as being due to the *F* region dynamo mechanism which gains prominence at sunset when the *E* region conductivity rapidly decreases [e.g., *Rishbeth*, 1971a; *Heelis et al.*, 1974; *Farley et al.*, 1986; *Batista et al.*, 1986]. Recent work shows that the longitudinal (local time) gradient in thermospheric zonal wind acting in conjunction with that in *E* region flux-tube-integrated Pedersen conductivity across the sunset terminator is primarily responsible for the dusktime increase of F region upward drift in the vicinity of the magnetic equator [*Crain et al.*, 1993a, b].

One of the noteworthy features of the morphology of the postsunset enhancement of *F* region vertical drift is its marked day-to-day variability. Part of this variability is due to geomagnetic-activity-associated perturbations in equatorial ionospheric electric fields. These electric field disturbances are known to arise through

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mechanisms such as the prompt penetration to low latitudes of magnetospheric/high-latitude electric field variations associated with rapid and prominent changes in the B_z component of the interplanetary magnetic field (IMF), substorms and intensifications of symmetric/asymmetric ring current [see, for example, *Fejer et al.*, 1991, and references therein; *Sastri et al.*, 1992; *Abdu et al.*, 1995], and the disturbance dynamo action [*Blanc and Richmond*, 1980; *Fejer et al.*, 1983; *Fejer and Scherliess*, 1995]. Significant day-to-day variability of postsunset upward drift, however, persists even during geomagnetically quiet periods [e.g., *Fejer et al.*, 1991; *Sastri et al.*, 1994]. The focus of this paper is on an extreme form of the quiet-time day-to-day variability, namely, the occasional development of an abnormally large postsunset enhancement of F region upward drift and hence its height. The objective is to explore the origin of such unusual evening enhancements of upward drift as a step in the direction of eventually gaining, a comprehensive understanding of the quiet-time variability of dusktime equatorial F region vertical drifts. We present evidence here to show that an abnormally large uplift of the dusktime F region consistently develops on quiet days with an abnormal development of the equatorial electrojet (EEJ) strength (and hence the zonal electric field that drives it) during the daytime and attendant changes in F region plasma density and height in the dip equatorial region. We advance the qualitative interpretation that the evidenced changes in the electric field and F region plasma density/height render the ambient thermospheric zonal winds and flux-tube-integrated Pedersen conductivity distribution conducive to a very effective F region dynamo action, leading to an abnormal enhancement of the height of the equatorial F region in the postsunset hours.

2. Observations and Discussion

The present work is based on data from the ionosonde and magnetometer networks in the Indian equatorial region. The details of the network stations are given in Table 1. Careful scrutiny of the ionosonde data of the dip equatorial station Kodaikanal for the period July 1957 to December 1969 yielded a data sample of 8 days with a conspicuously large postsunset rise of F region height. This extreme form of the quiet-time variability of F region height may be seen in Figure 1, wherein the temporal variation of the height of the bottomside F region, $h'F$ for the evening-midnight interval is shown for the 8 events that became available for study. The development of an impulsively large height rise over Kodaikanal during 1800-2000 LT on all 8 days is quite obvious from Figure 1. The deviation of the postsunset maximum of $h'F$ from the corresponding International Quiet Day mean varies from 52 to 117 km (16 to 45%; in seven out of the eight cases >23%) on individual days. The events studied here are thus noteworthy because the departure from the mean is much higher than the normal variability of ionospheric characteristics of 10-15%. The same inference follows even if the monthly median pattern of $h'F$ is taken as a reference as may be seen from Figure 1. The events correspond to geomagnetically quiet days ($Ap \leq 5$) with some of them being the designated International Quiet Days (IQD) of the respective months. They pertain to epochs of low solar activity with the monthly mean solar 10.7-cm flux in the range 72-93 flux units and daily values in the range 71-102 flux units. A preferential occurrence of the abnormal postsunset height rise in northern winter and equinoctial months is apparent in the data sample of

Table 1. Details of Stations

Station	Geographic Coordinates		Dip
	Latitude	Longitude	
	Ionosonde Network		
Delhi	28.63°N	77.22°E	42.4°N
Ahmedabad	23.00°N	72.60°E	34.0°N
Bombay	19.00°N	72.83°E	24.7°N
Hyderabad	17.35°N	78.47°E	21.5°N
Madras	13.08°N	80.28°E	10.5°N
Tirucurapalli	10.82°N	78.70°E	4.8°N
Kodaikanal	10.23°N	77.48°E	3.5°N
Trivandrum	8.55°N	76.87°E	0.6°N
	Magnetometer Network		
Alibag	18.63°N	72.87°E	24.5°N
Annamalainagar	11.37°N	79.68°E	5.4°N
Kodaikanal	10.23°N	77.48°E	3.5°N
Trivandrum	8.55°N	76.87°E	0.6°N

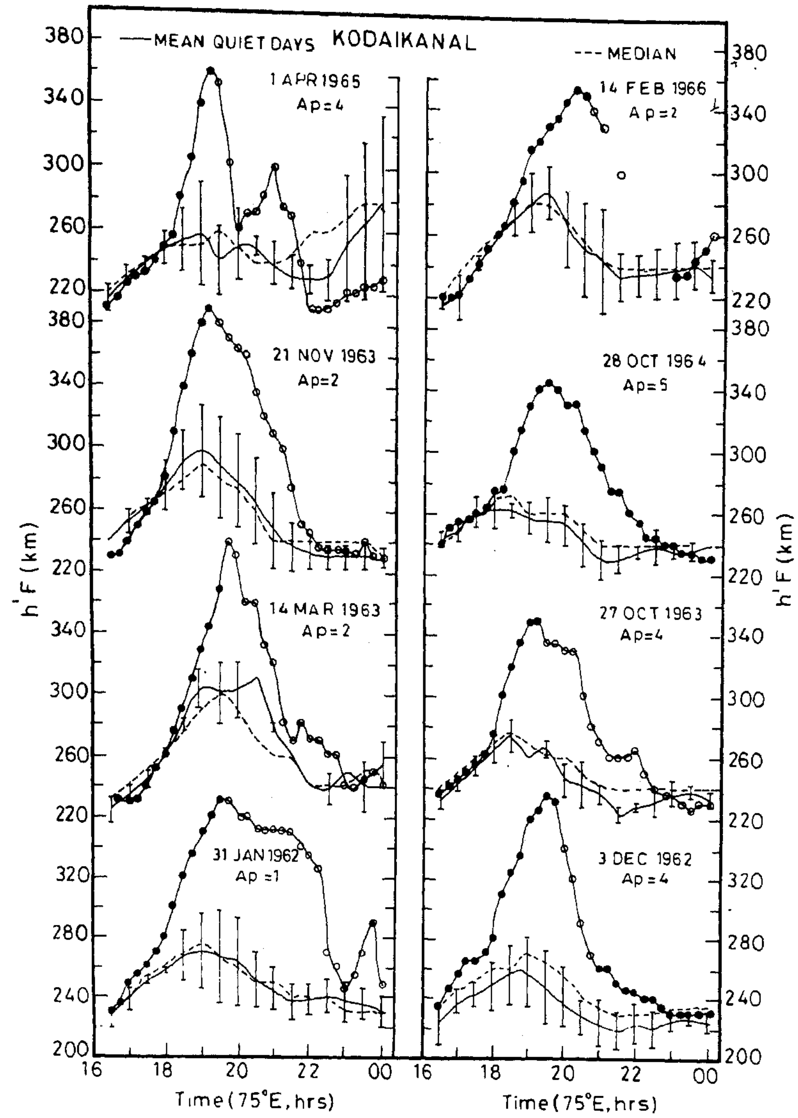

Figure 1. Variation of the height of the bottomside *F* region ($h'F$) at Kodaikanal (dip 3.5°N) during the evening-midnight period, illustrating the occasional occurrence of abnormally large postsunset height rise of the equatorial *F* region on quiet days (curves with solid circles). The monthly median values (dashed curve) and the mean values of $h'F$ for the International Quiet Days of the month are also shown for reference. Vertical bars represent the standard deviations of the mean values. Open circles indicate spread-*F* conditions.

this preliminary study. Examination of a much larger ionosonde database is, however, necessary to ascertain the seasonal/solar cycle trends in the occurrence of the unusually large postsunset rise of the equatorial *F* region. It is interesting to note from Figure 1 that equatorial spread-*F* (ESF) conditions followed the anomalous dusktime increase of *F* region height on 7 out of the 8 days in our sample. The occurrence of ESF conditions at Kodaikanal is generally low at solar minimum [*Sastri et al.*, 1975].

We have examined whether there are any distinct and repeatable (from event - to - event) changes during daytime in the strength of the equatorial electrojet (indicative of that in the equatorial zonal electric field) and resultant variations in the equatorial *F* region plasma density and height, on the days with an anomalous dusktime uplift of *F* region over Kodaikanal. The study is motivated by some known aspects of the equatorial electrodynamics. First, **E** × **B** vertical plasma drift due to the zonal electric field governs the daytime *F* region plasma density distribution in the dip equatorial region [see *Moffet*, 1979; *Anderson*, 1981, and references therein; *Preble et al.*, 1994; *Balan and Bailey*, 1995]. Modifications in *F* region plasma density brought about by temporal changes in the zonal electric field may effect, through the ion-neutral drag mechanism, the thermospheric zonal wind and its logitudinal gradient, which are important factors underlying the *F* region dynamo process. This is all the more the case because the longitudinal gradient in *E* layer conductivity across the sunset terminator is not expected to present significant day-to-day variability. Second, recent studies consistently show a close relationship between the strength of the equatorial ionization anomaly (EIA) in the early evening hours (1600-1800 LT) and postsunset generation of equatorial spread-F (ESF) irregularities, for which the dusktime enhancement of F layer vertical upward drift (i.e., elevated F layer) is a well-known prerequisite [*Raghavarao et al.*, 1988; *Sridharan et al.*, 1994; *Jayachandran et al.*, 1997].

We have made use of data from the magnetometer and ionosonde networks in the Indian sector for the purpose of assessing the changes in EEJ and F region plasma density and height of the equatorial F region (see Table 1 for details of stations). Out of the four magnetometer stations, Trivandrum and Kodaikanal are within the electrojet belt and Annamalainagar is at the northern fringe of the belt, while Alibag is well outside the influence of the electrojet. Data from this network are widely used in studies of the changes in EEJ under both quiet and disturbed conditions [e.g., *Rastogi and Patel*, 1975; *Sastri*, 1981a, b, 1988]. The ionosonde network stations cover the northern part of the equatorial ionization anomaly (EIA) region right from the magnetic equator to well beyond the crest.

In Figure 2 are shown the latitudinal profiles of ΔH, the deviation of the H-field from the nighttime base level, at specific daytime hours on 4 of the 8 days studied here (curves with solid circles). The local times are chosen mainly to bring out the departure of the diurnal

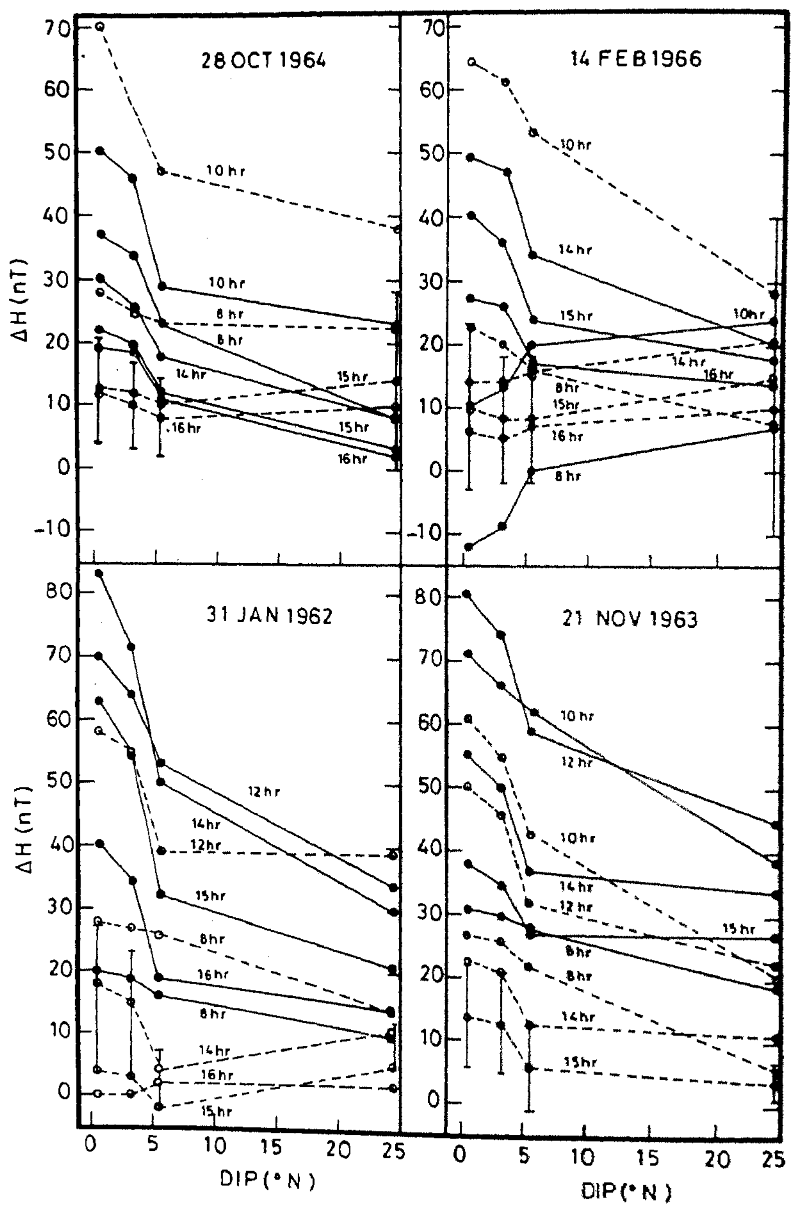

Figure 2. Examples of the dip angle variation of ΔH at specific hours on days with an abnormal postsunset increase of $h'F$ at Kodaikanal near the magnetic equator (curves with solid circles). The corresponding mean profiles of ΔH for the International Quiet Days of the month (curves with open circles) are also shown for reference. Standard deviations of the mean values are shown for 1500 LT for all days except October 28, 1964, for which they are shown for 1600 LT.

development of the strength of the EEJ on the event days from the quiet-time pattern of the month, which is also shown in the figure for reference (dashed curves with open circles). Theoretical and ground-based magnetometer studies show that EEJ manifests as a positive maximum in ΔH at the center of the electrojet belt, while ΔZ, the deviation of the Z - field from the nighttime base, assumes maximum negative (positive) values at the northern (southern) fringes of the belt [see *Onwumechilli*, 1967, and references therein]. The positive maximum of ΔH and the negative/positive maxima of ΔZ grow and decay in amplitude during the course of the day as the electrojet current varies, primarily as the electron density in the E region varies with the solar zenith angle. Moreover, on normal quiet days the Sq(H) phase, i.e., the time of diurnal maximum of H - field, at the dip equatorial stations mostly occurs in the interval 0930-1230 LT (in the interval 1030-1130 LT on 50 % of the days). It is only on $\sim$ 7% of the quiet days that the maximum occurs outside the specified interval, and these are termed as the abnormal quiet days (AQD) [e.g., *Last et al.*, 1976; *Sastri and Murthy*, 1978].

The normal buildup and decay of the dip equatorial enhancement of ΔH with a maximum around noon may clearly be seen in the mean profiles for the International Quiet Days (IQD) of the month presented in Figure 2. In contrast, on the days with an abnormal postsunset rise of the F region over Kodaikanal, there is a significant departure of the local time pattern of the dip equator enhancement of ΔH and hence of EEJ from the quiet-day pattern. The common feature noticeable on all 4 days presented in Figure 2 is the occurrence of higher values of EEJ in the postnoon hours (1300-1600 LT). This behavior is also seen on the 4 other days of our data sample but is not shown here to avoid repetition. Changes are also seen in the diurnal pattern of ΔZ at Annamalinagar (not shown here) that corroborate the perturbations seen in the EEJ (see, for example, *Sastri*, [1981a] for details of the ΔZ behavior on February 14, 1966). In addition, on 3 out of the 8 days, the diurnal maximum of the H - field at the electrojet stations occurred outside the normal interval of 0930-1230 LT. These days (January 31, 1962, December 3, 1962 and February 14, 1966) therefore belong to the AQD category. It has been shown earlier that the occasional abnormal shift of Sq(H) phase at electrojet stations is due to perturbations in EEJ charecteristic of counter-electrojet (complete or partial) conditions around the normal time of the durnal maximum of the H - field, and that enhanced EEJ conditions prevail either thereafter (around 1400 LT) or prior to (around 0800 LT) depending on whether the shift of Sq(H) phase is towards the afternoon sector (P.M. AQD) or forenoon sector (A.M. AQD) [*Sastri*, 1981a, b]. The results presented in Figures 1 and 2 thus suggest a linkage between the extreme forms of the day-to-day variability of the amplitude and phase of Sq(H) in the electrojet belt and the postsunset rise of the equatorial F region.

Figure 3 shows the latitudinal profiles of f_0F_2 during the early evening hours (1600-1800 LT) for the 4 days dealt with in Figure 2 (curves with solid circles). Also shown are the corresponding profiles of monthly median values of f_0F_2 (dashed curves) as well as mean values of f_0F_2 at 1800 LT for the International Quiet Days (IQD) of the month (for stations with adequate data coverage). It is well known that the diurnal pattern of development and decay of the equatorial ionization anomaly (EIA), characterized by crests on either side of the dip equator and a trough centered on it in the latitudinal profiles of f_0F_2, depends on the phase of solar cycle. For example, during equinoxes at solar minimum, EIA forms at 0900 LT and attains maximum development (when either the depth of the anomaly or the latitudinal separation of the two crests is maximum) at 1600 LT, followed by decay and eventual disappearance by 2100 LT. The diurnal manifestation of EIA also exhibits seasonal dependence at any epoch of the solar cycle. The latitudinal profiles of the monthly median f_0F_2 in Figure 3 clearly show a well-developed EIA at 1600 LT with the northern crest around 20° dip and its gradual decay thereafter, as can be expected. The behavior of EIA on days with an anomalously large postsunset uplift of the F region over kodaikanal differs from this pattern on two counts: (1) There is a significant reduction in f_0F_2 close to the dip equator, i.e., in the trough region of EIA during 1600-1800 LT and (2) the crest of the EIA is seen at higher latitudes (January 31, 1962 and November 21, 1963) and/or the depth of the EIA (ratio of f_0F_2 at crest to that in the trough region) is higher (February 14, 1966). Both of these features represent an intensification of EIA during the early evening hours on the days with an abnormal postsunset uplift of F region over Kodaikanal. It is established that EIA owes its existence to the fountain mechanism wherein plasma lifted up around the dip equator by $\mathbf{E}\times\mathbf{B}$ vertical drift diffuses downward along the magnetic field lines under the influnece of gravity and pressure gradient forces, leading to a trough of ionization centered on the dip equator and crests on either side of it [see *Moffet*, 1979; *Anderson*, 1981; *Preble et al.*, 1994; *Balan and Bailey*, 1995, and references therein]. EIA responds to changes in EEJ (zonal electric field) with a delay ($\sim$2 hours) because of the finite time taken for the plasma to get transferred from the equatorial F region to higher altitudes and latitudes. The delayed occurrence of the changes in EIA (early evening hours) with reference to those in EEJ (postnoon hours) on the event days (see Figures 2 and 3) is thus in conformity with the current understanding of EIA.

The height of the daytime F region in the vicinity of the magnetic equator is sensitive to vertical plasma drift due to the zonal electric field. Therefore there ought to be marked perturbations in F region height over Kodaikanal on the days with an abnormal postsunset height rise there because of the changes in EEJ. These height perturbations are to be seen in the height of peak electron density of the $F2$ layer (h_pF_2) and not in $h'F$. This is because $h'F$ is not sensitive to plasma transport processes during the daytime. Over this portion of the diurnal cycle, the vertical drift-related changes in $h'F$ will, in general, be obscured by ionization production by solar radiation, and the rate of change of electron density in the altitude range 200-300 km due to chem-

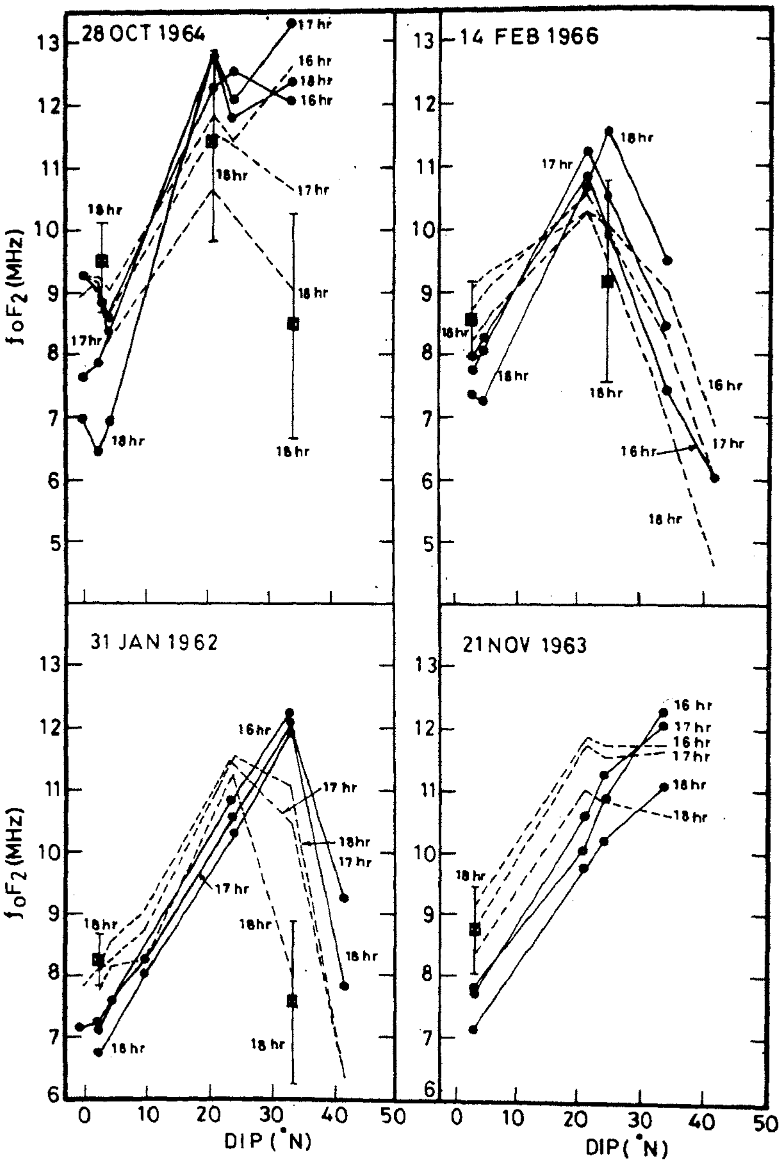

Figure 3. Dip angle variation of f_0F_2 in the Indian equatorial region at specific hours in the daytime, corresponding to the days of Figure 2 (curves with solid circles). The monthly median profiles of f_0F_2 are shown for reference. The mean values of f_0F_2 at 1800 LT for the International Quiet Days of the month are also shown, along with the standard deviations (for stations with adequate data).

ical loss tends to be greater than that due to vertical drift-induced change. Figure 4 presents the variation of h_pF_2 at Kodaikanal over the interval 0600-2100 LT for the 4 days corresponding to Figure 2 (curves with solid circles) along with the mean h_pF_2 for the International Quiet Days of the month. It is clear from Figure 4 that h_pF_2 is indeed higher over the period 1300-1700 LT on the event days, in comparison with the mean values for quiet days. The response of h_pF_2 to the forenoon (reduction) and afternoon (enhancement) changes in the zonal electric field (EEJ) is prominently seen on February 14, 1966 (see *Sastri* [1981a, 1982] for further discussion of this event from the viewpoint of AQD phenomenon and its effects on the F region). The variation of h_pF_2 at Kodaikanal is thus consistent with the expected effect of the inferred changes in EEJ and hence vertical plasma drift on F region plasma density distribution close to the dip equator. It is worth noting from Figure 4 that the conspicuously large postsunset uplift of the F region over Kodaikanal on the event days manifests not only in $h'F$ (see Figure 1) but also in h_pF_2, supporting the view that it is due to enhanced vertical plasma drift.

The cause-effect relationship between the perturbations in EEJ and plasma density/height of the equatorial F region in the noon-sunset period and the development of an abnormally large postsunset F layer height rise near the magnetic equator evidenced in the present study may be explained as follows. It is widely accepted that the postsunset enhancement of F region

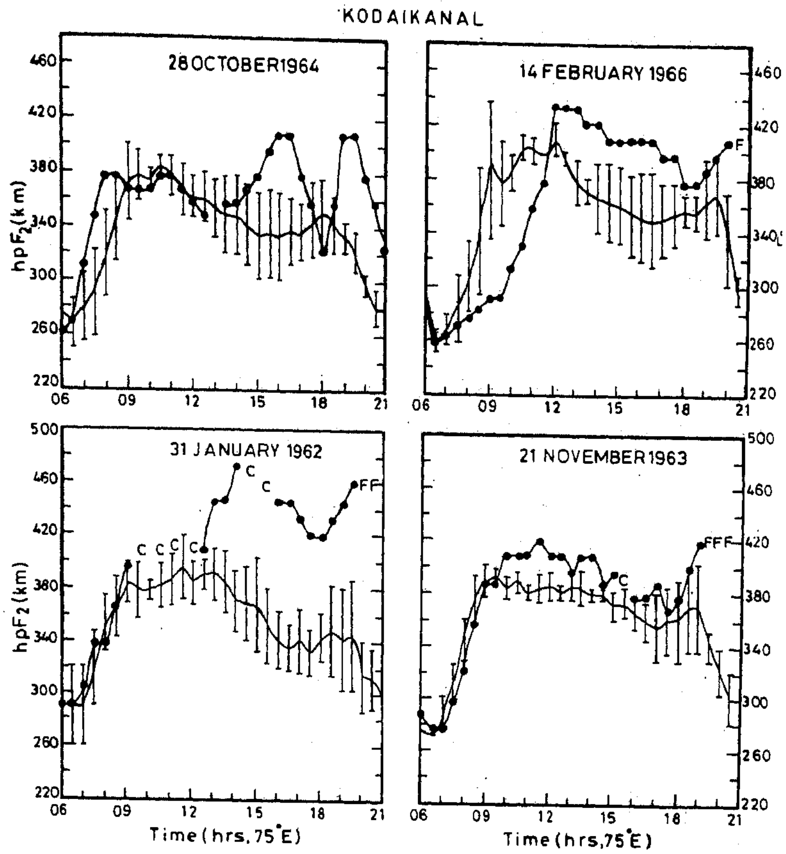

Figure 4. Variation of height of F region peak density (h_pF_2) at Kodaikanal over the interval 0600-2100 LT corresponding to the days shown in Figure 2 (curves with solid circles). The mean pattern of h_pF_2 for the International Quiet Days of the month is also shown for reference. Vertical bars represent standard deviations of mean values.

upward drift is basically due to the contribution of electric fields due to F region dynamo action [e.g., *Rishbeth,* 1971a; *Heelis et al.,* 1974; *Farley et al.,* 1986; *Batista et al.,* 1986; *Crain et al.,* 1993 a, b]. The main ingredients of F region dynamo action are thermsopheric zonal wind and its longitudinal (local time) gradient and the longitudinal gradient in flux-tube-integrated E region Pedersen conductivity across the sunset terminator. The latter, which depends on the alignment of the sunset terminator with the magnetic meridian, is not expected to undergo any significant day-to-day variations. It may, however, vary with season in any given longitude sector, leading to seasonal differences in the postsunset enhancement of F layer vertical drift and related phenomena like generation of ESF irregularities [e.g., *Tsunoda,* 1985]. The postsuneset enhancement of F layer upward drift is known to exhibit a positive dependence on solar 10.7-cm flux, $F_{10.7}$ [e.g., *Fejer et al.,* 1991; *Ramesh and Sastri,* 1995; *Sastri,* 1996]. However, it is unlikely that day-to-day variations in solar flux are responsible for the occasional anomalous development of the postsunset height rise observed at Kodaikanal. The variation in $F_{10.7}$ values on the event days with reference to monthly mean values is $\leq 10\%$ in our data sample. On the basis of the relationship between the postsunset peak of F region vertical drift (V_{zp}) at Kodaikanal and $F_{10.7}$ [*Ramesh and Sastri,* 1995; *Sastri,* 1996], we can expect a corresponding variability of $\sim$8% in V_{zp} in local winter and equinoctial months, relevant to present work (quantitative expressions for the dependence of dusktime F region height at Kodaikanal on $F_{10.7}$ are not available). It is therefore not unreasonable to attribute the anamously large dusktime rise of the F region over Kodaikanal to thermospheric zonal wind variability.

The thermospheric zonal winds due to solar forcing (high-latitude forcing due to auroral sources can be neglected because the events studied here belong to quiet days with $Ap \leq 5$) are westward by day and eastward by night, with the reversal in direction at $\sim$1600 LT [*Herrero and Mayr,* 1986]. The early evening (1600-1800 LT) is thus a period of large local time gradients in zonal winds. The zonal wind system at equatorial latitudes can effectively be modulated by the spatial distribution of F region plasma density (EIA) and its temporal variations through ion-neutral drag, which is resistive force in thermopsheric dynamics. Examples of this physical situation are: (1) the postsunset increase of eastward winds with a maximum around 2100 LT, which is generally understood as partly due to a decrease in ion-neutral drag associated with the postsunset uplift of the equatorial F layer [*e.g., Rishbeth,* *1971b; Heelis et al., 1974; Anderson and Roble, 1974]* and (2) the recently found anomalous and symbiotic latitudinal variations in neutral gas temperature, zonal winds, and electron density in the equatorial upper atmosphere, termed ETWA, which has been explained in terms of the effect, through ion-neutral drag, of EIA on zonal winds, which, in turn, influence the energy transport and hence the neutral temperature [*Raghavarao et al.*, 1991]. We interpret the early evening changes in EIA, particularly in h_pF_2 and f_0F_2 at Kodaikanal on the event days as responsible for the anomalous postsunset uplift of the F region over Kodaikanal. The decrease in f_0F_2 and increase in h_pF_2 (both are related and represent strengthening of the fountain process) reduce the drag on neutrals and enhance the zonal wind and its local time gradient just prior to sunset. The strengthening of the plasma fountain will, in addition, enhance the ratio of flux-tube-integrated Pedersen conductivity of the F to E region, in view of the increased plasma content along the flux tubes with high apex altitudes over the magnetic equator [*Crain et al.*, 1993a]. Both of these changes in the properties of the equatorial upper atmosphere constitute favorable conditions for a very efficient F region dynamo action, which is necessary to produce the observed abnormally large postsunset rise of equatorial F region on certain quiet days. Direct and simultaneous measurements of thermospheric zonal wind and F region vertical drift in the evening equatorial upper atmosphere are required to confirm the proposed origin of one of the extreme forms of quiet-time variability of dusktime F region vertical drift near the magnetic equator that is studied here.

Conclusions

1.Distinct and significant perturbations in the strength of the equatorial electrojet (EEJ) and equatorial F region plasma distribution are shown to precede the occasional abnormally large postsunset rise of the F layer near the magnetic equator that is observed in northern winter and equinoctial months of low solar activity.

2.The perturbations are characterized by postnoon enhancements of EEJ (zonal electric field) and attendant early evening changes in EIA. The observed changes in the F region plasma density distribution are interpreted as leading to modifications of the thermospheric zonal winds and flux-tube-integrated Pedersen conductivity distribution favorable for a very effective F region dynamo to operate, resulting in the observed anomalously large postsunset uplift of F region close to dip equator.

3.The present study strengthens the view that the postsunset behavior of equatorial ionosphere is sometimes predetermined by the properties of the thermosphere-ionosphere system in the early evening hours.

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J. H. Sastri, Solar-Terrestrial Physics, Indian Institute of Astrophysics, Koramangla, Bangalore 560 034, India(e-mail: jhs@iiap.ernet.in).

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