3.1. Introduction - Equatorial Spread F

The nighttime phenomenon of Equatorial Spread F (ESF) that refers to the generation of plasma density irregularities of a wide spectrum of scale sizes, spanning from few centimetres to few hundred kilometres, has been receiving the attention of ionospheric and plasma physicists alike for the last few decades. The ESF phenomenon was first reported by Booker and Wells (1938). They observed the spreading of the F-region trace on the ionograms of Huancayo that was 'caused' by the ionization irregularities. The ESF that manifests itself in various forms like spread in the F-region echoes in ground based ionosondes (Chandra and Rastogi, 1972), plumes in HF and VHF backscatter radars (Woodman and La Hoz, 1976), as intensity bite outs in the thermospheric airglow (Mendillo and Baumgardner, 1982), as depletion in plasma densities (or bubbles) in the in situ satellite and rocket measurements (Rino et al., 1981; Laakso et al., 1994), and also as scintillations in VHF and UHF satellite beacon receivers (Tsunoda, 1985; Sridharan et al., 1997; Rao et al., 1997; Abdur, 2001), is known to be due to the generation of ionospheric irregularities.

The equatorial F-region ionospheric irregularities occur when the plasma density at the bottomside of the F-region presents a non-tilted upward gradient $\nabla n$ (where $n$ is the plasma density), so that it is antiparallel to the gravitational acceleration ($g$) and both are perpendicular to earth's horizontal magnetic field lines at the magnetic equator. Under these conditions, any perturbations in the plasma density at the bottomside of the F-region can induce an electric field ($\delta E$) which may lead to a plasma instability known as Rayleigh-Taylor (R-T) plasma instability. Also, the eastward electric field ($E$) at the bottomside of the equatorial F-region generates an upward $E\times B$ plasma drift parallel to the plasma density gradient and antiparallel to 'g' which makes the plasma unstable [Fejer and Kelley, 1980]. The schematic diagram showing the linear R-T instability and $E\times B$ instability is given in Figure 3.1. The figure illustrates the bottom side of the equatorial F-region. In the
Figure 3.1. Schematic diagram depicting how the linear Rayleigh-Taylor and E×B instabilities operate on a sharp density gradient. The gravitational and Pedersen currents deposit charge in such a way that the perturbation drifts. E/B causes the disturbance to grow (Fejer and Kelley, 1980).
F-region, gravitational \[ \left( e n (\ddot{z} \times \dot{z}) / \Omega_z \right) \] and Pedersen \( (\sigma_p E) \) current flow, where \( e \) is the ion charge, \( n \) is the ion density, \( \ddot{z} \) is a unit vector parallel to \( \vec{B} \), \( \Omega_z \) is the ion gyro frequency and \( \sigma_p \) is the Pedersen conductivity. These currents are carried by the ions. Both gravity 'g' and electric field 'E' driven currents cause charge accumulation. The resultant polarization electric field amplifies the disturbance. The gravitational field 'g' is always antiparallel to electron density 'n' on the bottomside, while the \( \vec{F} \times \vec{B} \) process is only destabilizing when the plasma is moving upward.

The generalised R-T instability involves driving agencies such as gravity (Haerendel, 1973), electric fields (Hanson et al., 1986), zonal winds in the presence of tilted ionosphere (Kelley et al., 1981) and vertical winds (Sekar and Raghavarao, 1987) and is believed to be the causative mechanism for the development of ESF irregularities. The basic mechanism responsible for the generation of ESF is the R-T plasma instability followed by a hierarchy of other instabilities (Haerendel, 1973) eventually resulting in the generation of plasma density irregularities of wide ranging scale sizes and characteristics. Haerendel (1973) proposed the hierarchy of instability mechanism as follows: (i) Collisional R-T instability mechanism driven by the zero order electron density gradient, (ii) \( E \times B \) gradient drift instability arising due to the sharp electron density gradients set up by the collisional R-T instability mechanism. (iii) then collisionless R-T instability arising due to sharp electron density gradients and finally, (iv) kinetic drift waves growing off these irregularities as they attain large amplitudes. The basic idea of the multi-step (hierarchy) process for the growth of irregularities is now well accepted although there are some differences in details of the process.

The prereversal enhancement of F-region electric field is also known to be one of the prerequisite for the generation of spread F. The enhanced electric field pushes the F layer to a higher altitude, where the ion-neutral collision frequency is small, thereby creating a steep plasma density gradient in the bottom side of F-region. The bottomside of the F-region steepens at night due to chemical recombination effects and upward ambient electrodynamic forces. This in turn causes plasma density depletions or bubbles to be formed on the bottomside which then steepen on their top and nonlinearly rise to the topside by polarization (induced) \( E \times B \) motion and cause topside spread F. In other words, during the prereversal enhancement, the zonal
electric field component becomes strongly eastward, thereby enhancing the growth rate for the R-T instability. Figure 3.2 depicts the basic equatorial nighttime ionospheric F-region geometry under which ESF occurs. $N(y)$ represents the background zero order electron density as a function of altitude ($y$). Gravity, $g$, points down, the ambient geomagnetic field, $B$, is horizontal and pointing north ($z$), and $k$ represents a horizontal perturbation vector and points westward ($x$).

The primary Rayleigh-Taylor mechanism responsible for the generation of ESF essentially depends on the plasma scale length $L$, the acceleration due to gravity $\cdot g$, the ion-neutral collision frequency $v_{\text{in}}$, the eastward zonal wind in the presence of a westward gradient and vertically downward wind in the presence of an upward density gradient. The expression for the growth rate of the R-T instability in the nighttime F-region including vertical wind has been shown by Sekar and Raghava Rao (1987) to be

$$\gamma = \frac{1}{L} \left[ \frac{g}{v_{\text{in}}} + \left( \frac{v_{\text{in}}}{\omega_i} \right) w_x - w_z \right]$$  \hspace{1cm} (3.1)$$

where.

$v_{\text{in}}$ = ion-neutral collision frequency

$\omega_i$ = gyro-frequency of ions

Figure 3.2. Basic equatorial spread F geometry.
\[ w_x = \text{zonal wind (eastward)} \]
\[ w_z = \text{vertical wind (upward)} \]
\[ g = \text{acceleration due to gravity} \]
\[ L = \text{Plasma scale length} \]

The in situ measurements by vapour release techniques and nonlinear numerical simulations had shown that vertical winds could play a crucial role in the triggering of ESF [Raghavara et al., 1987; Sekar and Raghavara, 1987; Sekar et al., 1994]. Sekar and Raghavara (1987) by using equation 3.1 have shown that a downward wind of 1 m/s can cause the same growth rate as a 200 m/s eastward wind at 260 km, while a 16 m/s downward wind at 300 km can be as effective as that of gravitational drift.

Another important parameter controlling the onset of ESF is the nighttime thermospheric meridional wind whose amplitude and direction vary greatly from day to day. The F-region dynamo field arises from dynamo action by thermospheric winds produced by the pressure inequalities due to solar EUV heating, with contributions from heating at auroral latitudes. During daytime when the underlying E-region is sunlit and sufficiently conducting, it will short-circuit the polarization field developed in the F-region. The F-region polarization field has east-west components near the sunset and sunrise terminators, where the current geometry is strongly influenced by the rapid changes in E-region electron density due to recombination process. This east-west component gives rise to vertical drift. At night when the E-region conductivity is small, the short-circuiting effect disappears and the polarization field at F-region heights builds up. The F-region dynamo has higher internal impedance and is essentially a current generator. With regard to the neutral wind effects, it has been shown by Maruyama, (1988) and Mendillo et al. (1992) that poleward wind would inhibit ESF by pushing the F-region ionization to lower altitudes along the magnetic field lines, which would enhance the E-region conductivities thereby loading the F-region dynamo field and inhibiting the eventual lifting of the F-layer. With regard to the zonal wind, its role as a destabilizing factor for the R-T instability becomes more important in the presence of a zonal gradient in electron density, which normally is the case during sunset. Further, it is the same zonal wind that engenders the F-region dynamo by crossing with the N-S magnetic
field, which in turn is responsible for the post sunset F-region height rise. From the above discussion it could be construed that neutral winds, both zonal and meridional, the former through F-region dynamo and the latter by causing uplift/downpush of the F-layer and by bringing-in net changes in the field line integrated conductivities are very important with regard to the triggering of the primary R-T instability and many times may even hold the key to the enigmatic problem of the day to day variability of ESF. By coordinated experiments using ground based electromagnetic probing (both active and passive), covering visible to the radio frequency parts of the electromagnetic spectrum in different bands and also by in situ rocket and satellite borne measurements, supplemented by complex theoretical modeling, a fairly good understanding of the basic processes that are responsible for ESF has been obtained [Morse et al., 1977; Szczechewicz et al., 1981; Raghavara Rao et al., 1987]. Raghavara Rao et al. (1984, 1987) have reported experimental evidence for the presence of large-scale gradients in the horizontal and vertical motion of plasma around the height region of 200 km by releasing Barium-Strontium (Ba-Sr) cloud over Sriharikota rocket range (dip = 6.6°N) which was conducted at time of the onset of ESF.

A number of satellite borne and ground based optical and VHF radar based experiments have given information on the thermospheric neutral winds [Farley et al., 1970; Burnside et al., 1983; Raghava Rao et al., 1987; Herrero et al., 1988; Burnside and Tepley, 1989; Krishna Murthy et al., 1990; Sridharan et al., 1997]. Burnside et al. (1983) derived thermospheric meridional winds at Arecibo (Geog. Lat. 18.5°N; Geog. Long. 66.8°W) from incoherent scatter radar observations. They reported that in the spring and summer months, the meridional wind is strongest near 2100 AST with southward (equatorward) velocity ranging from 50 to 100 m/s. At about 0100 AST, slackening of the equatorward wind occurs, sometimes with even reversal, to recover later in the postmidnight period. They also observed that in winter months, the meridional winds are lower and the nocturnal variations are less pronounced as compared to all other seasons. Miller et al. (1986) deduced thermospheric meridional winds from ionospheric $h_{m}F2$ data implying a direct control of the meridional wind component on the height of maximum electron density ($h_{m}$). Herrero et al. (1988) by using in situ measurements from the Atmospheric Explorer
satellite obtained the daily variations of meridional wind at ±18° latitude for summer and winter months. They found that at 270 km a reversal of meridional wind, poleward to equatorward, occurs at around 2000 hrs LT. The equatorward wind reaches its peak at 2200-2300 hrs LT, the peak occurring later in winter than in summer. It subsides in the postmidnight period, reversing to poleward direction in the early morning hours, with the reversal occurring earlier in summer. *Burnside and Tepley* (1989) by using FPI technique at Arecibo showed typical nighttime variation of meridional wind, which generally agrees with the observations of *Burnside et al.* (1983). *Krishna Murthy et al.* (1990) devised a method of deducing nighttime equatorial thermospheric meridional winds from h′F data of ionograms of two closely spaced locations, Trivandrum (TRV) [8.6°N, 77°E, dip lat. 0.5°N] and SHAR (S) [13.7°N, 80.2°E, dip lat. -10°N] in the equatorial zone and their method had been validated by *Sekar and Sridharam* (1992) by using results from vapour release experiments from SHAR. *Sridharam et al.* (1997) by using a vapour release method over Shriharikota rocket range (dip -10°N) and a host of ground-based complementary experiments spread all over India showed the presence of large scale gradients in the ambient electric fields at -185 km altitude and also showed the presence of vertical winds of significant magnitudes at higher altitudes at the time of the onset of ESF. One of the significant results presented by them is the presence of large scale irregularities in the ion densities at heights above 250 km in a region of negative background density gradient. It is well appreciated that there are still certain enigmatic aspects like the day to day variability that remain to be understood.

Usually, after local sunset, the base of the F-region gets lifted up due to two main reasons (i) the recombination of molecular ions in the lower-F region and (ii) the electrodynamical lifting of the F-region due to the F-region dynamo [Rishbeth, 1981; Eccles, 1998]. The lifting of the F-layer to 300 km and beyond has been generally construed to be a necessary condition, though may not be sufficient [Rishbeth, 1981]. The exact mechanism responsible for the post sunset F-layer lifting, i.e., whether it is due to the F-region dynamo electric fields getting freed from the field line linked E-region loading (Farley et al., 1986) or it is due to the irrotational nature of the electric field at the sunset terminator manifesting itself as an enhanced zonal electric field (Rishbeth, 1971a) or whether it is in any way connected to the evening equatorial electrojet (Haerendel and Eccles, 1992) is still unknown. However, there are
supporting evidences for all the above mechanisms. Presently there are indications that it could as well be due to the original mechanism proposed by Rishbeth [Eccles, 1998]. All the aforesaid mechanisms are discussed in detail in chapter IV in context to the occurrence of spread F during the solar eclipse event. Whatever be the mechanism, the fact remains that, during the post sunset hours the equatorial F-region gets lifted up, the magnitude of the lifting varying from day to day, making it conducive for the primary R-T instability to get triggered in the presence of an initial perturbation [Kelley and Maruyama, 1992]. By using a mathematical model to simulate the high-latitude effect, Kelley and Maruyama (1992) showed also that the growth rate of R-T instability becomes significant when the electric field reverses to eastward and may remain so even when the electric field disturbance weakens due to the upward altitude excursion of the layer.

Although extensive experimental and theoretical work carried out in the past has thrown light on the understanding of the complex phenomena of ESF with regard to long term variabilities, under nearly identical conditions, in a given season and solar epoch, the day to day variability in the ESF occurrence is a continuing enigma in equatorial aeronomy. It is well known that the ESF shows a strong seasonal dependence at a given longitude and the nature of the dependence is different at different longitudes [Maruyama and Matuura, 1984; Tsunoda, 1985; Aarons, 1993; Aarons et al., 1999]. Maruyama and Matuura (1984) studied the seasonal-longitude conditions when ESF was not likely to occur and cited the latitudinal asymmetry in the electron density distributions during the non-ESF seasons as evidence of the existence of transequatorial neutral winds, while the Tsunoda (1985) described the seasonal-longitude conditions when ESF was likely to occur. Both approaches are consistent with the observed long-term morphology patterns, namely, that ESF activity is high at Atlantic longitudes during northern winter, at Indian longitude it shows a maximum occurrence during equinocial months in solar maximum years while over the Pacific and American longitudes it shows maximum occurrence during summer and winter solstitial periods respectively [Rastogi, 1980; Aarons, 1993; Subbarao and Krishna Murthy, 1994]. These have been understood to be due to the control, the magnetic declination might have on the phenomenon through the asymmetric E-region sunset (Tsunoda, 1985; Abdu et al., 1992) in both the hemispheres. Subbarao and Krishna
Murthy (1994) investigated the seasonal variation of ESF, during sunspot maximum and sunspot minimum years. They explained the seasonal and sunspot dependence of ESF in terms of the growth rate of irregularities by the generalized collisional R-T instability mechanism that includes the gravitational and cross-field instability terms.

Tsunoda (1985) showed that ESF activity can occur when a special relationship exists between the solar terminator and local magnetic field declination: when sunset is simultaneous at the conjugate E-regions, the eastward winds generates a polarization electric field which is maximally enhanced and provides optimum condition for the generation of ESF via the gradient drift or R-T instabilities. Abdu et al. (1992) analyzed range spread F data accumulated for a 12-year period (1978-1990) over the Brazilian low-latitude station and showed that higher ESF activity occurs for smaller differences in sunset times at the conjugate E layer. The studies on various ground based ionospheric data have shown a close relationship between the ESF and Equatorial Ionization Anomaly (EIA) [Raghavarao et al., 1988; Alex et al., 1989 and Jayachandran et al., 1997]. The Equatorial Ionization Anomaly (EIA) refers to the double-humped structure in the latitudinal profile of the F-region ionization density at low geomagnetic latitudes with a trough centered around the dip equator and two crests at ± 20° off the dip equator. Mainly, there are two factors which are responsible for the formation of EIA. (i) the E×B drift over the dip equator which pushes the ionization upwards, and (ii) the diffusion which takes the plasma away from the magnetic equator along the magnetic field lines. The uplifting of F region plasma around the dip equator depletes the ionization and enhances the zonal neutral winds relatively because of reduced ion drag. On the other hand, the ion drag over the crest of EIA results in a reduction of zonal neutral winds. This leads to the neutral anomaly [Hedin and Mayr, 1973] with enhanced neutral densities at the crest of EIA and also to a decrease of zonal winds and the associated increase of neutral temperature due to the conversion of kinetic energy to thermal energy referred to as the ETWA (Equatorial Temperature and Wind Anomaly) [Raghavarao et al. 1991]. Figure 3.3 depicts the EIA modulation (through ion drag) of zonal winds (top panel) and the resulting temperature variation with latitude (bottom panel) as shown by Raghavarao et al. (1991) and predicted by Hedin and Mayr (1973). The trough in temperature and the maximum in zonal wind are collocated with the trough of the well-known EIA. It
had been demonstrated that on days of strong development of EIA, the occurrence of ESF was more probable [Raghavara et al. 1988]. This aspect was made use of by Sridharan et al. (1994) in obtaining a possible precursor to ESF by means of bidirectional OI 630.0 nm thermospheric dayglow measurements. Though the linkage had been unambiguously demonstrated, the physical process still remains to be fully understood. One of the possible means is through the newly discovered ETWA which refers to the collocated temperature and pressure bulges along with the crest of EIA [Raghavara et al., 1987; 1993].

![Diagram of EIA modulation and vertical winds](image)

**Figure 3.3.** A cartoon depicting the observed features of the EIA modulation of zonal winds and the resulting temperature variation with latitude (Raghavara et al. 1993).

Raghavara et al. (1993) has suggested that the vertical neutral winds that are upward (downward) at the EIA crests (trough) can be possibly due to the setting up of a meridional circulation cell in association with ETWA. The DE-2 satellite data have also confirmed the presence of such winds. Further, Raghavara et al. (1978) has shown one-to-one correlation between the strength of the EIA and the time integrated strength of the EEJ by using the ground based magnetic data which further suggest that these processes are interrelated and the driving force might have a common origin.

With this background on the phenomena of ESF, the present chapter deals with the detailed investigations on (i) the role of thermospheric meridional winds on the
onset of ESF, (ii) the role of disturbance component of the electric field at E-region for the inhibition/development of ESF on magnetically disturbed days, and (iii) the solar activity dependence on the threshold height at which the R-T instability gets triggered. The results presented and discussed here-in appear to fill an unbridged gap in our present understanding of the effects of neutral/electrodynamical parameters on the triggering and sustenance of ESF associated with the day-to-day variability of ESF.

3.1. Database and method of analysis
The ionospheric data from two stations Trivandrum (TRV) [8.6°N; 77°E; dip 0.5° N] and SHAR (S) [13.7°N; 80.2°E; dip ~10°N] have been made use of following the method of Krishna Murthy et al. (1990). This method is based on the fact that at the magnetic equator, the F-region vertical drift during nighttime is solely due to \( \vec{E} \times \vec{B} \) where \( \vec{E} \) is the east-west electric field and \( \vec{B} \) is the geomagnetic induction. On the other hand, at locations slightly away from the equator, the meridional component of the neutral wind (U) also contributes to it in addition to diffusion. The nighttime h'F values from the quarter hourly ionograms from Trivandrum and SHAR are used to derive the observed vertical drift velocities \( V_o \), i.e.,

\[
V_o = \frac{d(h'F)}{dt}
\]

(3.2a)

where, \( d(h'F) \) is the difference in h'F at consecutive quarter hours and \( dt=15\times60 \) seconds. The electrodynamic drift \( V_d \) could be obtained from \( V_o \) as

\[
V_d = V_o - \beta H
\]

(3.2b)

Where \( \beta \) is the effective chemical loss coefficient and \( H \) is given by

\[
H = \left( \frac{1}{N} \frac{dN}{dh} \right)^{-1}
\]

(3.2c)

Where \( N \) represents the background electron density and \( h \) is the height. \( \beta H \) represents the correction for the apparent change in h'F due to chemical recombination
of ionisation in the base of the F region. Since during nighttime the amount of ionization underlying the F-region is negligible, there is no appreciable group retardation and for all practical purposes, h’F truly represents the base of the F-layer and hence \( \frac{d(h'F)}{dt} \) could be taken as the ionisation drift itself. The observed \( \frac{d(h'F)}{dt} \) thus obtained is the sum of the actual vertical drift and the apparent vertical drift due to chemical loss. The actual meridional wind has been estimated after correcting for the chemical loss and diffusion following the method described by Krishna Murthy et al. (1990). The ambiguous part of the scaling of the ionograms in the presence of ESF is discussed later. However there are no ambiguities before the triggering of ESF.

The meridional wind \( U \) is obtained from the equation,

\[
U = 2 \left( \frac{V_d \cos I - V}{\sin 2I} \right) - W_p \tan I
\] (3.2d)

Where \( V_d \) is the F-region plasma drift velocity at Trivandrum and \( V \) that at SHAR. I represents the dip angle, \( W_p \), the plasma drift velocity due to plasma diffusion and given by \( g/v_m \) where \( g \) is the acceleration due to gravity and \( v_m \) is the ion-neutral collision frequency. Thus the meridional wind speed is derived from a combination of the vertical motion of h’F and the calculated rate of chemical loss in the ionosphere [Equations (3.2a) and (3.2b)] from two stations, one over the equator where only electric fields and chemical loss are important and the other slightly away from the equator where meridional winds in addition to these two processes become important because of the inclined magnetic field lines. The chemical loss would cause an apparent upliftment of the F-layer while the effect of the other two processes causing the upward/downward movement of the layer would depend on their polarity. From equation 3.2d, it is clear that the meridional wind is directly linked with the vertical plasma drift. The meridional winds while causing the upward/downward movement of the F-layer along the magnetic field lines would be relatively unaffected by the plasma densities and their movement.

The error in the estimation of \( U \) due to inaccuracies in h’F values has been calculated to be about ±10 m/s. on non-ESF nights. Generally, the estimation of meridional winds under non-ESF conditions are from h’F values which can be scaled
to an accuracy of ±3.5 km. On the other hand, the inaccuracy in the scaling of h'F during the presence of spread F can be as large as ±15-20 km which can lead to an overall maximum error of ± 40-50 m/s in the estimated meridional wind depending on the sign of the inaccuracies in h'F at both the locations. The errors in U due to the chemical loss and diffusion have been estimated to be ± 15 m/s on non-ESF nights with the result that the overall error in the derived wind has been estimated to be about ±25 m/s [Krishna Murthy et al., 1990]. The scaling error can vary differently in magnitude and direction at both the locations during an ESF event depending on the nature of spread F appearance. The occurrence pattern and characteristics of ESF phenomena have significant deviations on magnetically disturbed days from their quite day behaviour. These departures, which have their origin in the response of the neutral and ionized regions of the atmosphere to geomagnetic disturbances arise essentially from electrodynamical/dynamical coupling of high latitude to low latitude ionospheric regions [Abdu, 1997; Fejer, 1997]. The inhibition and development of ESF on magnetically disturbed days will be discussed separately (section II).

1. ROLE OF MERIDIONAL WIND ON THE ONSET OF ESF

3.3. Estimation of meridional wind and its variabilities

In the present study, meridional winds (U) have been estimated for the period of March-April, 1998 using ionospheric data collected as a part of the Indian Solar Terrestrial Energy Programme (I-STEP), wherein a multi instrumental, coordinated campaign was conducted, addressing to a theme of role of neutral winds and electric fields in the triggering and sustenance of equatorial spread F. The day-to-day variability in the occurrence of ESF is still an enigmatic problem and through the present case study an attempt is made to improve the current understanding associated with it. Figure 3.4 depicts the ESF occurrence pattern at both the stations, Trivandrum (T) and SHAR (S), during the ISTEP campaign period of March and April 1998 along with the geomagnetic index Ap. The dark horizontal bar denotes the ESF duration over Trivandrum whereas the light horizontal bar denotes the ESF duration over SHAR. The ESF shows a significant day to day variability in its onset time; the time on ESF days varying from 1930-2030 hrs (82.5°EMT). Further, ESF gets triggered either simultaneously over both the stations or invariably Trivandrum
Figure 3.4. The occurrence duration of spread F on each day (March-April, 1998) at TRV and SHAR. The $A_p$ value of each day is shown on the right-hand side.
In general, ESF duration varied from 2-8 hrs on different days. Some of the characteristic features of thermospheric meridional winds during equinoctial period, associated with Equatorial Spread F (ESF) and their possible role in the triggering of ESF are presented through case studies of observational events under different geophysical conditions that essentially control the post sunset F-layer height (h'F) rise. The present study reveals that the polarity and magnitude of the meridional winds become significant with the equatorward wind being present when the h'F is below a critical height for the instability to get triggered. It should be noted here that the contribution in the determination of meridional winds (equation 3.2d) due to the diffusion term is negligible when the h'F is below 300 km where the ion-neutral collision term dominates [Krishna Murthy et al., 1990]. Also, the primary requisite condition for the onset of ESF is believed to be due to the electrodynamic lifting of the equatorial F layer to higher height region (beyond 300 km) by the electric fields generated near sunset by the F region dynamo [Rishbeth, 1981]. The model calculation by Kelley and Maruyama (1992) indicates the altitude of the F layer to be a crucial parameter to trigger ESF. Their study also reveals the role of electric fields and neutral winds in the magnetic meridional plane on the development of ESF during the post sunset hours. The R-T instability also favours high altitudes with low ion-neutral collision frequency. Hence, by considering these physical facts, an h'F of 300 km has been taken as some sort of a reference level to present the results. The results are depicted in panels with, the bottom most panel depicting the h'F variation over SHAR and Trivandrum, the middle panel showing the d(h'F)/dt Vs time and the top panel depicting the derived meridional winds (U). As a convention, poleward (northward) wind velocity is taken as positive and equatorward (southward) wind velocity is treated as negative. The distinctly different characteristic features of the meridional winds during ESF and non-ESF events are discussed here.

3. 3. 1. Case I: Occurrence of ESF with h'F > 300 km

Figure 3.5 depicts the time variation of h'F, d(h'F)/dt and meridional wind velocity (U) at bottom, middle and top panel respectively on 19-20 April 1998, when one of the longest events of ESF was recorded both in Trivandrum and SHAR and on 29-30
Figure 3.5. Nocturnal variation of $h'F$ (bottom panel) $dh'F/dt$ (middle panel) and the meridional wind (top panel) for the quiet days, April 19-20, 1998 ($A_p=4$, spread F day) and April 29-30, 1998 ($A_p=4$, non-spread F day).
April 1998, when no ESF was observed. The thick line represents meridional winds from ionograms when there is no ESF and hence it has lesser uncertainty while the thin line is an estimate when ESF is present. The maximum error in the derived meridional wind values during ESF and non-ESF times are shown in the figure along with the corresponding inaccuracies in the h'F values. On 19-20 April, the h'F was > 300 km at least up to 2100 hrs, while on 29-30 April, it remained around 250 km well past midnight. Both the days were magnetically quiet with \( A_p = 4 \) and hence the estimated meridional winds could be construed to be free of geomagnetic influence. On both the days the meridional wind was poleward till 1830 hrs and just after that the direction of wind has changed to equatorward. This transition was short lived on 19-20 April 1998 as the wind became poleward again at ~1945 hrs just at the time when the ESF got triggered in both SHAR and Trivandrum which continued till 0500 hrs with the h'F remaining at a level of 300 km. On the other hand there are distinct differences in the meridional wind pattern on 29-30 April. The polarity changed from poleward to equatorward by 1830 hrs, and continued to remain so till midnight with the h'F pegged around 250-300 km over Trivandrum.

The time variation of h'F, \( dh'F/dt \) and U on 30-31 March 1998 and 31 March - 1 April 1998 is shown in figure 3.6. Both these days were geomagnetically quiet with the \( A_p \) values at 8 and 9 respectively. On 30-31 March 1998, the post sunset height rise of F layer (h'F) has reached more than 300 km at ~ 1900 hrs. A large surge of poleward wind with magnitudes reaching as high as 125 ms\(^{-1}\) was estimated at ~2000 hrs and ESF was seen at ~1915 hrs itself extending to as late as 0400 hrs with a break around midnight for one hour. The meridional winds pattern during the onset time of ESF reveals that on the ESF day there had been a large equatorward wind of ~75 ms\(^{-1}\), at the time of ESF initiation ~1915 hrs with the h'F located at 275 km though later the direction of the meridional wind changed to poleward. On the other hand there is a subtle difference on 31 March - 1 April 1998 when there had been no ESF. The change over to equatorward wind occurred at ~1915 hrs in this case. The h'F which was > 300 km over Trivandrum around 1930 hrs came down steadily to < 250 km beyond 2200 hrs.

The examples presented above suggest that in addition to the base level of the F-region being at a critical height of 300 km the polarity and magnitude of the
Figure 3.6. Same as Figure 3.5. but for March 30-31, 1998 ($A_p=8$, spread F day) and for March 31-April 01, 1998 ($A_p=9$, non-spread F day).
meridional winds also might have a role in the triggering of ESF. These aspects are discussed later.

3. 3. 2. Case II: Occurrence of ESF with $h'F < 300$

The time variation in $h'F$ and the derived meridional wind at Trivandrum and SHAR on the geomagnetically quiet days of 21-22 April ($A_p = 7$) and 17-18 March ($A_p = 8$) is shown in Figure 3.7. In striking contrast to the earlier examples, these two days reveal the presence of ESF only over Trivandrum with the $h'F$ being lower than 300 km in both the locations during the post sunset periods. On 21-22 April, the direction of meridional wind changed to equatorward when the ESF too got triggered at ~1945 hrs with $h'F$ located at ~275 km. The duration of ESF was ~4 hrs. On the other hand on March 17-18 the $h'F$ was slightly higher and located at 290 km both at Trivandrum and SHAR. The onset of ESF coincides with equatorward polarity of the meridional wind with $h'F$ being at 275 km. The specific observations on these days are, though the $h'F$ was <300 km, equatorward wind was present when ESF got triggered, but the altitudinal extent of ESF has been rather limited with total absence of irregularities over SHAR separated by ~5° in latitude. As the ESF irregularities are field aligned, spread F occurring only over Trivandrum and not in SHAR (which is just separated by 5° latitude) implies that the irregularities are localised. The F-region field line when mapped from SHAR over the dip equator, the height difference is <70 km, which indicates restricted altitudinal extent of the ESF irregularities. This also implies that the non-linear evolution of ESF is restricted to the lower heights only. This observation highlights the multidimensional nature of ESF.

3. 3. 3. Case III: Occurrence of ESF on moderately disturbed days

Figure 3.8 depicts two examples of moderately disturbed periods 17-18 April 1998 ($A_p = 14$) and 23-24 April 1998 ($A_p = 15$). Remarkable changes in the nature of variation of meridional winds and in the $h'F$ values have been observed with the increase of magnetic activity. On 17-18 April, 1998 when the $h'F$ at both the stations were well above 300 km during the post sunset hours, one notices ESF getting triggered by 2000 hrs and continuing till 0300 hrs. The meridional wind polarity has also changed from poleward to equatorward at this time. On the other hand on 23-24 April the $h'F$ had remained rather low at ~275 km and the ESF was observed only at
Figure 3.7. Same as Figure 3.5, but for April 21-22, 1998 (A_p=7, spread F day) and for March 17-18, 1998 (A_p=8, spread F day), with the spread F occurrence confined only to TRV.
Figure 3.8. Same as Figure 3.5, but for April 17-18, 1998 ($A_p=14$, spread F day) and for April 23-24, 1998 ($A_p=15$, spread F day).
Trivandrum around 2100 hrs. when the poleward wind became equatorward with a significant amplitude (50 ms\(^{-1}\)). It is seen that the thermospheric meridional wind variations (fluctuations) are more on disturbed days as compared to quiet days.

3.4. Specific Observations

During the ISTEP campaign period of March-April, 1998, the \(h'F\) values just before the onset of ESF were obtained simultaneously from Trivandrum (T) and SHAR (S). In order to evaluate the possible role of meridional winds in the triggering of ESF, the \(h'F\) values for all the ESF days along with the estimated meridional wind values were consolidated and presented in Figure 3.9. The dark circle in this figure shows the meridional wind velocity corresponding to the \(h'F\) values taken just before the onset of ESF. The positive and negative values represent respectively the poleward and equatorward wind. An interesting pattern appears to emerge. Once the base height of F-layer (\(h'F\)) is greater than 300 km, irrespective of the polarity of the meridional wind, ESF would occur whereas equatorward wind enhances the possibility of its occurrence when \(h'F < 300 \text{ km}\) and up to a limit of \(\sim 275 \text{ km}\). The above major conclusion about the 300 km critical height is also seen clearly by using a scatter plot of the \(h'F\) values of Trivandrum in the Y-axis and the meridional winds in the X-axis corresponding to each of the ESF cases as shown in Figure 3.10. As it is clear from this figure, for ESF cases with \(h'F < 300 \text{ km}\), the meridional winds are negative (equatorward) and above 300 km, they spread from negative to positive (poleward). The consequences of this interesting result are discussed below. It is clear from figure 3.9 that when the \(h'F\) values are less than 260 km the magnitude of the equatorward winds does not play any role in triggering the ESF.

3.5. Results and Discussion

The present study has been undertaken to investigate the ionosphere-thermosphere conditions that favour the observed post sunset F-region height rise and the role of the associated meridional winds at this time leading to the onset of equatorial spread F at Trivandrum and SHAR during the equinoctial period. It is well understood now that the ESF phenomena which occurs in the nighttime F region of the equatorial ionosphere is generated by various plasma instability processes, with the Rayleigh-
Figure 3.9. The post sunset height rise \( (h'F) \) at TRV (T) and SHAR (S) observed during March-April, 1998 along with the estimated meridional winds at these times. The positive and negative values represent, respectively, the poleward (northward) wind and equatorward (southward) wind.
Figure 3.10. Scatter plot of the meridional wind velocity Vs. the $h'F$ values at TRV corresponding to each of the ESF cases of March-April, 1998.
Taylor (R-T) instability being the more important among them. The F-region electrodynamics and the thermospheric neutral dynamics play crucial roles in the triggering and sustenance of the instability. Since the R-T instability is inversely dependent on the ion-neutral collision frequency and the plasma scale length, steeper the gradient in the base of the F-region and higher it is in altitude, more favourable would be the conditions for the primary R-T mechanism to operate. In this context the electrodynamic lifting of the F-layer in the post sunset hours due to the F-region dynamo (Rishbeth, 1981) plays a crucial role [Kelley and Mursyama, 1992]. Rishbeth (1981) suggested that during nighttime when the F-region conductivity is dominant, the dynamo action of equatorial F-region eastward winds generates a polarization electric field which drives the post-sunset enhancement of the upward drifts and the super rotation of the equatorial upper atmosphere and ionosphere. Based on the occurrence pattern of ESF over Trivandrum a critical height of 300 km has been identified for h'F through the present investigations. This suggestion gets substantiated when the effects of neutral meridional winds are also taken into account.

For the present analysis, more attention has been given to the polarity of winds at the onset of ESF. The meridional winds estimated during ESF events are uncertain proportionally to the inaccuracy of scaling of h'F at Trivandrum and SHAR. Thick and thin lines in the same plot show the meridional wind estimated with and without ESF in ionograms. Temporal variability shown by the winds even before ESF and also their magnitudes reveals that it cannot be the transequatorial winds generated due to the differential heating between the summer and winter hemispheres. Further, the meridional winds deduced in the present study could be treated to represent the equinoctial months of March and April. These estimates are in conformity with the earlier results reported by Hari and Krishna Murthy (1995) wherein they had studied the seasonal variations of the thermospheric meridional winds using ionosonde data of Trivandrum and SHAR for the year 1989 and 1990. Their studies indicate that the abatement and reversal in direction of the equatorial wind is prominently seen in equinoxes over Sriharikota (dip ~ 10°N). They also showed that thermospheric meridional winds show a distinctly different pattern as compared with other longitudes i.e., while the polarity of the winds was mainly equatorward over Arequipa (Biondi et al., 1991) a prominent late night reversal to poleward has been observed over
Trivandrum. However, it may be noted that all the earlier studies were pertaining only to non ESF nights, aimed at bringing out long term variability while the present study emphasizes a comparison of meridional winds between ESF and non ESF nights before the onset of ESF.

The morphological features of h'F variation for spread F and non-spread F day for the equinoctial months of 1991 was given by Rama Rao et al. (1997). They showed that the h'F is higher on spread F days than on non-spread F days. Farley et al. (1970) and Abdul et al. (1983) also reported that the variations in h'F show different features on spread F and non-spread F days. Further, Rama Rao et al. (1997) suggested that this may be true for average variation in h'F, but not for the day-to-day variability of ESF. The altitude region to which the measured winds correspond would depend on the h'F at that instant. Typically the h'F reaches anywhere between 250-450 km during post sunset hours on ESF evenings. On days of non-ESF, it would be located between 220-300 km and therefore the estimated meridional wind would correspond to a wide altitude range of 220-450 km. This large altitudinal range is not a serious limitation as usually the vertical gradient of meridional winds is not very significant [Burnside et al., 1983; Raghava Rao et al., 1987; Sridharan et al., 1997]. The other factor that would have a say in the estimation of meridional winds would be the plasma diffusion. This parameter is rather small and insignificant throughout night when h'F is located ~300 km. (Krishna Murthy et al., 1990) while higher above (h'F > 350 km) it becomes significant and needs to be properly accounted for. Thus, the corrections to the deduced winds due to diffusion and chemical loss are different during ESF and non-ESF conditions.

As already mentioned, one of the most crucial elements of ESF is the post sunset lifting up of the F-layer to higher heights. The F-region dynamo (Rishbeth, 1971b; 1981) which generates zonal electric fields is believed to be responsible for the above uplifting. During daytime conditions on quiet days, the F-region dynamo field effectively gets shorted out by the highly conducting E-region through the equipotential field lines. At sunset, when the E-region conductivity rapidly decreases, it effectively releases the hold on the F-region dynamo. The special conditions that prevail at the sunset terminator in the form of a steep zonal gradient in the E-region conductivity enables the generation of a surge in the electric field which would cause a
sudden uplifting of the base of the F-layer making it conducive for the operation of the R-T instability [Rishbeth, 1971b; 1981; Heelis et al., 1974; Batista et al., 1986; Farley et al., 1986; Crain et al., 1993; Eccles, 1998]. Further, Batista et al. (1986) and Crain et al. (1993) showed that the amplitude of the sunset enhancement of equatorial F layer-vertical drift depends on the thermospheric zonal wind and the gradient in flux tube integrated Pedersen conductivity across the day-night terminator. Such enhancement in the F-region E x B drift in the vicinity of the dip equator is a characteristic feature observed during solar maximum epoch [Fejer, 1981]. This is more so during equinoctial periods over the Indian longitude. Further, a reasonable estimate of the vertical plasma drift velocity and hence the electric field itself could be made by monitoring the rate of change of h'F during post sunset hours [Bittencourt and Abdu, 1981]. They showed that the vertical drift obtained from time variations of h'F represent the true plasma vertical drift when h'F is above 300 km as chemical loss will be quite small. In other words, the recombination process can significantly affect ionosonde drift measurements when the height of the reflecting layer is below ~300 km. These estimates have been supported by independent radar measurements [Woodman, 1970; Fejer 1981].

The F-region dynamo driven by the zonal winds and the thermospheric meridional winds together has shown several interesting features. In the absence of measured zonal winds the base height of the F-region during sunset hours is a good indicator for the prevailing zonal winds. In general, when the F layer is lifted up beyond 300 km by the F-region dynamo, one notices ESF getting triggered irrespective of the polarity of the meridional winds. On the other hand, when h'F is lower than 300 km, which implies somewhat weaker F-region dynamo, ESF is seen to get triggered only when there is an equatorward wind of significant amplitude. The required amplitude would depend on how low h'F is located i.e. lower the h'F, larger would be the required amplitude. Also, at lower heights for the instability to occur, other agencies like the zonal winds (eastward wind in the presence of westward gradient) and vertically downward winds in the presence of an upward gradient have to contribute [Sekar and Raghavarao, 1987]. However, there is hardly any information available on the nature of vertical winds except for some results based on DE-2 satellite data and from the sporadic vapour release experiments [Raghavarao et al., 1987, Sridharan et al., 1997]. While offering an explanation to the prevailing
latitudinal structure of the vertical winds while studying the phenomena of Equatorial Temperature and Wind Anomaly (ETWA). Raghavarao et al. (1988, 1993) suggested that the upward winds over the crest region of the Equatorial Ionisation Anomaly (EIA) and the downward winds over the trough regions could as well constitute a meridional circulation cell. The two pressure ridges that get formed as a consequence of ETWA on both sides of the dip equator could as well drive the circulation with the return flow located in the lower thermosphere. Earlier results on ESF have revealed close association with the EIA and ESF: stronger the anomaly more probable would be the occurrence of ESF [Raghavarao et al., 1987; Sridharan et al., 1994]. Under these circumstances strong converging equatorward flow would be associated with a strong EIA which in turn would result in vertically downward winds over the dip equator, enhancing the possibility for ESF to occur.

In the light of the above discussion, converging equatorward winds would assist the plasma instability while diverging poleward winds would desist the same. Also, it is clear from this study that once the h'F base height of the F-layer is below 300 km the plasma instability could not operate by itself because of the competing forces and it needs to be assisted by other forces like the equatorward winds. If h'F > 300 km then gravity by itself may cause the instability and the role of meridional winds would then be secondary. The study also reveals that the threshold or critical base height at which R-T instability gets triggered also changes with solar cycle (as shown in a separate study in section III).

II. STUDIES ON THE DEVELOPMENT/INHIBITION OF ESF DURING MAGNETICALLY DISTURBED DAYS

3.6. A case study of the disturbed day events
The onset of ESF, which is a nighttime phenomenon, is closely associated with dusk time electrodynamics of the equatorial ionosphere. The present investigation using ionograms and magnetograms during the equinoctial period of March-April 1998 on several magnetically disturbed days has revealed certain interesting aspects of the inhibition/development of ESF in the post sunset hours. The Equatorial Ionosphere-Thermosphere System (EITS) is characterized by a host of unique geophysical phenomena like the EEJ, EIA and ESF, which are inter-related and are primarily
driven by the electric fields in the ionosphere. It is well established that during magnetically disturbed periods, the electric fields present in the ionosphere deviates substantially from their quiet time values [Woodman, 1970; Matsushita and Balsley, 1977; Walker, 1973; Carpenter and Kirchoff, 1974; Blanc et al. 1977]. These changes over equatorial latitudes reveal a close linkage to the high latitude processes [Fejer et al., 1979; Gonzales et al., 1979; Kelley et al., 1979; Reddy et al., 1979].

As a consequence of these variations in the electric fields, during disturbed periods, the occurrence pattern of the equatorial geophysical phenomena show significant deviation from their normal quiet time behaviour [Abdu, 1997; Fejer, 1997]. The origin of electric field disturbances are believed to be in the magnetospheric and ionospheric dynamos [Fejer, 1986; Sastri, 1988; Fejer and Scherliess, 1997].

The low latitude disturbances of duration more than 1 hour are believed to have originated at high latitudes as a result of enhanced energy deposition during geomagnetic disturbances (Blanc and Richmond, 1980; Fejer et al., 1983) and they could either decrease or on occasions reverse the quiet time electric field pattern depending upon its intensity and the background conditions. Blanc and Richmond (1980) suggested that there are two generalised sources of mechanisms that can, at least qualitatively, account for temporal and spatial behaviour of the electric field in middle/low latitudes during geomagnetically disturbed periods. The first mechanism is the so-called magnetospheric dynamo, in which dynamic interactions between the solar wind and the magnetosphere cause a flow of electric currents connecting the magnetosphere and high-latitude ionosphere. Part of these currents, associated with their electric fields, penetrate directly into lower latitudes through the conducting ionosphere. The second mechanism, which has been examined by Blanc and Richmond (1980), is called the ionospheric disturbance dynamo (IDD). The thermospheric wind produced by auroral heating can alter the global circulation and consequently generate electric fields and currents in middle/low latitudes by means of ionospheric dynamo action.

The background ionosphere-thermosphere system plays a crucial role in the triggering and sustenance of ESF. The electrodynamics and the neutral dynamical forcings essentially dictate the triggering/inhibition of ESF. During magnetically disturbed periods, since the electrodynamics due to prompt penetration electric
fields and also due to the disturbance dynamo set forth due to the additional energy deposition at high latitudes and the neutral dynamics set up in the process of disturbing the additional energy and momentum to the rest of the globe are severely altered. the ESF would also be getting affected correspondingly. During post sunset hours, the sudden activation of the F-region dynamo generates a surge of zonal electric field, which results in the steep lifting of the base of the F-region over the magnetic equator and the rejuvenation/intensification of EIA. The bottom side steep gradient in the electron density of the F-region makes it susceptible for the plasma instability to get triggered resulting in the Equatorial Spread F (ESF). Fejer and Scherliess (1977) by using empirical model reported that enhanced leakage of high-latitude electric fields to lower latitudes and ionospheric disturbance dynamo electric fields are important additional sources of equatorial plasma drift and ionospheric current variability, during and shortly after magnetically disturbed conditions. The disturbance time electric fields, winds, and wave motions can cause large changes in height structure through vertical transport of the plasma and through temperature and composition changes. The effect of the disturbance time response of the equatorial ionosphere in producing modifications in the strength (intensity) of the equatorial electrojet and in the development of the equatorial ionization anomaly which in turn control the post sunset upliftment of the F-layer leading to the occurrence of ESF is investigated in this case study.

3.7. Data and method of analysis
The data for this study were obtained as a part of the ISTEP campaign of March-April 1998 organized for the study of the role of electric fields and winds in the generation of equatorial spread F. The h'F values scaled from the 15 minutes interval ionograms obtained from the KEL IONOSONDES from the equatorial location of Trivandrum (TRV; geog. lat. 8.5°N; geog. long. 77°E; dip −0.5°N) and Sriharikota (SHAR; geog. lat. 13.7°N; geog. long. 80.2°E; dip −10°N), an off-equatorial location were used to derive the thermospheric meridional winds on these days during 1800-0600 hrs (next day) following the method developed by Krishna Murthy et al. (1990). The northward (pole ward) wind is taken as positive and southward (equator ward) wind is taken as negative, as both Trivandrum and SHAR are locations in the northern hemisphere.
The magnetic field perturbations (ΔH) in the horizontal component of the geomagnetic field (H) obtained as deviations from the midnight time values at the equatorial station of Trivandrum and at Alibag (ABG: geog. lat. 18.6°N; geog. long. 72.9°E; dip -12.8°) a station outside the equatorial electrojet are used to obtain the equatorial electrojet strength. The difference (ΔH_{TRV} - ΔH_{ABG}) represents the equatorial electrojet strength over Trivandrum, where ΔH_{TRV} and ΔH_{ABG} are the ΔH values respectively at Trivandrum and Alibag.

### 3.8. Results and Discussion

The events of occurrence/non-occurrence of ESF on Internationally Disturbed (D) days during March-April 1998 have been studied to identify the background conditions contributing to the disturbed day behaviour of the F-region in relation to the observed variations in other ionospheric parameters like the equatorial electrojet strength, D_s, and K_p index. The disturbed day response of the equatorial electrojet strength is indicated in terms of a disturbance component of the electrojet strength as:

\[
[D\Delta H_{TRV} - D\Delta H_{ABG}] = [\Delta H_{TRV} - \Delta H_{ABG}]_D - [\Delta H_{TRV} - \Delta H_{ABG}]_{I,Q,DAY,NOON},
\]

where \([\Delta H_{TRV} - \Delta H_{ABG}]_D\) is the electrojet strength on the D-day and \([\Delta H_{TRV} - \Delta H_{ABG}]_{I,Q,DAY,NOON}\) represents the International Quiet days' average for the month.

The overall view of disturbed day events of occurrence/non-occurrence of ESF with the corresponding post sunset F-region height rise (h'F) and the sum of the disturbance component of \([\Delta H_{TRV} - \Delta H_{ABG}]\) over the time interval 1000-1500 hrs on these days are shown in Table 3.1. The EIA forms generally around 0900-1500 hrs with the crest of ionization close to the dip equator (Trivandrum) to begin with, gains in strength and then moves poleward with the intensification of crests in the afternoon period. Hence the duration of 1000-1500 hrs is the general build up time for the EIA.

Figure 3.11 shows the plot of \(\sum \{\text{disturbance component of } [\Delta H_{TRV} - \Delta H_{ABG}]\}\) Vs h'F corresponding to each of the D-days taken for the present study (bottom
Figure 3.11. Variation of the post sunset height rise as a function of \( \sum \{ \text{disturbance component of } [\Delta H_{TRV} - \Delta H_{ABG}] \} \) during 1000-1500 hrs on D-days (bottom panel) and the variation of the thermospheric meridional winds on these days (top panel).
panel), which indicates a fairly linear variation implying the dominant role of the large negative values of the sum of the disturbance components during the period 1000-1500 hrs on certain disturbed days in limiting the h’F rise below 300 km so that the post sunset F-region height rise does not exceed the critical height of 300 km for the triggering of Rayleigh-Taylor instability for the onset of ESF (Rishbeth, 1981).

Table 3.1. International Disturbed (D) Days

<table>
<thead>
<tr>
<th>Date</th>
<th>A,</th>
<th>h’F (km) at TRV</th>
<th>Sum of the disturbance component of</th>
<th>ESF/ No ESF</th>
<th>Meridional wind (MW) at the time of h’F (max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.3.98</td>
<td>58</td>
<td>362</td>
<td></td>
<td>ESF(*)</td>
<td>-110.2</td>
</tr>
<tr>
<td>11.3.98</td>
<td>28</td>
<td>315</td>
<td>-23</td>
<td>ESF(*)</td>
<td>-7.0</td>
</tr>
<tr>
<td>21.3.98</td>
<td>35</td>
<td>375</td>
<td>86</td>
<td>ESF(*)</td>
<td>29.2</td>
</tr>
<tr>
<td>29.3.98</td>
<td>20</td>
<td>353</td>
<td>-12</td>
<td>ESF(*)</td>
<td>29.3</td>
</tr>
<tr>
<td>10.4.98</td>
<td>16</td>
<td>340</td>
<td>-43</td>
<td>ESF(*)</td>
<td>-62.5</td>
</tr>
<tr>
<td>17.4.98</td>
<td>14</td>
<td>358</td>
<td>33</td>
<td>ESF(*)</td>
<td>-51.8</td>
</tr>
<tr>
<td>24.4.98</td>
<td>35</td>
<td>262</td>
<td>-211</td>
<td>No ESF(o)</td>
<td>47.1</td>
</tr>
<tr>
<td>25.4.98</td>
<td>26</td>
<td>275</td>
<td>-145</td>
<td>No ESF(o)</td>
<td>-40.8</td>
</tr>
<tr>
<td>26.4.98</td>
<td>31</td>
<td>268</td>
<td>-164</td>
<td>ESF(*)</td>
<td>-29.4</td>
</tr>
</tbody>
</table>

The events of non-occurrence of ESF on the disturbed days are seen to be associated with very large negative values of the sum of the disturbance component. It is seen that as the negative value of the sum of the disturbance component decreases and increases gradually in the positive direction (i.e. positive disturbance components), the h’F goes on increasing above 300 km and all these cases of disturbed days are associated with the occurrence of ESF, as one of the pre-requisites for the occurrence of ESF is satisfied. The top panel of the diagram shows the
thermospheric meridional winds at the time of the postsunset F-region maximum height \([h'F \text{(max)}]\) rise on each of the disturbed days. Most of these days are characterized by the presence of equatorward wind at this time. The implications of the polarity of the meridional winds before the onset of ESF have been discussed earlier.

The disturbance time response of the equatorial ionospheric E and F regions in terms of the observed characteristics of the different phenomena manifested during day and night time hours on certain selected disturbed days is shown in Figures 3.12, 3.13, 3.14, 3.15 and 3.16. These figures show the time variations of the electrojet strength and the disturbance component of the electrojet strength during 0530 hrs. to 0530 hrs. next day, along with the \(h'F\) (TRV) and meridional winds during the time period of 1800 hrs to 0530 hrs next day, for the disturbed days of March 10, 11 and 21 and April 24 and 26, 1998. The negative value of the disturbed component of the electrojet strength is shown in dark black shades and the duration of the ESF is indicated by thick lines. Typical ionograms illustrating the ionospheric conditions on these days are also shown.

3.9. Specific observations on International Disturbed days

\((i)\) \hspace{1cm} 10.3.1998 \((A_p = 58)\)

The long duration ESF event (Figure 3.12) on this day is preceded by a weak negative disturbance component of duration \(\approx 2\) hrs in the pre noon period and a similar positive component around noon. The electrojet strength of fairly large magnitude (max \(\approx 60\) nT) in the noon period indicates the normal development of the EIA with sufficient strength (Raghava Rao et al., 1978) which has resulted in a large post sunset F-layer height rise (\(\sim 362\) km) and a very long duration ESF (Raghava Rao et al., 1988). The associated thermospheric meridional wind is also in the equatorward direction and is of fairly large magnitude (\(\sim 120\) m/s). Both these factors are conducive for the formation of strong ESF. The typical ionograms during this day are shown at the bottom of this figure which illustrate the conditions existing in the equatorial E and F regions, especially the presence of strong \(E_{eq}\) layer.
Figure 3.12. Panel A represents the \( h'F \) variation and the variation of thermospheric meridional winds on 10.03.1998 with occurrence of a long duration ESF event and a very weak disturbance component of \([\Delta H_{TRV} - \Delta H_{ABG}]\) around noontime. Time variation of EEJ strength \([\Delta H_{TRV} - \Delta H_{ABG}]\) along with the disturbance component of \([\Delta H_{TRV} - \Delta H_{ABG}]\) are shown in panel B and corresponding variations in \( K_p \) and \( D_s \) in panel C. The sample ionograms representing the ionospheric conditions during daytime and during post sunset hours are shown at the bottom.
Figure 3.13. Same as figure 3.12, but for 11.03.1998 with the occurrence of a short duration ESF. The presence of a large negative disturbance component of $|\Delta H_{TV} - \Delta H_{ABG}|$ during the noontime may be noted.
Figure 3.14. Same as figure 3.12, but for 21.03.1998 with the occurrence of a long duration ESF event. The presence of a large amplitude positive disturbance component of $|\Delta H_{TRV} - \Delta H_{ABG}|$ around noon time is noticeable on these day.
Figure 3.15. Same as figure 3.12, but for 24.04.1998 with no ESF. The presence of a very large amplitude negative disturbance component of $[\Delta H_{TRV} - \Delta H_{ABG}]$ during the noon hours which has resulted in the disappearance of $E_{s4}$ is particularly noticeable.
26-04-1998 (D)

Ap=31   Σ Kp=33

Figure 3.16. Same as figure 3.12, but for 26.04.1998 with a very long duration ESF and large amplitude negative disturbance component of $[\Delta H_{TRV} - \Delta H_{ABG}]$ during the noon hours which has resulted in the disappearance of $E_s$. 
(ii) 11.3.1998 ($A_p = 28$)

It is clear from Figure 3.13 that the spread F is present on this day only for a short duration and the associated meridional wind, though in the equatorward direction, is also insignificantly small ($\sim 7$ m/s). The disturbance component of the electric field of duration $\sim 6$ hrs around the noon hours has shown a large amplitude of $\sim 30$ nT at $\sim 1230$ hrs. The effect of this negative disturbance component around the noon period on this day is to reduce the electrojet strength to a level $\sim 50$ nT which resulted in a weakening of the EIA development and a subsequent reduction of the post sunset F-region height rise ($\sim 315$ km). This might be the reason for sustenance of ESF only for a short duration.

(iii) 21.3.1998 ($A_p = 35$)

The significant effect of a large amplitude ($\sim 35$ nT) positive disturbance component centered around the noon hours is to enhance the strengthening of the EIA development, which has resulted in a strong ESF event of very long duration (Figure 3.14). The poleward meridional wind of amplitude $\sim 29$ m/s associated with $h'F \approx 375$ km does not seem to have any effect as the F-region height rise itself is very significantly large (much above 300 km).

(iv) 24.4.1998 ($A_p = 35$)

On this day a remarkable inhibiting effect of a large magnitude ($\approx 60$ nT) negative disturbance component on the sustained development of EIA in the afternoon hours is noticed [Figure 3.15]. This has resulted in the inhibition of the post sunset height rise of F-layer to higher altitudes and the $h'F$ value observed was $\approx 262$ km, much below the critical height of 300 km for the occurrence of ESF. The inhibition of EIA development during 1000-1600 hrs by the large amplitude negative disturbance component of the magnetic field is further corroborated by the disappearance of $E_{\text{eq}}$ in the ionograms during the above period. However, the late evening rejuvenation of EIA coinciding with the reappearance of $E_{\text{eq}}$ could not lift the ionization to higher heights necessary for the occurrence of ESF. The presence of a fairly large amplitude
poleward meridional wind at the time of \( h'F \approx 262 \) km is also not favouring the triggering of Rayleigh-Taylor instability at such low heights of the F-region.

(iv) 26.4.1998 \((Ap = 31)\)

The general features on this day were same as those observed on 24.4.1998; but with a low value of \( h'F = 268 \) km, there was a long duration ESF occurrence which was in association with an equatorward wind of \( -29.4 \) m/s. The inhibition of EIA development in the afternoon hours as evidenced by the \( E_{eq} \) disappearance at 1400 hrs is caused by the large amplitude \( (\approx 40 \) nT) negative disturbance component during 1100-1730 hrs [Figure 3.16]. The occurrence of the long duration ESF in this case may be attributed to the dominant role of equatorward wind as discussed earlier in the preceding section of this chapter.

The effect of the disturbance component of the magnetic field which is observed simultaneously in the \( f_nF_2 \) variation at different location of Trivandrum, SHAR, Waltair and Ahmedabad is one of the important aspects of the present study. The nature of these variations on disturbed days and quiet days have important roles as it indicates the electrodynamic condition favouring the occurrence/non occurrence of ESF.

Figure 3.17 (a) depicts the variation in \( f_nF_2 \) and \( h'F \) respectively during 0600-1800 hrs and 1800-0600 hrs (next day) along with the electrojet strength at Trivandrum during this period on the disturbed day of 21.3.1998 \((Ap = 35)\) and on a quiet day, 17.3.1998 \((Ap = 8)\). As mentioned earlier, 21.3.1998 is characterized by the presence of a very long duration ESF with a large \( h'F \approx 375 \) km at the time of onset of ESF whereas 17.3.1998 showed the ESF only for a short duration with \( h'F \approx 300 \) km, close to the critical base height of F-layer for the triggering of ESF. The variations in the relevant parameters on 17.3.1998 are taken as representative control day variations observed on a quiet day with respect to which the disturbed day variation on 21.3.1998 are compared in terms of the electrodynamic conditions leading to the enhancement/inhibition of EIA with the subsequent occurrence/non occurrence of the ESF event. The \( f_nF_2 \) variations on 21.3.1998 are typical with the presence of noontime bite out coinciding with the peak electrojet strength (also coinciding with the peak value of the positive disturbance component of the
Figure 3.17a. Day time variation in $f_0F_2$ and nighttime variations in $h'F$ are shown on 21.03.1998, a day characterized by the occurrence of a long duration ESF event along with the corresponding variations in the quiet control day of 17.03.1998 (top panel). The variations in the electrojet strength [$\Delta H_{TRV} - \Delta H_{ABC}$] on these days are shown in the bottom panel.
magnetic field shown in figure 3.14) with symmetrical hump like structure. These variations reflect the enhanced EIA developed on 21.3.1998 unlike the weak pattern of EIA with significantly large $f_0F_2$ values around noontimes (corresponding to the weak electrojet intensity) manifested on 17.3.1998. Apparently the positive disturbance electric field (during the positive disturbance component of the magnetic field shown in figure 3.14) corresponding to this period has rejuvenated the EIA development to its full strength to give rise to $h'F \approx 375$ km and a long duration ESF.

Figure 3.18 shows the comparison of the percentage of fluctuations in $f_0F_2$ [i.e. $\delta (f_0F_2)$] relative to the control day variation in $f_0F_2$ at the different locations during 0600-1800 hrs. The figure shows the presence of a dominant and near simultaneous fluctuation on $f_0F_2$ (hatched) at different locations corresponding to the prominent disturbance component variation of 21.3.1998. The amplitudes of $\delta (f_0F_2)$ corresponding to this time period show an increase from Trivandrum to Waltair followed by a sharp decrease from Waltair to Ahmedabad. This feature of the amplitude variation with latitude that is increasing amplitude with latitude indicates the strengthening of EIA resulting from the modification produced by the positive disturbance component (or equivalently an eastward electric field disturbance component) with the negative sign of the fluctuations indicating depletion of ionization. This case illustrates the role of the enhanced EIA development occurrence of long duration ESF on the magnetically disturbed day in comparison to the marginal situation of the presence of a short duration ESF preceded by a weak EIA on the control day.

Figure 3.17 (b) illustrates the daytime and nighttime conditions prevailing on the disturbed day of 24.4.1998 ($Ap=35$), which did not show up the occurrence of ESF whereas the quite control day of 16.4.1998 ($Ap=7$) is characterised by the occurrence of a long duration ESF with $h'F=321$ km and marked by the presence of a well defined noontime ($f_0F_2$) bite out similar to $f_0F_2$ bite out observed on the disturbed day of 21.3.1998 [Figure 3.17 (a)]. The large $h'F$ rise in the post sunset hours preceded by a large noontime $f_0F_2$ bite out as observed on the disturbed day of 21.3.1998 ($Ap=35$) and the quiet control day of 16.4.1998 ($Ap=7$) with $h'F > 350$ that in both cases have resulted in long duration ESF. Similarly there is a very good similarity in
Figure 3.17b. Same as Figure 3.17a, but for 24.04.1998 without the occurrence of ESF.
Figure 3.18a. The fluctuations in $f_0 F_2 [\delta(f_0 F_2)]$ on 21.03.1998 with respect to the control day of 17.03.1998 are shown at different locations over India. The variation in the disturbance component of $[\Delta H_{TRV} - \Delta H_{ABG}]$ observed on 21.03.1998 is shown in the bottom panel.
the $f_0F_2$ variation observed on the disturbed day of 24.4.1998 ($Ap=35$) and the control
day of 17.3.1998 ($Ap=8$), which showed a very short duration ESF with $h'F=300$
km, while the disturbed day of 24.4.1998 with $h'F=262$ km did not show the
presence of any ESF at all. The very absence of a clear cut noontime bite out in the
$f_0F_2$ on this day followed by the $h'F=262$ km are indicative of the inhibition of EIA as
well as the occurrence of ESF: whereas the control day in this case, namely,
16.4.1998 has show the presence of a well defined EIA and subsequent occurrence of
a long duration ESF. The comparison of the relevant parameters on these disturbed
days indicate the extent of departure/inhibition of EIA development on the disturbed
day in comparison to the well developed EIA and ESF on the control days. Figure
3.18 (b) illustrates the time variations of the percentage of simultaneous $f_0F_2$
fluctuation [$\delta (f_0F_2)$] relative to the control day values of $f_0F_2$ at the various locations
which shows the comparatively larger amplitudes at Trivandrum relative to other
locations corresponding to the disturbance component of the magnetic field
(Figure 3.15) and the positive sign of $f_0F_2$ fluctuations indicating accumulation of
ionisation with a positive gradient towards the equator, resembling an inhibition of
EIA.

All these events of ESF/non ESF occurrence can be considered to give a gross
picture of the nature of equatorial E and F region response in terms of the role of the
disturbance time electric field, its strength and polarity in modulating the growth and
development of the EIA and its effects on the sunset electrodynamics of the F-region
leading to the generation/inhibition of ESF.

3.10. Summary and Conclusions

The case studies presented in this section point to the important role played by the
polarity and magnitude of the disturbance electric field in the strengthening and
rejuvenation of the EIA which lead to the post sunset F-region height rise above the
critical height of 300 km required for the triggering of the Rayleigh-Taylor instability
and the occurrence of ESF [Rishbeth, 1981]. If the polarity and magnitude of the
disturbance is such that it is largely negative and is present around the noon hours, it
has an inhibiting effect on the strengthening of the EIA resulting in the post sunset F-
region height rise much less than the critical height of 300 km, and in the non-
Figure 3.18b. Same as figure 3.18a, but for 24.04.1998 with respect to the control day of 16.04.1998.
occurrence of ESF. Abdu et al. (1991, 1993) have discussed the important role of the transient prompt penetration electric fields in causing expansion or contraction of EIA depending on their polarity and amplitude. Also as shown by Devasia et al. (2002), when the post sunset h′F < 300 km, the polarity and magnitude of the thermospheric meridional winds at this time become significant, with the equatorward wind being associated with the triggering of ESF even under the control of disturbance electric field which may have an inhibiting effect on the strengthening of EIA.

The equatorial F-region electric fields are zonally westward during late evening hours on normal days, while they sometimes reverse to eastward on magnetically disturbed days. The quiet time westward electric field and typical low altitude of the F-layer (typically < 300 km) results in stable bottom side F-region gradient or almost with a very low generalized R-T growth rate for the generation of ESF. The growth rate becomes significant when the electric field reverses to eastward. According to model calculations by Kelley and Maruyama (1992), reversal of the electric field by itself is not sufficient to trigger intense ESF. The altitude of the F-layer has a crucial role in that the layer also must be lifted to a high enough altitude so that the gravitational term in the Rayleigh-Taylor growth rate equation (3.1) becomes strong. It is in this context that the polarity and magnitude of the disturbance electric field can have a modulating effect on the development of the EIA and thereby giving a proper lifting of the F-layer to altitudes where the growth rate of R-T instability becomes large.

The close linkage between the EIA and ESF i.e. on days of strong development of EIA, the occurrence of ESF being more probable was shown by Raghavaraao et al. (1988), Alex et al. (1989), Sridharan et al. (1992), Jayachandran et al. (1997) and Whalen (1998, 2001). The basic mechanism controlling the EIA generation i.e. the E×B upliftment of the F-region plasma over the dip equator is initiated by the E-region electric field (E) which becomes magnetic disturbance controlled through the disturbance electric field modulation. It may be pointed out that the effect of the observed f0F2 increase [i.e. the increasing positive values of δ(f0F2) towards Trivandrum observed on 24.4.1998] corresponding to the large negative disturbance component of the EIEJ strength is an indication of the inhibition of the EIA development, with the opposite situation, namely, EIA enhancement being manifested corresponding to the increasing negative values of δ(f0F2) outwards from Trivandrum,
observed on 21.3.1998 during the large positive disturbance component of the EEJ strength. Tanaka (1981) has presented the nature of $f_i F_j$ response during the storm of 9 April 1980 during which the simultaneous increase and decrease of $f_i F_j$ at the anomaly crest and trough respectively were observed. Thus the disturbance neutral wind can also be a major source of EIA modification arising from thermospheric disturbances generated by energy deposition at high latitudes.

The above case studies, though limited in number, seem to bring out a coherent picture of the equatorial E and F regions response to the magnetic disturbance and consequent departures in the manifestation of the phenomena associated with it.

III. STUDY ON THE VARIATION OF F-LAYER CRITICAL HEIGHT ($h'F$) WITH SOLAR ACTIVITY AND THEIR CONTROL ON THE OCCURRENCE OF ESF

3.11. Solar activity linked variabilities in the thermospheric meridional winds

As mentioned earlier, the development/inhibition of ESF is associated with the direction as well as the magnitude of the meridional wind and also with the disturbance component of the zonal electric field in the E-region. A comprehensive understanding of this ESF phenomenon has become extremely relevant with increased dependence on satellite based communication and other applications like Geodesy in the light of a strong positive correlation of ESF with solar activity [Rastogi, 1980; Chandra and Rastogi, 1972]. The variability linked to the solar activity could be understood through the change brought about in the basic ionospheric conditions and, the dependence on the geomagnetic activity could be understood by electrodynamical and neutral dynamical coupling processes of the MITS (Magnetosphere - Ionosphere - Thermosphere System) [Chandra and Rastogi, 1970; Chandra and Rastogi, 1972; Leon et al., 1958]. Some of the characteristic features of thermospheric meridional winds at the time of post sunset F-region height ($h'F$) rise during the equinoctial period of March-April, 1998 were found to have a possible role in the triggering of Equatorial Spread F (ESF) (Devasia et al., 2002) and this have been explained in detail in the earlier section. It has been found that the polarity and magnitude of the meridional winds become significant, with the
equatorward wind being associated with the occurrence of ESF when $h'F < 300$ km. The conjecture being that there would be an associated downward wind over the dip equator as part of a meridional circulation cell getting set up due to the strong EIA and the associated ETWA. For the onset of ESF with $h'F > 300$ km, the polarity of the meridional wind does not seem to have a significant role as the basic pre requisite condition that the $h'F$ should exceed a critical height ($\approx 300$ km) is satisfied irrespective of the presence of meridional winds with either polarity.

In the light of an already established strong positive correlation of ESF with solar activity (Chandra and Rastogi, 1972; Rastogi, 1980) and of the important role of equatorward meridional winds in triggering the plasma instability responsible for the generation of spread F, it is natural to expect a solar activity dependence for the critical height ($h'F$) for which the ESF would occur in the normal circumstances as well as the nature of the meridional winds associated with the occurrence of ESF when the $h'F$ is less than the critical height. The study by Chandra and Rastogi (1972) reveals the occurrence of mainly two types of spread F over magnetic equator at Trivandrum (dip $-0.5^\circ$N); firstly the range spread F which is more common in high sunspot years and occurs in the pre-midnight period and is well correlated with the post sunset $h'F$ increase; and secondly the frequency spread F which is more common in summer of low sunspot years and usually occurs in the pre dawn period and does not seem to have much dependence on $h'F$ variations. It is possible that any seasonal or solar activity dependent variabilities in the basic F-region parameters will cause corresponding changes in the critical height of $h'F$.

3.12. Data and method of analysis

With an aim to study the occurrence of ESF over the magnetic equator and its dependence on the solar activity, the $h'F$ values from 15 minutes interval ionograms obtained simultaneously from Trivandrum (8.5°N; 77°E; dip 0.5°N) and SHAR (13.7°N; 80.2°E; dip 10°N) during 1800-0600 hrs (next day) during 1993 to 1998 have been used to derive the thermospheric meridional winds. It is to be noted here that the data for these years include only those corresponding to the equinoctial months (March, April, September and October). All the data available for the equinoctial months of the aforesaid years have been used to study the solar cycle modulation of the critical base height of the F-layer ($h'F$) which plays an important
role in triggering the onset of ESF. The method for deriving the thermospheric meridional wind is already discussed in the section 3.2. Poleward winds are taken as positive and equatorward winds are denoted as negative.

3.13. Results and discussion

As discussed earlier, when \( h'F < 300 \text{ km} \), equatorward wind enhances the possibility of ESF occurrence with downward wind over the equator through the establishment of a meridional circulation cell. This would imply that converging winds over the dip equator would enable triggering of ESF and vice versa. The physical process which is responsible for the close linkage between ESF and EIA is believed to be through the newly discovered phenomenon of Equatorial Temperature and Wind Anomaly (ETWA) which refers to the collocated temperature and pressure bulges along with the crest of EIA [Raghavarao et al., 1987; 1993]. As suggested by Raghavarao et al. (1988, 1993) the upward winds over the crest region of the EIA and the downward winds over the trough regions could constitute the meridional circulation cell. During equinoxes at solar maximum, the EIA continues to persist till early morning hours, thereby supporting the large frequency of ESF during this period. On the contrary, during solar minimum periods, the EIA development to its full strength is confined to the afternoon hours with its strength diminishing fast towards the evening hours with the result that the occurrence of ESF is less frequent. The basic mechanism controlling the EIA generation is the \( \vec{E} \times \vec{B} \) upliftment of the F-region plasma over the dip equator, which is solar activity dependent through the solar cycle variation of the E-region electric field \( (E) \), which initiates it.

For enabling the primary R-T instability mechanism the two crucial parameters, as discussed earlier, are the base height and the plasma scale length, \( L \). Since the R-T instability is inversely dependent on \( v_{in} \) and \( L \) (see equation 3.1), steeper the gradient in the F-region base and higher it is in altitude, more favourable would be the condition for the primary R-T instability mechanism to operate. In other words, for any given \( L \), the higher the base height, lesser would be the \( v_{in} \) and hence the growth rate \( \gamma \) would increase exponentially with height. As the parameters \( v_{in} \) and \( L \) are dependent on the temperature, neutral density as well as electron density,
Figure 3.19. Top panel shows the meridional wind velocity corresponding to the post sunset F region height rise on ESF days for the year 1993 to 1998. The square symbol shows the minimum threshold required for the onset of ESF. The average 10.7 cm solar flux variation for the year 1993 to 1998 is also shown here by a continuous line joining the circle. The bottom panel shows the variation in average h′F for each year (1993 to 1998) relative to the average 10.7 cm solar flux.
which in turn are dependent on solar activity, it is possible that the threshold height at which R-T instability gets triggered also changes with solar cycle. Any seasonal or solar activity dependent variabilities in the basic F-region parameters will cause corresponding changes in the critical height of h'F. Figure 3.19 (top panel) depicts the variation in meridional wind velocity with h'F for the period 1993 to 1998, when ESF was observed. It shows that the threshold or critical base height for the triggering of ESF is low during low solar activity while high during high solar activity. It means that during equinox at solar maximum, large threshold height is required to trigger the R-T instability mechanism. It is clear from this figure that there is a significant solar cycle modulation of the critical base height of the F-region by as much as ± 50 km for the occurrence of ESF. A clear-cut solar activity dependence on the average critical base height of the F-layer is also shown in figure 3.19 (bottom panel).

![Diagram](image)

Figure 3.20. The average h'F critical height variation (for the period 1993 to 1998) with average sunspot number.

Further, figure 3.20 depicts the variation of average critical base height of the F-layer with average sunspot number for the year 1993 to 1998. It is clear from this figure that the average h'F critical height shows a direct correlation with the average sunspot number. As the sunspot number decreases, the average height of the h'F also decreases and vice versa. Since, the neutral densities at any given altitude is strongly controlled by the solar activity, the neutral collision frequency will effectively take...
down the critical altitude of occurrences of spread F and this is one of the reason that during solar minimum the spread F would occur even when threshold height is low.

The present investigation reveals that the occurrences of ESF depends on the solar activity with the threshold height attaining higher altitude during solar maximum and lower during solar minimum, thus favouring the conditions for the primary R-T instability mechanism to operate in regions of reduced $v_m$ and increasing the frequency of occurrence of ESF.