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The persistence of equatorial spread F – an analysis on seasonal, solar activity and geomagnetic activity aspects

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Abstract. The persistence (duration) of Equatorial Spread F (ESF), which has significant impact on communication systems, is addressed. Its behavior during different seasons and geomagnetic activity levels under the solar maximum (2001) and minimum (2006) conditions, is reported using the data from the magnetic equatorial location of Trivandrum (8.5° N; 77° E; dip 0.5° N) in India. The study reveals that the persistence of the irregularities can be estimated to a reasonable extent by knowing the post sunset F region vertical drift velocity (V_z) and the magnetic activity index K_p. Any sort of advance information on the possible persistence of the ionospheric irregularities responsible for ESF is important for understanding the scintillation morphology, and the results which form the first step in this direction are presented and discussed.

Keywords. Ionosphere (Electric fields and currents; Equatorial ionosphere; Ionospheric irregularities)

1 Introduction

Equatorial Spread F (ESF) is one of the most complex phenomena of the nighttime equatorial ionosphere involving a hierarchy of plasma instabilities, one providing the base for the other, and resulting in the generation of plasma density irregularities of wide ranging scale sizes, under favorable ionospheric and thermospheric conditions. These irregularities in the electron density distribution of the ionosphere over the equatorial region frequently disrupt space based communication and navigational links by causing severe amplitude and phase scintillations. The occurrence of these ionospheric scintillations is associated with the presence of spread in the ionograms. Understanding the favorable conditions for their onset, growth and persistence are thus of paramount importance in addition to the physical processes leading to the generation of these irregularities in the ionosphere.

There are three fundamental questions with regard to the ESF phenomena. The first one is its occurrence itself, the second one being its duration once it gets triggered and the third aspect would be its intensity. Some sort of a reasonable understanding has emerged with regard to its triggering based on the background ionosphere/thermosphere conditions (Abdu, 2001; Devasia et al., 2002; Smitha et al., 2006, and the references therein). Both the aspects of triggering and sustenance largely depend on the background electrodynamical and neutral dynamical conditions in the F-region. During evening hours, close to sunset, the F-region plasma densities and dynamo electric fields in the E-region decrease and the Appleton anomaly (due to the $\boldsymbol{E}\times\boldsymbol{B}$ drift, during daytime) begins to fade. The development of the F-region dynamo field at sunset causes the pre reversal enhancement of the zonal electric field and moves the ionospheric plasma upward (PRE vertical drift) allowing the Appleton anomaly crests to intensify. As a consequence of the electrodynamical forcings and also chemical recombination, soon after sunset, steep vertical plasma density gradients form in the bottomside of the F-layer. The upward density gradient being opposite in direction to the gravitational force ($\boldsymbol{g}$) makes this configuration quite favorable for the triggering of the Rayleigh-Taylor (R-T) plasma instability that causes the onset and growth of plasma density irregularities in the ionosphere. The local growth rate of the R-T instability is given by the equation (Sekar and Raghavarao, 1987):

$$\gamma = 1/L\{[g/\nu_{in}] + [E_X/\boldsymbol{B}] + [W_X(\nu_{in}/\Omega_i)] - W_Z\} \qquad (1)$$

where W_x and W_z are the zonal and vertical winds respectively, E_x is the zonal electric field in the F-region, L is the plasma scale length, $\boldsymbol{B}$ is the geomagnetic field and Ω_i is the ion gyro-frequency.

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It is now fairly well established that in the presence of an initial perturbation, the vertical electron density gradient through its plasma scale length L, and the base height of the F-region (essentially through the ion neutral collision frequency (υ_{in})) are extremely important for the instability to get triggered. The growth rate of the primary Rayleigh-Taylor instability is inversely proportional to both L and υ_{in} (Ossakow, 1981). In addition to these two, the neutral wind components (both vertical and zonal) also have a control on the growth rate, in the presence of an opposing gradient thus enhancing the growth rate (Raghavarao et al., 1987; Kelley, 1989). On the other hand, a poleward meridional wind, (diverging with respect to the dip equator) would stabilize the ionosphere by pushing additional ionization down to the E-region along the geomagnetic field lines. This would increase the E-region conductivity and reduce the effect of the F-region dynamo that causes the upliftment of the base of the F-layer to greater heights (Maruyama, 1988; Mendillo et al., 1992). The third component, namely the vertical wind would have a direct effect on the growth rate, similar to that of gravity, by physically separating the ions and electrons and by generating a polarization field (Sekar and Raghavarao, 1987; Raghavarao et al., 1993). All these factors, more or less independent of each other, display significant variability on the occurrence or non-occurrence of ESF, thus making it a many body problem. As a consequence, it shows a large day-to-day variability in its occurrence. The statistical occurrence pattern of ESF is well understood (Aarons, 1993). The theoretical foundation based on the R-T instability mechanism is both widely accepted and used successfully in nonlinear numerical simulations (Ossakow and Chaturvedi, 1978; Sekar and Raghavarao, 1997, and the references therein).

Morphological studies in the past have revealed that, in the Indian longitudes, equinoctial months are favored for the ESF occurrence. Several other aspects like the control of the magnetic declination (Abdu et al., 1981) and the possible link of the equatorial ionization anomaly (Valladares et al., 1983; Raghavarao et al., 1988; Sridharan et al., 1994) etc. have also been demonstrated with regard to its occurrence, in addition to the negative correlation of ESF with magnetic activity (Bowman, 1974; Rastogi et al., 1981) and positive correlation with solar activity (Chandra and Rastogi, 1970). Most of the earlier studies, irrespective of which one of the different manifestations of ESF, namely the spread in the F-region echoes in the ionograms, VHF and UHF scintillations, airglow intensity bite outs or occurrence of the so called plumes in the coherent backscatter echoes etc., generally did not distinguish between the triggering and persistence of the ESF irregularities and dealt with ESF mainly on the basis of its occurrence percentage, except in the recent study by Bhattacharya (2004) wherein the lifetime of a plasma bubble and the effect of the E-region conductivity on the non-linear evolution of the plasma bubbles has been discussed. It has been shown that the E-region resistivity together with F-region polarisability introduces another time scale in the non-linear evolution of equatorial bubbles, and this is the time scale for discharging the bubbles.

Apart from its occurrence and its variability, the other aspect of ESF is its persistence or duration once triggered and this has important implications in the context of understanding the role of ionospheric scintillations on the radio wave propagation through the region of equatorial ionospheric irregularities. Once the irregularities are generated, as rightly understood, by the plasma instability triggering mechanism, the growth and decay would be governed by the relative importance of the stabilizing and destabilizing factors and their temporal variabilities. It is thus extremely important to understand the factors that control the duration of ESF, as the presence of these irregularities, in addition to their amplitudes, is the one that would affect the communication links with the space borne systems.

In this paper, emphasis is given to the specific aspect of persistence or duration of ESF on magnetically quiet days and its variability with seasons under the two extreme solar activity conditions, during the solar maximum year (2001) and the solar minimum year (2006), and attempts are made to physically explain the observed characteristics of duration of ESF under these varied conditions.

2 Database

Ionosonde data recorded during each day of the solar maximum year of 2001 and minimum year of 2006 have been made use of in this study. Quarter hourly ionograms from Trivandrum (dip lat. 0.5° N) during magnetically quiet days ($A_p \leq 20$) of these years constitute the database. We have adopted the commonly used method of using the information on the evening time ionospheric F-layer height ($h'F$) variations to compute $dh'F$/dt or equivalently the $\boldsymbol{E} \times \boldsymbol{B}$ drift for obtaining the Pre-Reversal Enhancement (PRE) zonal electric field in the evening time F-region. The vertical drift velocity V_z (PRE) of the layer as given by $V_z = d(h'F)/dt$ should be close to the real F-region vertical plasma drifts for layer heights ≥300 km (Bittencourt and Abdu, 1981; Batista et al., 1986), which usually is the case during evening hours for the solar maximum years. The velocity of the bottom side F layer is in a way related to the onset of spread F irregularities as the irregularity onset occurs on the bottom side (Fejer et al., 1996). The F-region height rise due to chemical losses is of the order of 5 m/s and is negligible when compared to large vertical drift velocities due to the PRE (Krishna Murthy et al., 1990; Basu et al., 1996; Anderson et al., 2004). Another method for deriving the F-region drift has been evolved by using the information on *hm*F2 values (Liu et al., 2004, and the references therein).

In this study, only those ESF events which appear before 20:00 LT are considered, thus considering only the freshly generated irregularities. Also the study is based on the ESF events as observed by the ionosonde, which is sensitive to a particular scale size of irregularities. It is also to be noted that no distinction has been made between the range and frequency spread F in this study.

3 Results

Figure 1 depicts the average ESF duration along with their standard deviations against the Prereversal drift velocity for the years of 2001 and 2006 irrespective of the months. Discrete intervals of 5 m/s for V_z have been used to study the response of ESF duration to this parameter. From the figure, it is quite evident that on an average, the ESF duration bears a positive relationship with V_z during both the years. The ESF duration tends to show a saturation effect, when the V_z value exceeds 40 m/s during the solar maximum year of 2001. However in the case of the solar minimum year of 2006, similar effect could be seen when V_z values exceed 20 m/s. The large error bars in the plot indicate that for a given V_z, there is a large scatter in the ESF duration. This feature suggests that the ESF duration does not uniquely depend on the magnitude of V_z alone, though the trends appear to come out well.

The important role of V_z in controlling the seasonal and solar cycle variabilities in the persistence of ESF is brought out in Fig. 2. The parameter V_z is again taken at intervals of 5 m/s and the total percentage occurrence of the ESF events over different ranges of V_z are shown in the bottom panels of Fig. 2a and b, for the years of 2001 and 2006, respectively. For the winter months (D-months: November, December, January and February) and Equinoctial months (E-months: March, April, September, October) of the solar maximum year of 2001, ESF is found to occur on all days when the value of V_z exceeds 30 m/s, but for the summer months (J-months: May, June, July, August), this threshold value seems to be only 15 m/s. On the other hand, for the solar minimum year of 2006, the threshold value of V_z is around 25 m/s during the D months. It has been very difficult to deduce any such threshold value during the J and the E months, as the number of events itself were very low. It may be noted here that the high percentage occurrence seen for very low V_z (5 m/s) during E months could be an artifact due to very low number (three) of cases available.

The top panels in Fig. 2a and b represent the average ESF duration with the standard deviation in each interval of V_z. The positive relationship of ESF duration with V_z is reflected in all the seasons for 2001. But, this feature is seen only for the D and E months of the solar minimum year of 2006. It is also clear from the figure that the ESF events attain a steady duration of over 400 min (400–600 min), when the V_z values are in the range of (30–70 m/s) during the D and E months of the solar maximum period. For the solar minimum year shown in Fig. 2b, almost all of the ESF events are with duration in the range of 200–500 min and the corresponding V_z values are between 5–30 m/s. For the solar maximum year also, V_z values in the range of 10–30 m/s (largely during the J months) are found to sustain ESF with duration in the range of 200–400 min and for higher duration events larger values of V_z above 25 m/s are needed. The duration of the ESF events show distinctly different variation patterns in response to the amplitudes of V_z in all the seasons under the solar maximum and minimum conditions.

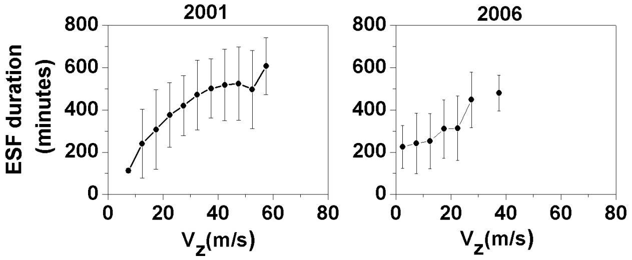

Fig. 1. Plot of the average ESF duration, with the standard deviation, against the PRE drift velocity (V_z), taken in intervals of 5 m/s, for the solar maximum and minimum years of 2001 and 2006.

Another geophysical parameter, which controls the onset, growth and persistence of ESF, is the geomagnetic activity. In order to establish any possible relationship between the duration of ESF and the overall geomagnetic activity, the data base on ESF events was extended to include all the events of both the solar maximum and minimum years irrespective of the level of geomagnetic activity. The majority of the ESF events during both the years are confined to $K_p \leq 4$. Figure 3 represents the average ESF duration with the standard deviation, during the solar maximum and minimum years of 2001 and 2006, as a function of the corresponding average K_p index, taken at intervals of 0.5. The K_p index shown is the 6 h mean K_p value prior to the local sunset (i.e. during 06:00–12:00 UT which corresponds to 11:30–17:30 IST). This criterion for the 6 h mean K_p index highlights the effect of disturbance dynamo electric fields which affect the equatorial plasma drifts a few hours after the onset of large auroral disturbances (Fejer et al., 1999). From the figure, it is very clear that during 2001, the average ESF duration decreases from 500 min to 200 min with increase in K_p value from 0 to 5. But in 2006, decrease had been from 300 min to 200 min for the same changes in K_p.

Figures 4a and b show the season wise classification of the average ESF duration on the K_p index, taken at intervals of 0.5, for 2001 and 2006 respectively. Bottom panel of the figure shows the percentage occurrence of the ESF events against the different intervals of K_p. The top panels show the average ESF duration, with the standard deviation, against the K_p values. The figure shows that during the D and E months of 2001, ESF duration on an average decreases with the K_p value. This feature of decreasing ESF duration with magnetic activity is not clearly seen for the J months, rather first a decrease in the ESF duration reaching a minimum and then an increase with the K_p value is observed. On the other

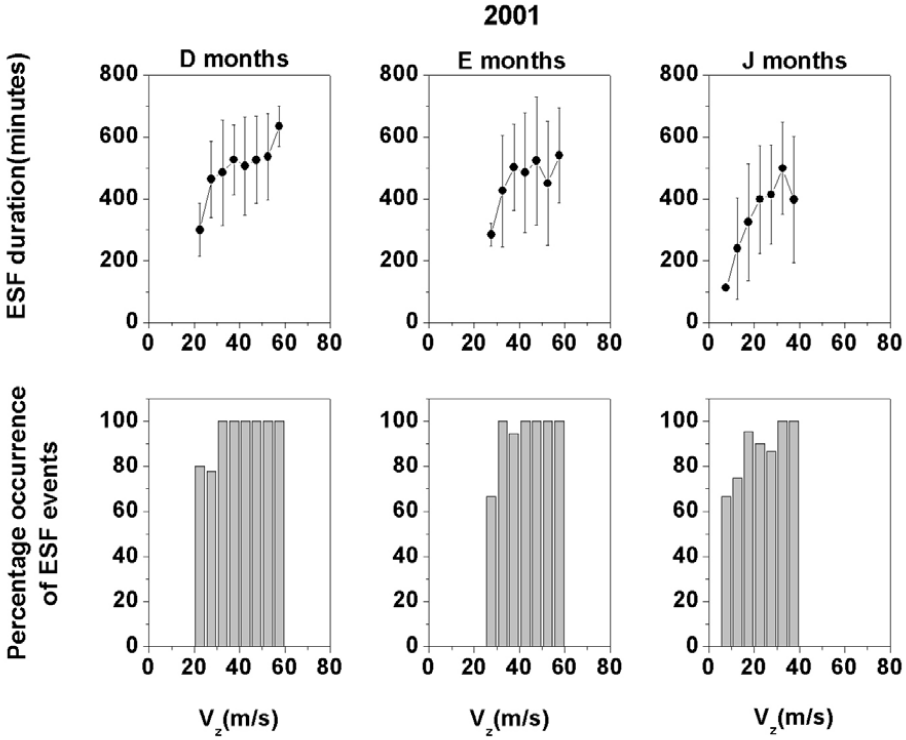

Fig. 2a. Distribution of the percentage occurrence of ESF events (bottom panel) and the ESF duration with the standard deviation (top panel) against the PRE (V_z) drift velocity for the different seasons during the solar maximum year of 2001. V_z values are taken in intervals of 5 m/s.

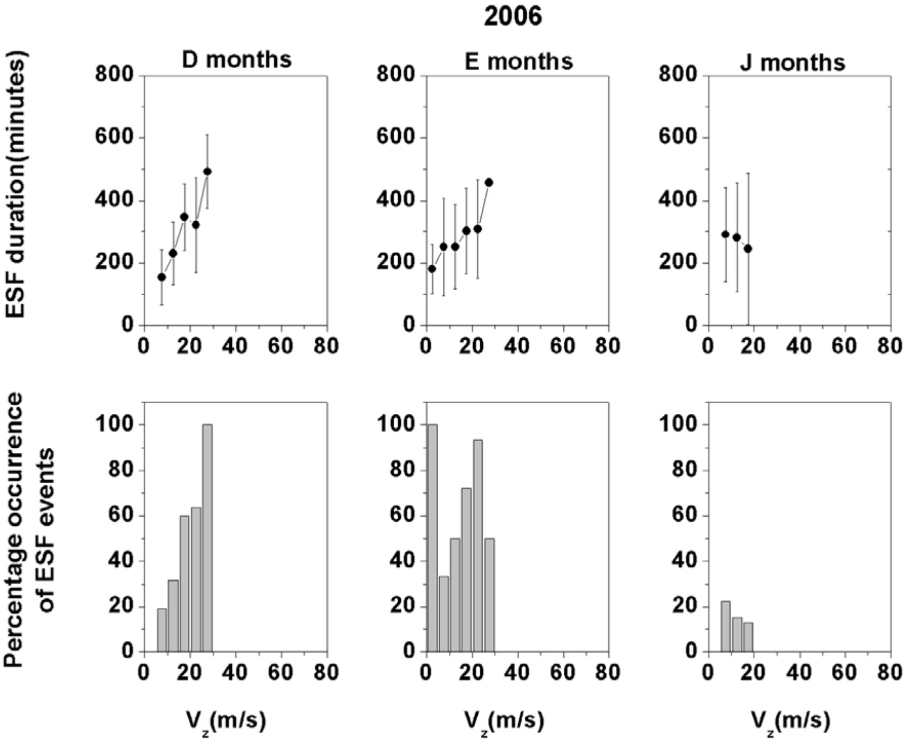

Fig. 2b. Same as for Fig. 2a, but for the solar minimum year of 2006.

hand, during 2006, the ESF duration is found to decrease with increasing K_p values, more significantly, during the E and J months. During the D months, this feature is not clearly discernable.

The above results indicate that the prereversal velocities of the F-layer and also the prevailing geomagnetic conditions over the equatorial ionosphere appear to have significant control on the growth and sustenance of the ESF irregularities. These are discussed below.

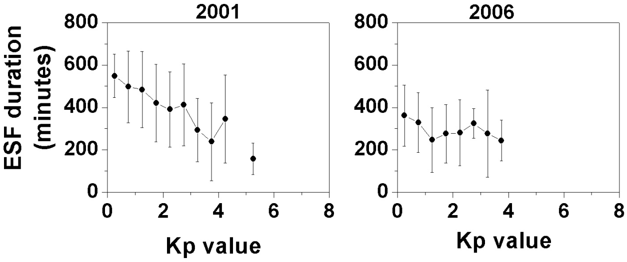

Fig. 3. Plot of the average ESF duration, with the standard deviation, against the magnetic activity index K_p, taken in intervals of 0.5, for the solar maximum and minimum years of 2001 and 2006.

4 Discussion

The attempts in the past to understand the equatorial spread F, had been mainly through morphological studies. They were confined to identifying and, confirming the various manifestations of the nighttime equatorial ionosphere which represents one and the same phenomena, namely, the generation of plasma density irregularities of different scale sizes and also specifically to its nonlinear evolution. While the percentage occurrence of ESF had been addressed to quite extensively in the literature, the persistence or duration of ESF, which is one of the crucial factors while studying its effects on radio communication, has not been investigated in detail till now. The longevity of the generated irregularities would essentially depend on the stabilizing forces which are the plasma diffusion in the higher heights (>350 km) and the chemical re-combination in the lower heights (<250 km). At the same time, the growth rate of the irregularities is inversely proportional to the ion neutral collision frequency, υ_{in} (Raghavarao et al., 1987) which decreases exponentially with height. The plasma diffusion along the geomagnetic field lines of force increases exponentially with height, due to its inverse relation with υ_{in}. The height centered around 300 km incidentally happens to be the transition region from the chemically controlled to transport dominated F-region (Banks and Kockarts, 1973). Somayajulu et al. (1975) quantitatively showed that the duration of short period ESF agreed well with the time constant of the chemical loss process, which indicates the possible role of the base height of the F-layer with regard to the duration of ESF once it is triggered. It was also shown by them that on long duration spread-F nights, fluctuations were observed in the east-west electric field, thereby indicating that fluctuating electric field is one of the prerequisites for ESF generation or sustenance.

The present analysis shows that the onset and persistence of ESF during different seasons under geomagnetically quiet conditions of the solar maximum and minimum periods respond to the magnitude of the PRE drift velocity (V_z) of the F-region. Further, the equatorial F-layer vertical drift is observed to depend on the level of the geomagnetic activity also. At Jicamarca, Peru, the dusk time peak in F-layer vertical drift is found to decrease with geomagnetic activity during equinoctial period, but to increase during local winter (Fejer et al., 1991). However, at Trivandrum, India, Namboothiri et al. (1989), noted the peak (maximum) drift velocity decreased as the geomagnetic activity changes from quiet to moderate conditions ($A_p \sim 15$–20), but again increased well above the quiet time values for high geomagnetic activity levels ($A_p > 25$).

Addressing to the possible relation of ESF occurrence with magnetic activity, it is well documented in the literature (Lyon et al., 1958; Somayajulu and Krishnamurthy, 1976), that there exists an inverse relationship between them (Rao and Mitra, 1962). The possible physical explanation for the control of the magnetic activity on the ESF duration could be understood only through its electrodynamical effects, i.e., through the electrodynamical coupling of the high latitude-low latitude ionosphere. The electric fields of the high latitude ionosphere promptly get communicated to the equatorial latitudes through the highly conducting ionosphere. On the other hand, the neutral dynamical coupling, though energetically very significant and capable of altering the thermosphere-ionosphere system involves the physical transport of energy and mass and hence its effect would be felt only with a time delay which can vary anywhere from 12–20 h (Gonzales et al., 1979; Pant and Sridharan, 1998).

The onset of ESF is thus the result of a complex, multidimensional problem, wherein many independent parameters like electric fields, neutral winds and neutral temperatures have independent control on its evolution, in addition to the initial perturbation levels. All these parameters have their own day-to-day variability. Therefore for a given magnetic activity level, ESF might show variability even with regard to its persistence or duration. In our present analysis, we have tried to look into the aspects using the K_p values as an index representing the background conditions.

5 Conclusion

A clear-cut relationship between the duration of equatorial spread F and the dusk time F region vertical drift during different seasons as well as with magnetic activity index K_p seems to be emerging. The relation ship is also controlled by the solar activity level with the solar maximum period

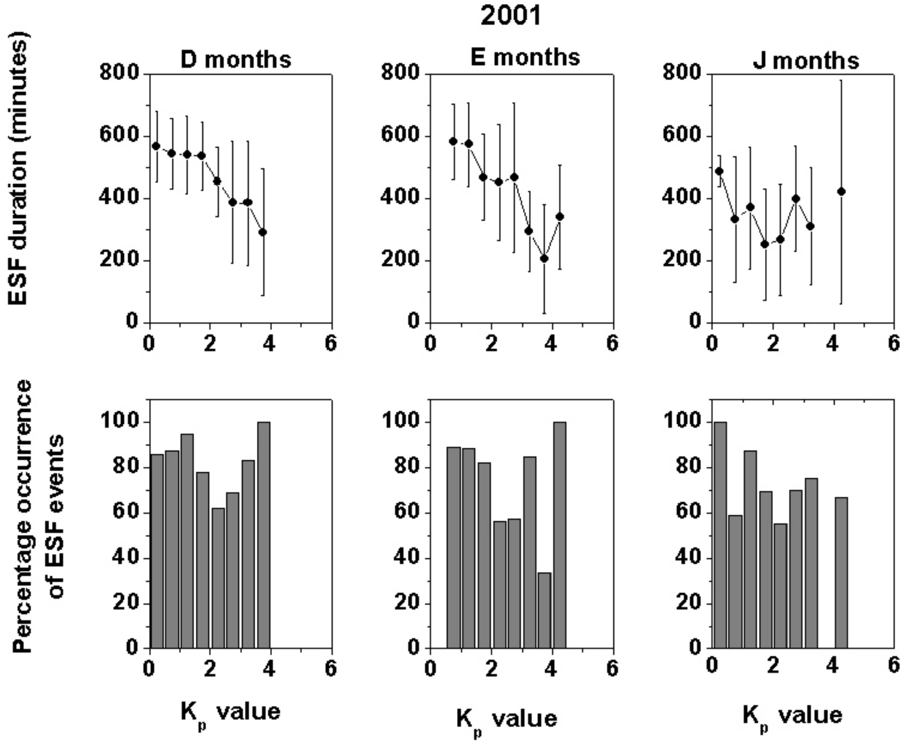

Fig. 4a. Distribution of the percentage occurrence of ESF events (bottom panel) and the average ESF duration with the standard deviation (top panel) against the magnetic activity index K_p for the different seasons during the solar maximum year of 2001. K_p values are taken in intervals of 0.5.

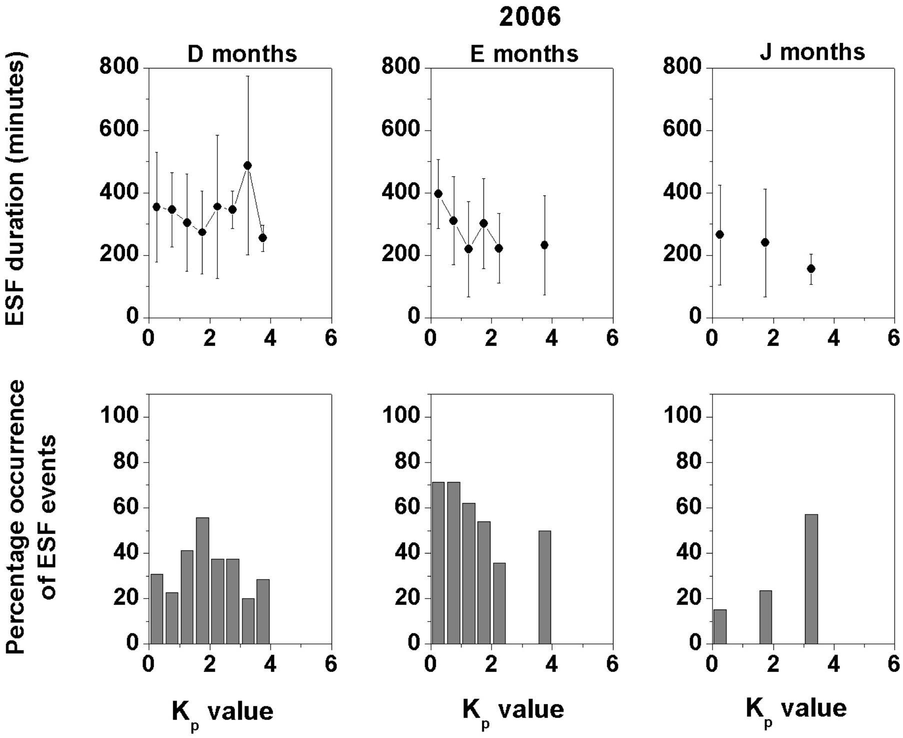

Fig. 4b. Same as for Fig. 4a, but for the solar minimum year of 2006.

showing a strong dependence between the various parameters governing the generation of ionospheric plasma irregularities. The additional electrodynamical forcings make the F-region base the most favorable region for the persistence of the irregularities. Knowing the level of magnetic activity and V_z or the post sunset $h'F$, one could make a reasonable estimate of the duration of ESF. This is considered to be an extremely important input for establishing reliable communication links, through the medium of the ionosphere.

Even though the study is based on the entire two-year's data, it is felt that the database is not sufficiently large enough to model the observed characteristics of the ESF over a complete solar cycle. The seasonal changes in the computed V_z values are probably caused by the seasonal changes in the thermospheric winds. Using the present database, within the limitations, the modeling of the persistence of ESF as a function of season, solar activity and geomagnetic activity could still be attempted; outlining the possibilities and limitations for forecasting ionospheric irregularity activity in the region for a low and high solar activity periods.

As a concluding remark, it may be stated that the magnitude of PRE V_z and its time of appearance is an important indicator of a post sunset development of ESF and its persistence, but other characteristics of the equatorial plasma electrodynamics may also become significant when the $h'F$ is below the critical level (e.g. equatorial thermospheric meridional wind – Devasia et al., 2002).

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