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Key Points:

- Investigated the local time dependence of ESF irregularities and their relation to low latitude Es layers during geomagnetic storms.
- Aarons criteria for different seasons under geomagnetic storms are examined.
- Examined the role of low latitude Es layers on the generation of ESF irregularities during geomagnetic storms

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A Statistical Study on The Local Time Dependence of Equatorial Spread F (ESF) Irregularities and Their Relation to Low-Latitude Es Layers Under Geomagnetic Storms

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Abstract In this paper, we present a study on the local time dependence of equatorial spread F (ESF) irregularities and their relation to low-latitude Es layers in response to geomagnetic storms using simultaneous observations of two ionosondes one located at Tirunelveli (8.73°N, 77.70°E), an equatorial station and other located at Hyderabad (17.36°N, 78.47°E), an off-equatorial station during the years 2007–2015 that covers solar cycles 23 and 24. The Aarons criteria for the ESF irregularities for different seasons under geomagnetic storms are evaluated. In the category I, we noticed partial enhancement in prereversal enhancement (PRE) during postsunset resulting in ~30% occurrence of spread F instead of total inhibition during equinox and winter seasons. Also, occurrence of ESF in summer is suppressed by only ~75% due to partial increase in PRE. In category II, we observed presunrise height enhancement mostly during winter, which caused ESF to occur at ~50% followed by equinox and summer. The results presented here suggest that many are actually not following the Aarons criteria possibly due to not considering other background conditions. Accordingly, we examined the plausible role of low-latitude Es layers on the generation of ESF irregularities under these categories during geomagnetic storms. We noticed the absence/presence of Es layers in both categories during postsunset and postmidnight hours resulting in increase/decrease of PRE due to modifications in the field-line-integrated Pederson conductivity. Accordingly, the results suggest that one of the plausible reasons for ESF irregularities not following Aarons criteria is linked to the variability of the low-latitude Es layers.

Plain Language Summary The electric fields and winds in the equatorial and low-latitude ionosphere are modified during geomagnetic storms due to coupling of solar wind-magnetosphere-ionosphere in the high latitudes. Accordingly, the occurrence of equatorial spread F (ESF) irregularities are significantly affected by the geomagnetic storms depending upon the time of the onset of the geomagnetic storm. We classified our observations into three categories based on Aarons criteria under different seasons to examine the role of geomagnetic storms on the generation/suppression of ESF irregularities based on the onset conditions of magnetic storms over India. The observations suggest that many ESF events could not follow this criterion due to not having included other background conditions. Accordingly, we examined the role of low-latitude Es layers, which may affect the field-integrated conductivities of the E and F regions during the onset times of ESF irregularities using larger data. The results suggest that whenever Es layers are present (absent) at low latitude, suppression (generation) of premidnight or postmidnight ESF irregularities at Tirunelveli is on rise. So these results suggest that if the low-latitude Es layers are taken into account, occurrence of ESF irregularities may be explained better by the above criteria.

1. Introduction

As the Earth's magnetic field lines are nearly horizontal over magnetic equator, the equatorial ionosphere is a bed for variety of plasma instabilities to cause plasma disturbances and plasma irregularities. The plasma irregularities caused due to plasma instabilities and plasma disturbances due to traveling ionospheric disturbances pose severe problems to the communication and navigation systems and interfere with surveillance operations as well as disruption in detection and tracking of aircraft, missiles, satellites, and other targets (Booker & Wells, 1938; Doherty et al., 2004; Sunda et al., 2015). So understanding the thermosphere-ionosphere magnetosphere interactions that control the electrodynamics behind dynamical evolution of

ionospheric irregularities under disturbed periods is most important for communication system, civilian applications, etc. (Conker et al., 2003; Hlubek et al., 2014; Kintner et al., 2007).

During the geomagnetic storms, equatorial and low-latitude zonal electric fields primarily affected by the two sources: (1) penetration of high-latitude convection electric fields of magnetospheric origin (called prompt penetration electric field) and (2) disturbance dynamo electric field (DDEF) originated at the high latitudes due to the global thermospheric wind circulation caused by Joule heating. During the magnetic storm, a southward turning of the interplanetary magnetic field (IMF) B_z component initiates a growth of substorm activity and a rapid increase of high-latitude convection electric field. This expansion is faster than the magnetosphere can respond, so that the high-latitude convection electric fields penetrate into the low-latitude ionosphere (e.g., Kelley et al., 1979; Kikuchi et al., 2000; Huang et al., 2007; Kikuchi et al., 2008). Magnetic storm time-enhanced high-latitude heating generates strong equatorward neutral winds. These disturbance winds generate a westward/eastward electric field on the dayside/nightside at the low-latitude ionosphere, which is opposite to the quiet time patterns (e.g., Blanc & Richmond, 1980; Fuller-Rowell et al., 2002; Maruyama et al., 2005; Scherliess & Fejer, 1997). The PP electric field transmits almost instantly to the equatorial regions through the propagating of transverse magnetic mode in the Earth ionosphere waveguide (Kikuchi, 1986) with the eastward/westward polarities during the day/night. The disturbance dynamo (DD) electric field develops more slowly as it takes several hours to setup the disturbance winds and the associated dynamo electric fields after which they continue for many hours due to the neutral air inertia (Maruyama et al., 2005). The zonal component of the DD electric field is in westward during the daytime, which is opposite to the daytime ionospheric dynamo electric field, while eastward will be in night (Blanc & Richmond, 1980).

The equatorial ionosphere is known to be affected by several forces acting from below and above including the magnetospheric convection, ionospheric dynamo disturbances, and different kinds of wave disturbances (Blanc & Richmond, 1980; Araki et al., 1985; Kikuchi, 1986; Abdu, 1997; Abdu et al., 2003; Carrasco et al., 2005, 2007). These disturbances can affect the winds, waves, composition, and electric fields of the E and F regions, which are responsible for excitation of large number of plasma instabilities such as Rayleigh-Taylor (R-T) instability, gradient drift instability, two stream instability, and vertical $E \times B$ drift of plasma over the magnetic equator to generate the ionospheric irregularities (Abdu, 2001; Kelly, 1989). The equatorial ionospheric irregularities are manifested as spread F in the ionograms, scintillations in trans-ionospheric radio signals, plasma bubbles in airglows, and plasma plumes in radars (Aarons & Das Gupta, 1984; Dabas et al., 1989; DasGupta et al., 1985; Rastogi et al., 1981). Significant progress has been made in the past in understanding the seasonal, solar cycle, and geomagnetic storm variations in occurrence pattern of scintillation (Chakraborty et al., 1999; Chandra et al., 2003; Michael et al., 2000; Su et al., 2007). Based on simultaneous recordings of nighttime scintillation experiments using chain of meridional stations in the India, latitudinal extent of ionospheric irregularities producing ionospheric scintillation are investigated (Dabas & Reddy, 1986; Somayajulu et al., 1984).

Significant advancements were also made by the previous researchers to examine the generation or inhibition of ionospheric irregularities at the equatorial and low latitude under geomagnetic disturbances according to the local time onset of maximum negative excursion of Dst index and severity of magnetic storm (Aarons, 1991; Aarons & Das Gupta, 1984; Dabas et al., 1989; DasGupta et al., 1985; Rastogi et al., 1981). The occurrence of ESF irregularities varies with longitude, latitude, local time, seasons, solar, and geomagnetic activities (Kelley, 2009). While seasonal and latitudinal variations of quiet time disturbances are broadly understood, still quantification of storm time disturbances and their longitudinal effects are not yet completely understood due to lack of measurements and complexities involved in its physical understanding. Many researchers across the globe have worked on the occurrence of scintillation activity and spread- F irregularities, and they found some empirical relationship in terms of different geomagnetic indices (like K_p and Dst), which are defined by the magnetospheric and ionospheric currents. Aarons and Das Gupta (1984) have suggested that the occurrence of postmidnight scintillation is enhanced if the recovery phase of the storm starts at midnight to presunrise to the local time sector. The necessary condition for the generation of F -region irregularities in the nighttime equatorial ionosphere is believed to be the rise of F layer to higher heights where the effect of recombination becomes unimportant for the R-T instability. Dabas et al. (1989) investigated the local time effects on the scintillation activity during the different

phases of magnetic storms. They divided several magnetic storm events into three categories, namely, categories A (06:00–18:00 LT), B (18:00–00:00 LT), and C (00:00–06:00 LT) according to the local time when the Dst index reaches its minimum. They observed that category C magnetic storms are more favorable for generation of irregularities at the magnetic equator. They investigated ionosonde data to suggest that enhancement in postmidnight ionospheric height ($h'F$) and spread- F occurrence could be due to geomagnetic storms.

Aarons (1991) analyzed the equatorial scintillation data during the magnetic storms based on the geomagnetic indices (K_p and Dst) at different longitude sectors and concluded that the ring current could play a leading role either directly or indirectly for establishing the conditions for the occurrence of equatorial F -layer irregularities. Aarons (1991) categorized geomagnetic storms into three categories, based on the maximum negative excursion of Dst index, namely, categories I (10:00–16:00 LT), II (00:00–06:00 LT), and III (18:00–22:00 LT). They found that category I is more favorable for the inhibition of scintillation activity. Banola et al. (2001) had verified that the local time of maximum intensity of ring current could be playing a role to establish the necessary conditions for scintillation activity. And their study showed that the scintillations at low latitudes can be inhibited or triggered during the magnetic storms, depending up on the phase of magnetic storms and its local time of occurrence. During the magnetically disturbed periods, Martinis et al. (2005) studied the development (or inhibition) of equatorial ionospheric irregularities using AE-parameterized Fejer Scherliess model for disturbance vertical drifts. They reported that drivers of the equatorial vertical plasma drifts can have prompt or delayed effects in the premidnight sector (where ESF generation and suppression can occur), as well as in the postmidnight period (where ESF generation dominates). They suggested the role of interplanetary electric field (IEFy) in ESF development/inhibition.

On the other hand, some studies have showed good relationship between Es-layer disruption/formation and evening hour prereversal enhancement (PRE) vertical drift and equatorial spread F under geomagnetically quiet times (Stephan et al., 2002; Abdu et al., 2003; Carrasco et al., 2005, 2007; Batista et al., 2008; Joshi et al., 2013). Abdu et al. (2003) showed that larger amplitudes of PRE are associated with disruption of the Es layer and the smaller PRE amplitudes are associated with nondisruption of Es layers. Carrasco et al. (2005) reported that presence of Es layers in the evening hours can influence the intensity of PRE development and capable of modifying the longitudinal/local time gradient in the E -layer Pederson conductivity. Batista et al. (2008) investigated the relationship of spread- F occurrence/generation at the magnetic equator with the presence of Es layer at the conjugate E region along the magnetic field line. They suggested that integrated field line conductivity is not significantly affected by the occurrence of Es layer if it is located at conjugate E region, which can only map to above base of the F layer and its presence is not sufficient to suppress the vertical drift to cause spread- F generation. However, none of these studies has addressed the role of Es layers during geomagnetic storms.

The main objective of this work is to present the virtual height variations and spread- F occurrence under geomagnetic storms and investigate the sources for the generation/inhibition of ionospheric irregularities over the magnetic equatorial station at Tirunelveli. In this study, a total of 73 moderate to intense geomagnetic storm events are identified and classified them into three categories according to Aarons (1991) criteria, which is commonly accepted criteria to explore the occurrence of ionospheric irregularities. As per the criteria, (1) category I: if the maximum negative excursion of Dst occurs during the day time hours between at 06:00–18:00 LT and well before the sunset, the height of the ionospheric F layer gets disturbed and ionospheric irregularities (spread F) are completely or partially inhibited on the following night. (2) Category II: if the maximum negative of Dst occurs during the midnight-down (at 00:00–06:00 LT), the height of the ionospheric F layer first rises and then falls, which generated the ionospheric irregularities. (3) Category III: if the recovery phase start or maximum excursion of the Dst occurs during the sunset-midnight (at 18:00–00:00 LT), the occurrence of ionospheric irregularities will not affect and will occur as they do on undisturbed night. Since Aarons (1991) has only considered the phase of the Dst index and its local time but not considered the other effects such as field line-integrated conductivity effect and seeding of the instability by gravity waves in his proposed mechanism, the present work examines the possible role of other parameters on the occurrence or nonoccurrence of plasma irregularities over the equatorial station at Tirunelveli. Here, mainly an attempt has been made on the role of low-latitude Es layers in the generation/inhibition of plasma irregularities during magnetic storms. Since low-latitude Es layers play major role in ESF onset, it is believed that low-latitude Es layers during storm time also influence the

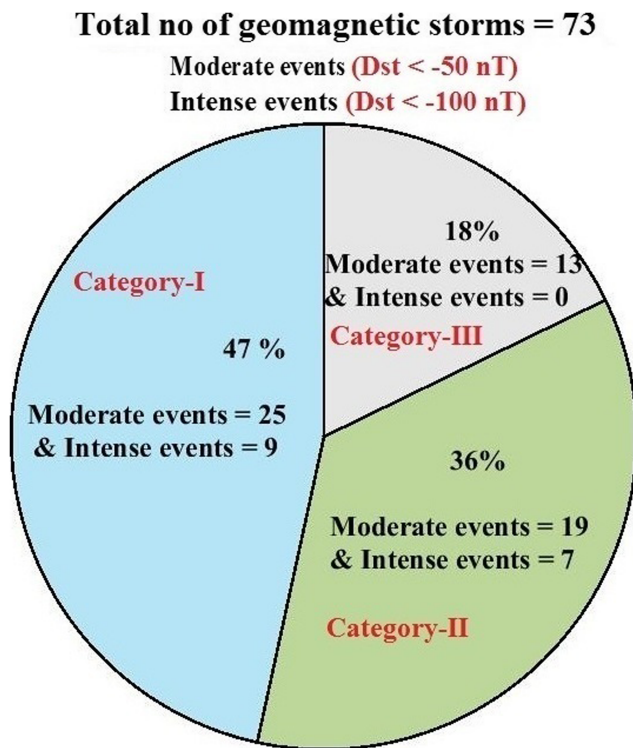


Figure 1. Classification of geomagnetic storm events based on the Aarons (1991) criteria, depending upon the maximum excursion of Dst (SYM-H) falling under different local times, namely, 06:00–18:00 LT (category I), 00:00–06:00 LT (category II), and 18:00–00:00 LT (category III).

ESF. As the E region at Hyderabad is connected to the base of the F region at 250 km at magnetic equator, any changes in the E -region density can have significant impact on the ESF irregularities as field-integrated conductivity plays important role in deciding the growth of the plasma irregularities. It is believed that low-latitude Es layers may be modified due to modified winds/electric fields during the geomagnetic storms, and hence, examining their role in the generation of ESF irregularities is very important (e.g., Li et al., 2006; Sripathi et al., 2018). The study also investigates the seasonal response of early morning height rise and their relation to occurrence of ionospheric irregularities during the disturbed conditions. These results along with their possible scientific explanations are discussed here.

2. Data Sets

In order to investigate the role of geomagnetic storms on ionospheric irregularities and to find possible relationship between low-latitude Es layer and equatorial spread F (ESF) under geomagnetic storms, two CADI ionosondes each located at an equatorial station at Tirunelveli (geog: 8.73°N, 77.7°E, and geom: 0.34°N) and a low-latitude station Hyderabad (geog: 17.36°N, 78.47°N, and geom: 8.76°N) are utilized. We identified 73 geomagnetic storms (moderate and intense storms, $Dst < -50$) during the years 2007–2015 in solar cycles 23 and 24 where ionosonde observations were available. The CADI ionosonde data are manually scaled to identify the F -layer height and ESF duration at every 10 (at times, 15 min) interval to study the effect of $h'F$ (virtual height) variations on the spread F during disturbed conditions. Simultaneously, the ionosonde data as obtained from Hyderabad, a low-latitude station is also scaled for virtual height ($h'Es$) and critical frequency ($foEs$) of Es layer. To study the role of low-

latitude Es layers on $h'F$, ionosonde data at Hyderabad is scaled for only 35 magnetic storm events due to the lack of simultaneous data availability at both Tirunelveli and Hyderabad stations. The geomagnetic indices, namely, IMF B_z , AU/AL, and Dst are also utilized to identify the effects of geomagnetic activity and magnetospheric electric fields.

2.1. Classification of Geomagnetic Storms According to the Aarons Criteria

To examine the effects of geomagnetic storms on the occurrence characteristics of ionospheric irregularities, a total number of 73 geomagnetic storms have been selected. The total number of geomagnetic storms is categorized into three different categories based on the local time of maximum negative excursion of Dst index as suggested by Aarons (1991) since Dst index (SYM-H) is widely used parameter to identify the storm time disturbance level. The prompt penetration electric fields likely to play role in modifying the equatorial electric fields in the early part of the storm and can cause ESF irregularities to either enhance or suppress, but they also depend on the strength of Dst index. So the Dst index is indeed a measure of solar wind parameter, indirectly. The empirical model as developed by Fejer and Scherliess (1997) for storm-time electric fields over equatorial locations using Jicamarca incoherent scatter radar vertical drifts by taking AE index into account provides broad physical picture for the Aarons criteria. According to this model, postsunset ESF irregularities can be either generated or suppressed depending upon the orientation of storm time electric field. Similarly, eastward DDEFs can cause postmidnight ESF irregularities. As Dst index has been used widely in Aarons criteria to classify the occurrence characteristics of ESF irregularities, we used same index here in our storm events.

Out of 73 magnetic storms, 34 belong to category I, 26 belong to the category II, and 13 events belong to the category III as shown in the Figure 1. As it is believed that the geomagnetic activity is very much dependent on the season, the magnetic storm events are again classified into equinox, summer, and winter seasons. In the category I, out of 32 magnetic storms, 18 belong to the equinox, 8 belong to the summer, and 6 events belong to the winter. In category II, out of 26 events, 14 events fall in the equinox, 6 each in the summer

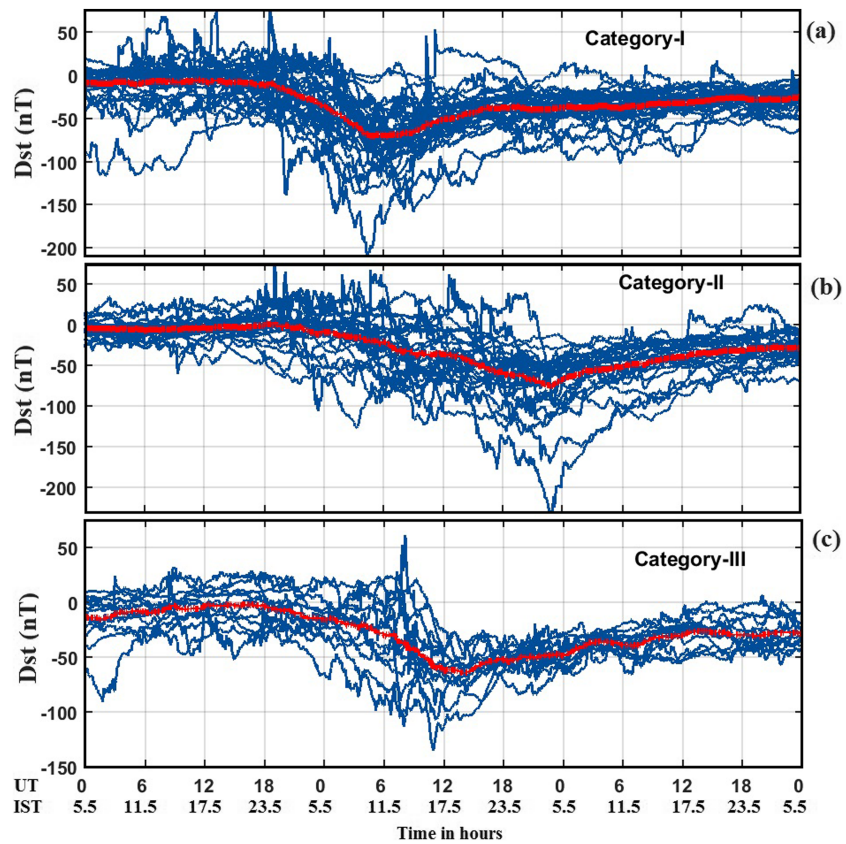


Figure 2. (a–c) The temporal variation of Dst index (the Dst curves are outdated according to the Aarons criteria) during the geomagnetic storms under (a) category I (34 events), (b) category II (26 events), and (c) category III (13 events). In each panel, the red color line shows the average value of Dst index.

and winter. The details of the storms selected for the present study, and its classifications are shown as pie chart in Figure 1. Figures 2a–2c show the Dst index variations during the magnetic storm time under these three categories, respectively, where red colored line show the mean value of Dst index. In addition, we identified 35 events having simultaneous observations at Tirunelveli and Hyderabad to examine the possible role of low-latitude Es layer for the generation or inhibition of the plasma irregularities over equatorial region during storms over Indian sector. Out of these 35 storm events, 14 belonging to category I, 13 belonging to category II, but only 8 events belong to the category III.

3. Results

3.1. Response of Plasma Irregularities Under Geomagnetic Storms

First, we present typical examples of temporal variation of virtual height and occurrence of spread F during magnetic storm events under three categories as proposed by Aarons (1991) and show that some of them are following and some of them are not following this criterion.

3.1.1. Magnetic Storm of 24 April 2012 (Category I)

This magnetic storm is an intense geomagnetic storm, which occurred on 24 April 2012, where the Dst index reached its maximum value -120 nT at 10:30 IST. This storm falls under the category I as the maximum suppression of the Dst or recovery phase of the storm falls under the daytime. Figures 3a–3d (left) show the magnetic storm of 24 April 2012 along with the corresponding parameters IMF B_z , AU/AL, Dst, and h'F height variations during 23–25 April 2012. The lower panel of the Figure 3 shows the altitude variation of the ionospheric F -layer height. The red color line with error bars represents the variation of virtual height of five international quiet days (IQDs); during April 2012, the five IQDs are 06, 08, 09, 16, and 30. The blue color bar indicates spread- F occurrence duration over the equatorial station at Tirunelveli. The storm sudden

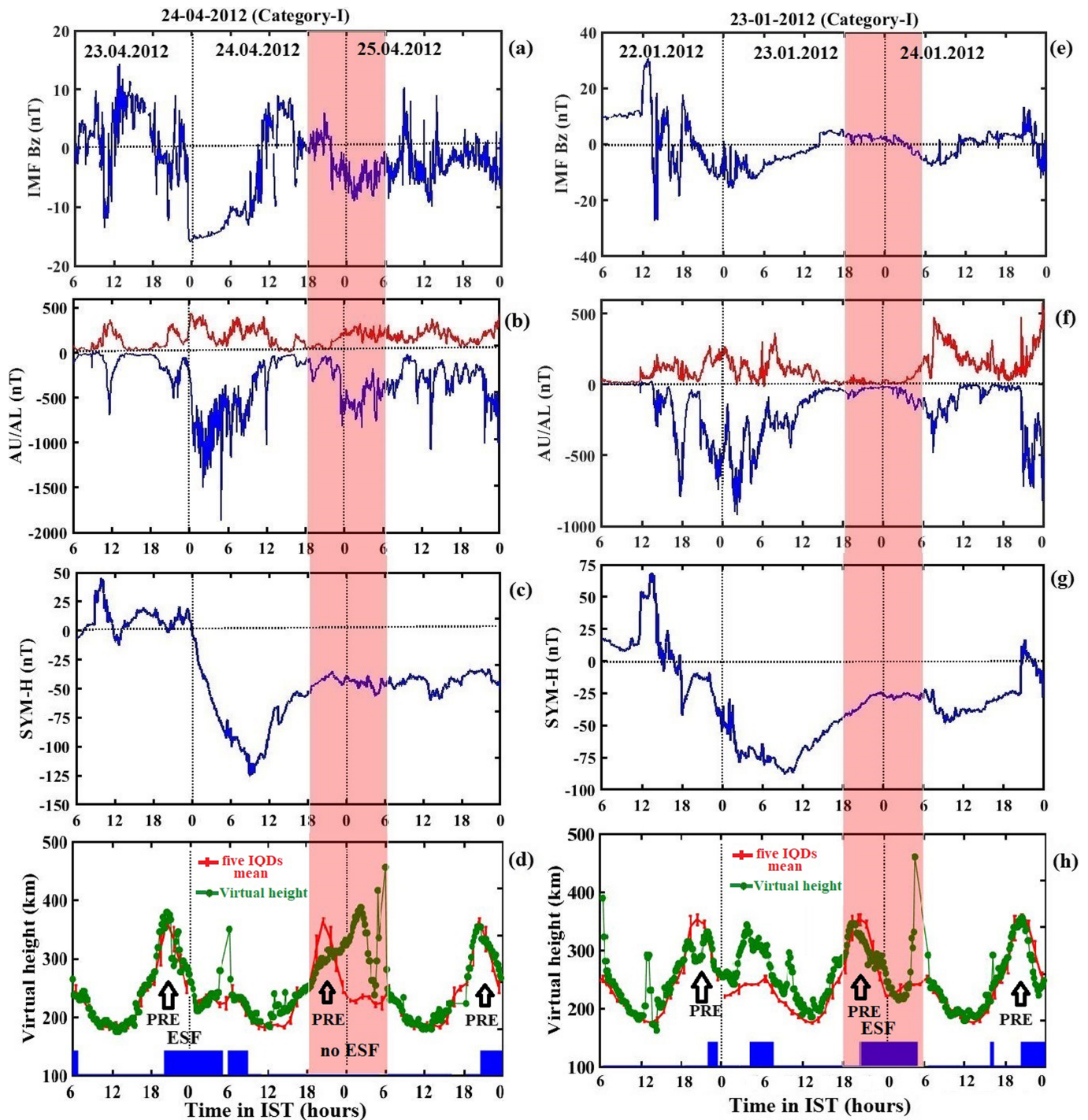


Figure 3. (a–h) Typical examples of geomagnetic storms under category I. Panels (a)–(d) show the magnetic storm occurred during 23–24 April 2012 that satisfies the Aarons criteria. Panels (e)–(h) show magnetic storm observed on 22–24 January 2012 that is not satisfying the Aarons criteria. The upper panels (a) and (e) show the interplanetary magnetic field B_z , panels (b) and (f) shows the AU/AL, (c) and (g) Dst variations, and (e) and (h) the lower panels of the figure show the h F (km) variations over the equatorial station at Tirunelveli. The red color line with error bars shows five international quiet day (IQD) mean variation of virtual height. The blue color bar plot in lower panels shows the spread- F occurrence.

commencement occurred at 22:30 IST hours on 23 April 2012. After about an hour, the Dst started decreasing attaining the lowest value of -120 nT at 10:30 IST (Figure 3c). From the Figure 3c, it can be seen clearly that on 24 April, no significant height rise is observed and the irregularities are inhibited

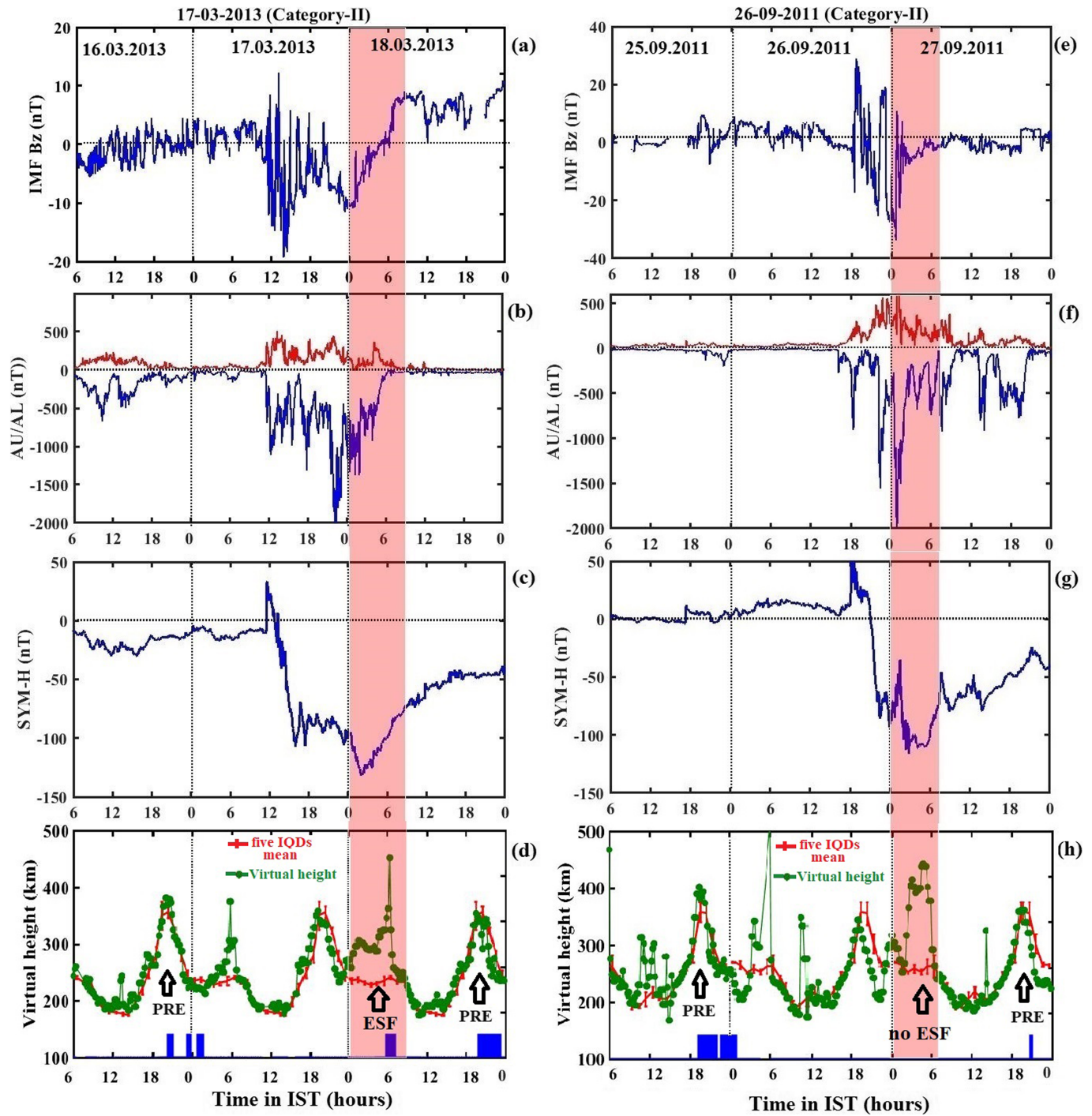


Figure 4. (a–h) Typical examples of geomagnetic storms under category II. Panels (a)–(d) show the magnetic storm occurred during 16–18 March 2012 that satisfies the Aarons criteria category II. Panels (e)–(h) show the magnetic storm observed on 25–26 September 2011 that is not satisfying the Aarons criteria category II. The upper panels (a) and (e) show the interplanetary magnetic field B_z , panels (b) and (f) show the AU/AL, panels (c) and (g) show the Dst variations, and (e) and (h) the lower panels of the figure show the h'F (km) variations over the equatorial station at Tirunelveli. The red color line with error bars shows the IQD mean variation of virtual height. The blue bar plot in the lower panels shows the duration of spread-F occurrence.

during that night (shaded region in red color). This feature follows the category I of the Aarons criteria. However, from the figure, we can see that before and after the storm on 23 and 25 April, postsunset PRE height enhanced leading to the generation of ionospheric irregularities on the following nights.

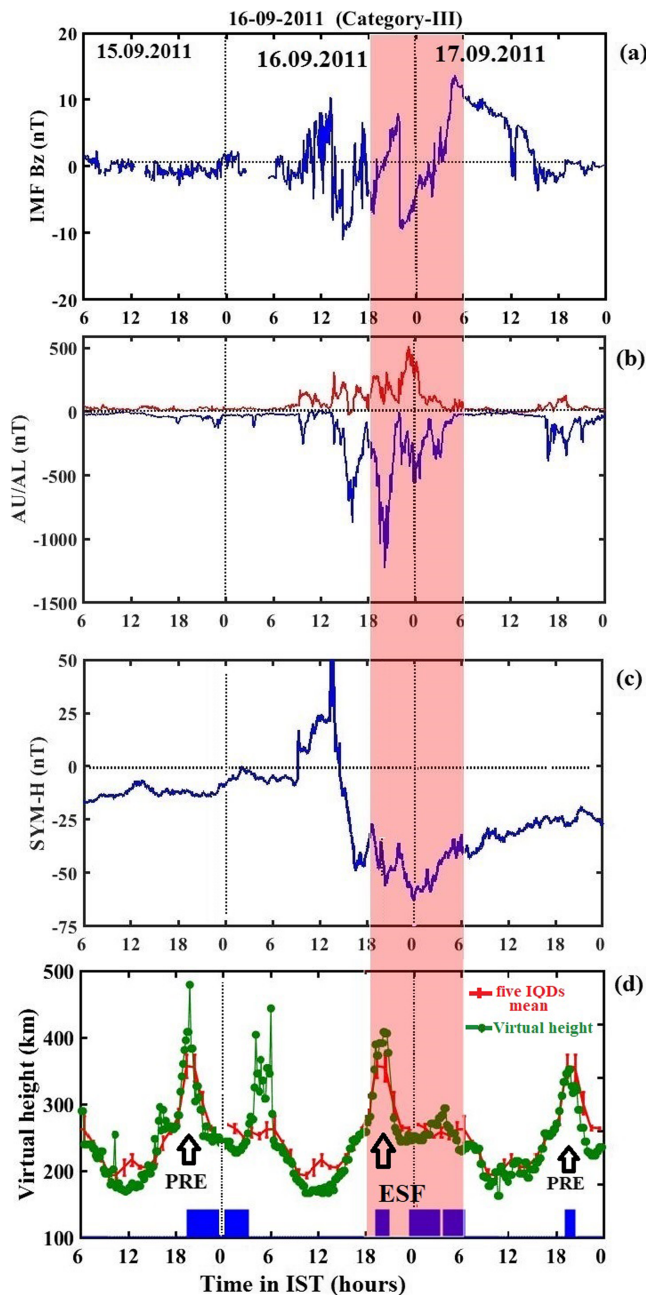


Figure 5. Typical example of a magnetic storm that occurred during 16–18 September 2011, which falls under the Aarons criterion category III.

2011, is shown in Figures 4e–4h. The upper two panels show the IMF B_z and AU/AL variation, while the lower two panels show the Dst and hF variations. The red color line with error bars shows the mean variation of virtual height of five IQDs; during March 2012, IQDs are 06, 08, 11, 19, and 23. The bar plot in blue color indicate spread-F occurrence duration over Tirunelveli. The sudden commencement of this magnetic storm occurred at 17:30 IST reaching a negative maximum Dst value -118 nT around at 05:30 IST on 27 September (Figure 4g). During the main phase of magnetic storm, AL reached its maximum value, that is, -2000 nT at 00:30 IST on 27 September (Figure 4f), and at the same time, IMF B_z with value of -25 nT was in southward direction (Figure 4e). The height variation of the F layer over Tirunelveli on 26 September 2011 at 05:00 IST enhanced and reached its maximum value 450 km (shaded region) and after an hour decreased and reached its value ~ 200 km at 05:00 IST. During this event, though the F -layer

3.1.2. Magnetic Storm of 23 January 2012 (Category I)

In Figures 3e and 3f (right), while the upper two panels show the IMF B_z and AU/AL, the bottom two panels (g) and (h) show the Dst variations and hF variations at Tirunelveli with spread-F occurrence indicated by the bar plot (blue) in the lower panel during 22–24 January 2012. In the bottom panel, the red color line with error bars represents the mean variation of virtual height of fine IQDs; during the January 2102, IQDs are 04, 14, 18, 19, and 31. This magnetic storm was moderate geomagnetic storm with a peak of Dst -75 nT at 11:30 IST on 23 January 2012. The virtual height variation of the F layer over Tirunelveli on 23 January reached up to 350 km at 19:00 IST in the recovery phase of storm, but after one hour or so, ionospheric irregularities started appearing during 20:00–05:00 IST (shaded region in red color). According to the Aarons (1991) criteria, ionospheric regularities should have been suppressed on 23 January night (shaded region in red color), but during this event, ionospheric irregularities are occurred on every night during 22–24 January 2012, a period that fall before the main phase, main phase, and after the main phase of magnetic storm. So this feature does not justify the Aarons criteria I.

3.1.3. Magnetic Storm of 17 March 2013 (Category II)

Figures 4a–4d (right) present the variation of an intense magnetic storm, which occurred on 17 March 2013 quite similar to previous Figure 3. However, this magnetic storm comes under the category II as the maximum suppression of storm falls during the postmidnight and before the sunrise hours. The sudden commencement of this storm occurred at 12:00 IST hours on 16 March. The maximum negative excursion of Dst exhibited the peak of Dst -132 nT at 02:30 IST hour on 17 March 2013. Figures 4e–4h (left) show (e) IMF B_z , (f) AU/AL, (g) Dst index, and (h) hF (km) variations, respectively, during 16–18 March 2013. The red color line with error bars shows the mean variation of virtual height of five IQDs; during March, IQDs are 07, 08, 13, 25, and 26. The blue color bar (in the lower panel) indicates the duration of spread-F occurrence.

The height variation of the F layer over Tirunelveli on 17 March after the maximum excursion of the Dst or recovery phase in the magnetic storm showed a large enhancement and reached its maximum value as high as ~ 470 km at 06:00 IST. This height enhancement over the Tirunelveli is one of the contributing factors for the generation of ionospheric irregularities during the recovery phase of magnetic storm. The spread F occurred at 05:30–07:00 IST on 18 March 2013 (shaded region), which follows the Aarons criteria II. The delayed DDEFs must have the played a role to increase the F -layer height over time and caused of the generation of ionospheric irregularities.

3.1.4. Magnetic Storm of 26 September 2011 (Category-II)

An intense geomagnetic storm, which occurred during 25–27 September 2011, is shown in Figures 4e–4h. The upper two panels show the IMF B_z and AU/AL variation, while the lower two panels show the Dst and hF variations. The red color line with error bars shows the mean variation of virtual height of five IQDs; during March 2012, IQDs are 06, 08, 11, 19, and 23. The bar plot in blue color indicate spread-F occurrence duration over Tirunelveli. The sudden commencement of this magnetic storm occurred at 17:30 IST reaching a negative maximum Dst value -118 nT around at 05:30 IST on 27 September (Figure 4g). During the main phase of magnetic storm, AL reached its maximum value, that is, -2000 nT at 00:30 IST on 27 September (Figure 4f), and at the same time, IMF B_z with value of -25 nT was in southward direction (Figure 4e). The height variation of the F layer over Tirunelveli on 26 September 2011 at 05:00 IST enhanced and reached its maximum value 450 km (shaded region) and after an hour decreased and reached its value ~ 200 km at 05:00 IST. During this event, though the F -layer

height is enhanced, spread F was suppressed in the early morning hours on 27 September 2011. The suppression of spread- F irregularities in the shaded region represents that this magnetic storm is not following the Aarons category II.

3.1.5. Magnetic Storm of 16 September 2011 (Category III)

This storm occurred during 15–17 September 2011, and this was the moderate magnetic storm with the maximum negative Dst value reaching -75 nT. Figures 5a–5d show the variation of IMF B_z , AU/AL, Dst, and $h'F$ (km), respectively. The sudden commencement of the magnetic storm occurred at 15:00 IST on 15 March, and the maximum negative Dst value of -60 nT occurred at 00:00 IST on the next day. At the time of maximum Dst excursion of this storm, which occurred between the sunset and premidnight hours, the virtual height did not change much between 23:30 and 02:30 IST (shaded region), but irregularities occurred, which are similar to undisturbed night. It may be noticed that before $\sim 23:30$ IST and after 03:00 IST, F -layer height rises and falls that may generate the ionospheric irregularities. As per the Aarons criteria, the height and generation of spread F should not be affected by the storm. As category III is independent of Aarons criteria, we focus our studies on other two categories only in the subsequent sections.

3.2. Seasonal Variation of Spread- F Occurrence Under Magnetic Storms

3.2.1. Category I

Now to examine the effects of geomagnetic storms on the occurrence characteristics of spread F over the equatorial station at Tirunelveli, we have categorized 32 magnetic storm events of category I into three seasons (equinox, summer, and winter) based on the data availability between the years 2007–2015. It may be mentioned that the magnetic storm events occurred in February–April and August–October fall under equinox, magnetic storms occurred in May–July months falls under summer, and the magnetic storms occurred during the November–January Months fall under winter season.

Figure 6 shows the seasonal variation of the $h'F$ (km) variations and percentage occurrence of ionospheric irregularities (spread F). The top three panels of the figure show Dst variations; the middle three panels show the $h'F$ (km) variations with bold black lines representing the average value of $h'F$ (km), between 12:00 and 00:00 IST during the recovery phase of magnetic storms (shaded region in the top panels) during equinox, winter, and summer seasons, respectively. The lower three panels are showing the maximum percentage occurrence of the spread F during disturbed time (between 12:00 and 00:00 IST). The percentage occurrence is calculated by dividing the number of days when spread F was observed to the total number of days at every 15 min. From Figures 6b and 6c, it has been seen that percentage occurrence of spread F during the equinox depends on the height enhancement of the ionospheric F layer during evening hours and 25% spread- F occurrence observed during the nighttime. The average F -layer height enhanced between 18:00 and 21:00 IST and reached its maximum value at 19:00 IST. After 30 min, the generation of ionospheric irregularities starts and reached maximum percentage occurrence of spread F 20:00 IST. During the equinox season, occurrence of ionospheric irregularities is not satisfied based on the Aarons category I.

From the figure, during summer, season ionospheric irregularity formations are not depending on height enhancement of F layer. In Figure 6e PRE height is suppressed at 18:00–20:00 IST, but spread F occurs only 25% in the premidnight hours. During the summer season, suppression of $h'F$ (suppression of PRE) satisfies the Aarons category I, but generations of spread F is not expected as per Aarons category I. During the winter season, the percentage occurrence of ionospheric irregularities is less compared to the equinox and summer seasons. From Figure 6h–6i, it has been seen that the percentage occurrence of spread F is 20% between at 19:00–22:00 IST (Figure 6g) and at 19:00 IST $h'F$ (km) shows the altitude variation or PRE enhancement (Figure 6h). The percentage occurrence of ionospheric irregularities is enhanced at 23:00 IST as soon as ionospheric F -layer height is enhanced, and the percentage occurrence has reached 30%. So these features show that the occurrence of ionospheric irregularities over the equatorial region during the magnetic storm time is not completely following the Aarons category I criterion.

3.2.2. Category II

Figure 7 represents the seasonal variation of ionospheric F -layer height and the percentage occurrence of spread F with local time at equatorial station at Tirunelveli in the recovery phase of magnetic storms of category II. The top three panels of the figure show Dst variations, the middle three panels are representing $h'F$ variations between 00:00 and 12:00 IST during the recovery phase of magnetic storms (shaded region in the top panels), and solid black color lines are indication of average value of $h'F$. The lower three panels are

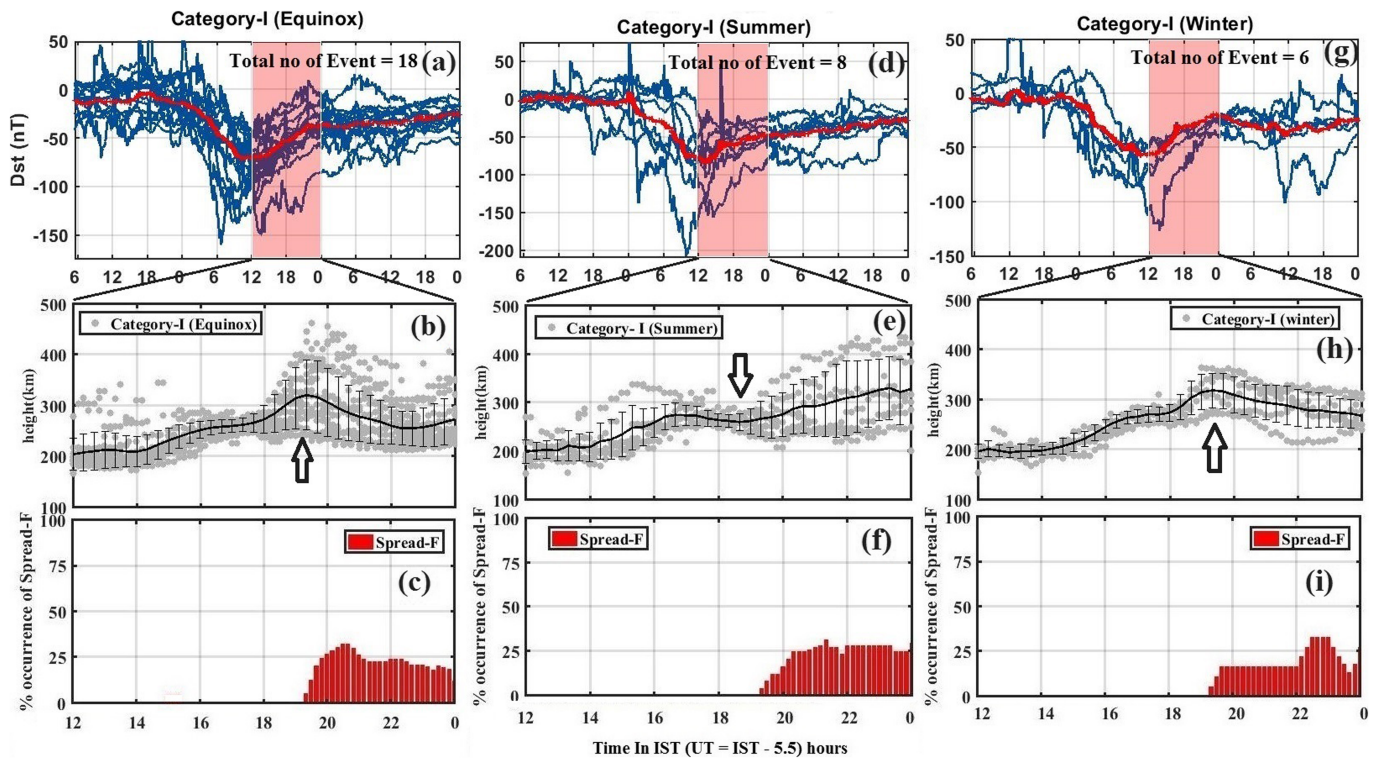


Figure 6. (a-i) Seasonal (equinox, summer, and winter) classification of magnetic storms under category I. (a, d, and g) The Dst variations. (b, e, and h) The ionospheric height ($h'F$) variations. (c, f, and i) The percentage occurrence of spread F over Tirunelveli for shaded region in top panels of the figure (between 12:00 and 00:00 IST hours). The upward/downward arrows show the enhancement/reduction.

showing percentage occurrence of spread F over the low-latitude station at Tirunelveli. From the figure, in the equinox season, the average altitude variation of the $h'F$ is enhanced at 05:00 IST (Figure 7b). The percentage occurrence of spread F is observed 20% (Figure 7c) before the height enhancement. After the height enhancement in the F layer, the percentage occurrence of spread F reduced. During the equinox season, observations show that ionospheric irregularities may or may not depend on the morning hour height enhancement. During the summer season, as shown in Figure 7e, shows the average height enhancement at 03:00 IST but reduced later. The percentage occurrence of spread F during the midnight is 60%, and after that, the occurrence got reduced up to 06:00 IST. During the summer season, magnetic storms are not completely justifying the Aarons criterion. It is also noticed that the percentage occurrence of spread F is more during the summer compared to other seasons and reached 60%, and large variation in the virtual height with large standard deviation is observed at 02–04 IST.

During the winter season, the generation of ionospheric irregularities is found to be dependent on the height enhancement in the presunrise of the F layer. In Figure 7h, $h'F$ starts increasing at 04:00 IST and enhanced its maximum average value 400 km at 05:30 IST and starts decreasing, after around an hour it decreased and reached its value 200-km altitude at 06:30 IST. Though only 20% of occurrence of spread F is noticed between 01:30 and 04:00 IST, the percentage occurrence suddenly started increasing at 05:30–06:30 IST and reached 50%. This enhancement in the percentage occurrence of spread F is related to the presunrise height enhancement. The sudden increase in the occurrence of irregularities during this period could be linked to the early morning production of plasma irregularities. So this feature is following the Aarons category II.

3.3. Possible Role of Low-Latitude Es Layers in the Occurrence of ESF Under Magnetic Storms

As we have seen that Aarons criteria are followed in some cases but not in other cases, we studied the reasons for this behavior with the help of simultaneous observations of Es layers at low-latitude station, Hyderabad. For this study, a total of 35 geomagnetic storm events are selected where we have

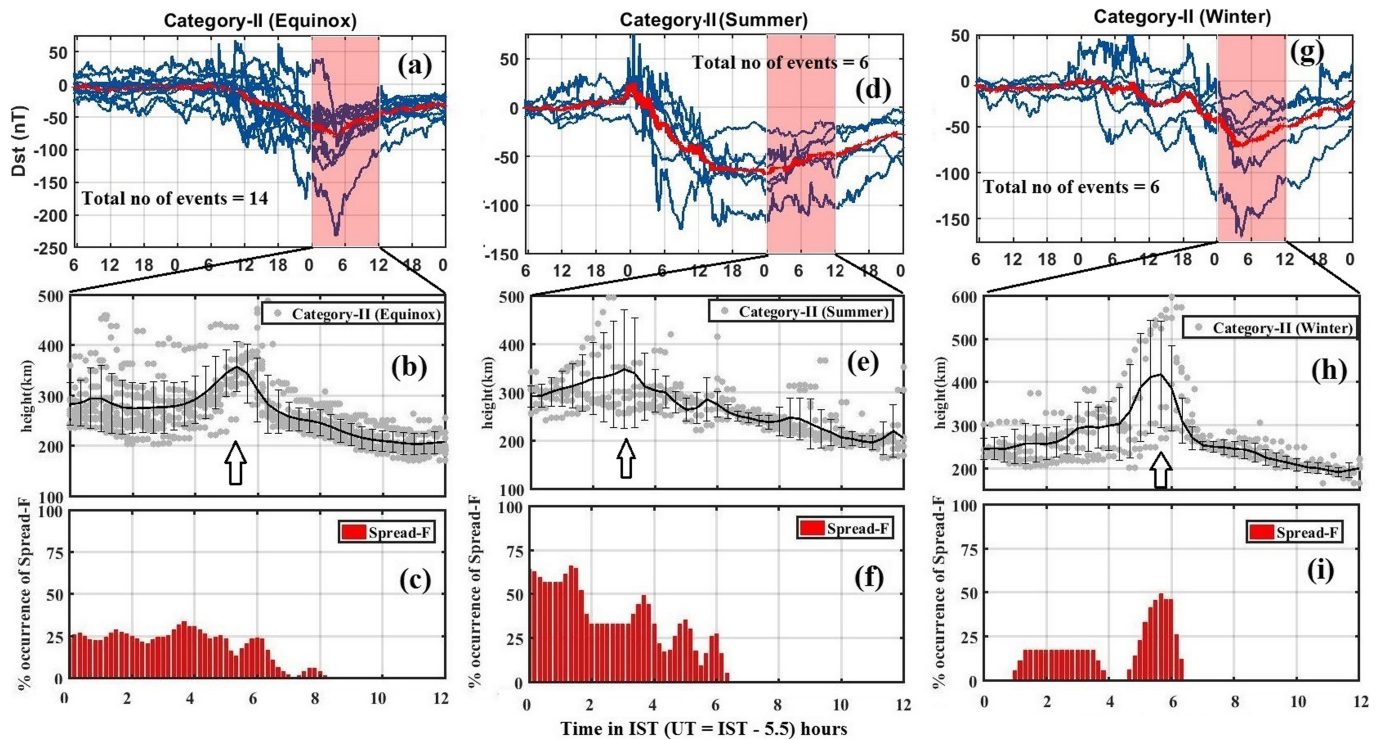


Figure 7. (a–i). Seasonal classification of the magnetic storms under category II similar to Figure 6. The three upper panels show the Dst variations (a, d, and g), the middle panels show the ionospheric height ($h'F$) variations (b, e, and h), and lower panels show the percentage occurrence of spread F (c, f, and i) over Tirunelveli shown in shaded region in top panels of the figure (between 00:00 and 12:00 IST hours) or during the recovery phase of magnetic storms. The upward/downward arrows show the enhancement/reduction.

simultaneous observations and categorized into three different categories (categories I, II, and III). Out of 35 geomagnetic storms, 14 storms fall in category I, 13 falls in category II, and 8 for category III. Several studies have focused on the generation of ESF irregularities and its relationship with the Es layer under quiet times (Abdu et al., 2003; Batista et al., 2008; Carrasco et al., 2005, 2007; Stephan et al., 2002). In order to investigate the possible influence of the Es layers at the conjugate regions and spread- F generation/suppression at the magnetic equatorial region, the ionosonde data are analyzed for spread F (equatorial station, Tirunelveli) and Es layer (low-latitude station, Hyderabad) occurrence during these magnetic storms.

Figure 8a presents (top panel) the temporal variation of virtual height ($h'F$) of F layer for 14 days of category I between 12:00 and 00:00 IST (afternoon to midnight hours) over an equatorial station at Tirunelveli. The evening hours at around 19:30 IST mean value of $h'F$ reached its maximum value ~ 320 km, and maximum spread- F occurrence is observed at $\sim 20:30$ IST (Figure 8b). Figure 8c shows the base height ($h'Es$ in km) of Es layer at low-latitude station at Hyderabad, while critical or top frequency ($foEs$ in MHz) of Es layer is shown in the Figure 8d. The first panel in the bottom of Figure 8e (left) shows the percentage occurrence of Es layers over low-latitude station at Hyderabad. The vertical blue color line shows the starting time of Es layer disruption or reduction in its values at $\sim 19:30$ IST at Hyderabad station. From the figure, we can see clearly that the disruption of low-latitude Es layer and $h'F$ enhancement at equatorial station occur near simultaneously. When the disruption of Es layer occurs at low-latitude station, simultaneously, $h'F$ is enhanced. The percentage occurrence of spread F is also increased to $\sim 30\%$ at $\sim 20:30$ IST due to enhancement of $h'F$ as seen at $\sim 19:00$ IST. At the same time, the percentage occurrence of Es layer is reduced to $\sim 10\%$ at $\sim 20:30$ IST, which is significantly low.

Figures 8f–8j are similar to Figures 8a–8e but for other category (category II) and another time between 00:00 and 12:00 IST (midnight to afternoon hours). The top panel of the figure shows the variation of virtual height ($h'F$) of F layer for 13 events over an equatorial station at Tirunelveli. It can be seen that the mean value of $h'F$ has reached its maximum value of ~ 370 km at around 05:30 IST in the morning hours

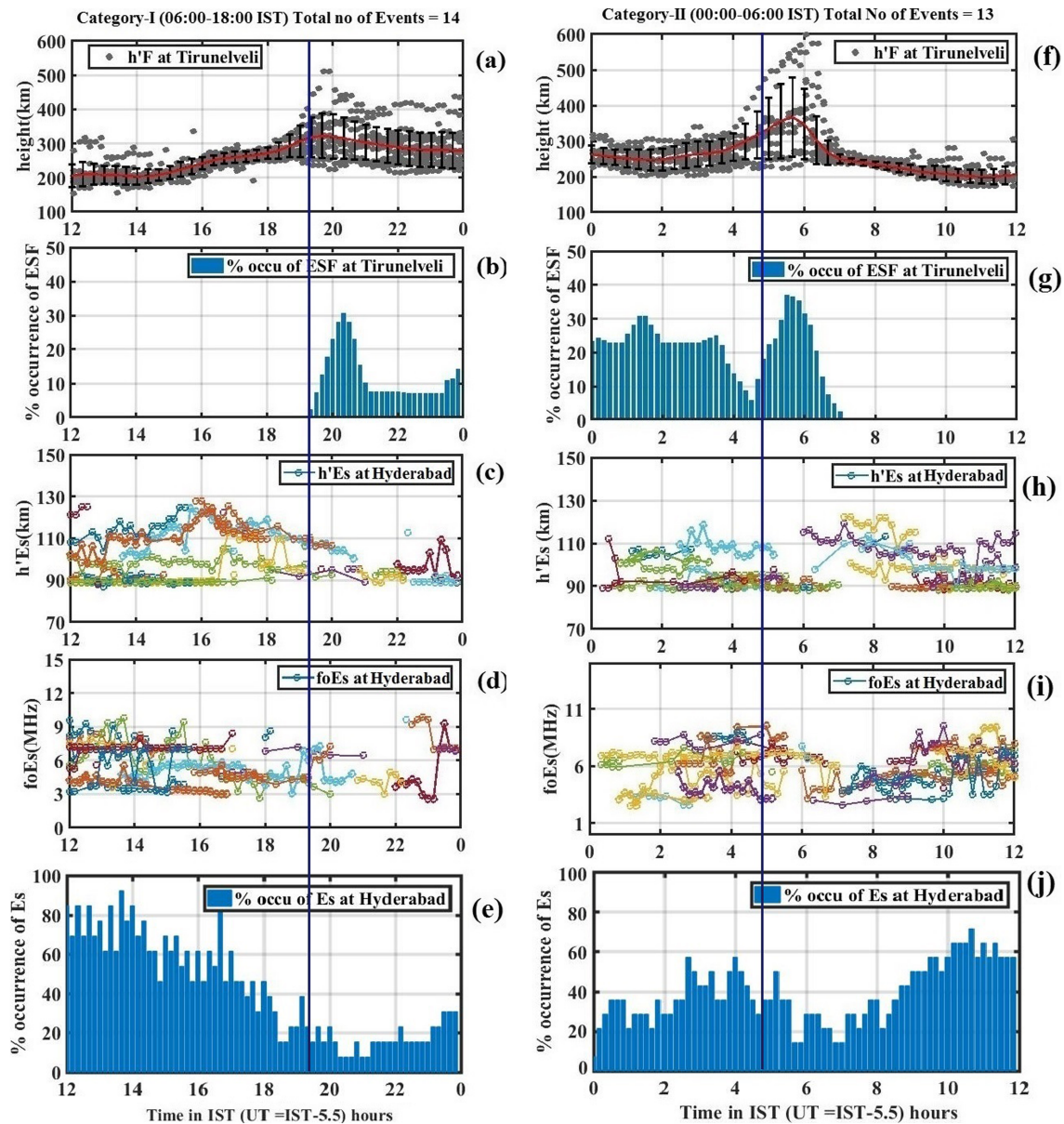


Figure 8. (a-j) The temporal variation of ionospheric parameters namely virtual height ($h'F$ in km) between 12:00 and 00:00 IST (category I) and 00:00–12:00 IST (category–II) at Tirunelveli (in panels a and e). The red color line shows the average value of $h'F$ (in panels b and f); the percentage occurrence of equatorial spread F (ESF; in panels c and g); virtual height of Es layer in kilometer ($h'Es$) over the low-latitude station, Hyderabad; and (in panels d and h) top frequency of Es layer ($foEs$ in MHz). The percentage occurrence of Es layers (in panels e and j) in categories I and II are also shown. The vertical blue color lines show the starting time of Es-layer disruption.

with the percentage occurrence of spread F that is estimated to be at $\sim 38\%$ (Figure 8g). Figures 8h and 8i represent $h'Es$ (km) and $foEs$ (MHz) variations at low-latitude station at Hyderabad. The bottom panel of Figure 8j (right) shows the percentage occurrence of Es layer in this category II. From the figure, we can see that the disruption of Es or reduction in $h'Es$ and $foEs$ values during the presunrise hours results in enhancement in F -layer height with percentage occurrence of spread F also enhancing over the equator. The percentage occurrence of the Es layer got reduced to $\sim 15\%$ at $\sim 05:30$ IST at the low-latitude station. The vertical blue line at $\sim 05:00$ IST shows the starting time of Es-layer disruption or reduction, and it can be seen that at nearly the same time, $h'F$ also starts enhancing and reached its maximum average value at $\sim 05:30$ IST.

4. Discussion

It is known that the ionospheric irregularities are generated at the bottomside of the F layer in the nightside where electron density gradient exists in the ionosphere, but these irregularities evolve nonlinearly as they rise to higher altitudes and develop into plasma bubbles. The generation or inhibition of ionospheric irregularities is very much dependent on the height of the F layer during the evening hours or prereversal time. During geomagnetic storms, usually plasma irregularities are suppressed in the postsunset period, while they are generated during postmidnight sector. Rastogi and Aarons (1980) and Rastogi et al. (1981) have noted that the occurrence of spread F during the evening hours is related to the rapid enhancement in the F layer. Many experimental and theoretical works have been performed to find the relationship between the solar wind parameters and ionosphere. During the geomagnetic storms, it is believed that intense currents disturb the quiet time ionosphere where equatorial ionosphere can be controlled by magnetospheric and IMFs with short-term variations that could be explained by the action of auroral sources (Fejer et al., 1979; Rastogi & Patel, 1975).

The results presented for 24 April 2012 magnetic storm event (Figure 3) suggest that though ionospheric height ($h'F$) is significantly enhanced at ~02:00 and 05:30 IST as compared to the mean of quiet days where virtual height has reached its maximum value of ~400 and 500 km over Tirunelveli during the recovery phase of the storm (red color shaded region in Figure 3), but no ESF has been detected. On contrary, as per the Aarons criteria, during the magnetic storms, if negative excursion of the Dst index occurs presunset hours, it can modify the eastward electric field to westward, which can ultimately reduce the F -layer height to inhibit the ionospheric irregularities. In Figure 3, we noticed significant reduction during the evening hours but significant enhancement after midnight hours in virtual height compared to the quiet days mean value and suppression of ionospheric irregularities (no spread F) during this event where the recovery phase of magnetic storm was ongoing. This suggests that other parameters are playing roles in suppressing the spread F onset on this night. It is known that ring current can influence the eastward electric field, but other factors such as low-latitude Es layers, IMF B_z , and AU/AL could also be influencing. On 24 April, between ~18:00 and 21:00 IST, the IMF B_z was fluctuating between positive and negative. Thus, ionospheric irregularities could have been affected during this event and suppressed on the following night due to the combined effect of injection of ring current and IEFy electric field. Other possible reason for suppression of spread F is DDEF, which produces the westward electric field opposite to eastward electric field during the evening hours over the magnetic equator.

In contrary, the geomagnetic storm of 23 January 2012 as shown in Figure 3 suggests that the enhancement of F -layer height at ~19:00 IST on 23 January is responsible for onset of ionospheric irregularities on the following night between 20:00 and 05:00 IST. According to the Aarons (1991), this was a category I magnetic storm; thus, during this event, ionospheric irregularities should have been suppressed on the following night. We can see from Figure 3 that during recovery phase of magnetic storm between 18:00 and 06:00 IST on this night, IMF B_z was positive and AU/AL were not showing any significant fluctuations. So during the recovery phase of magnetic storm, ring current is dominating without additional injection. Thus, the evening hour eastward electric field is not affected by the ring current injection to cause westward electric field. There is something additional parameter that is missing, which may be influencing the spread F occurrence.

Now we examine the results on magnetic storm of 17 March 2013, which falls under the category II as shown in the Figure 4. From the figure it can be seen that $h'F$ is enhanced up to ~450 km altitude on 18 March at ~06:00 IST (early morning) that caused spread F at 06:00–07:00 IST (red color shaded region). Contrary to this, the magnetic storm on 26 September 2011 showed inhibition of ionospheric irregularities during recovery phase of the magnetic storm on 27 September 2011 (midnight-to-postmidnight period) as shown in Figure 4. On 27 September, $h'F$ enhanced and reached its maximum value of ~480 km at 05:00 IST (in the shaded region) and fell down. During both geomagnetic storm events that fall under category II, the source for the height enhancement is not only disturbance electric fields but also additional factors such as low-latitude Es layers, IMF B_z , and AU/AL could also be playing role for the generation of the eastward electric field during the morning hours. Martinis et al. (2005) reported that Dst index is not the parameter to be used for spread- F occurrence. Rather, solar wind or high-latitude parameters such as interplanetary electric field and AU/AL should be used.

The analysis of the magnetic storm of 16 September 2011 that falls under category III showed that the occurrence of spread F over equatorial station at Tirunelveli during main and recovery phases of the storm is as per the Aarons criteria. On 16 September, $h'F$ enhanced at 19:00 IST and reached its maximum value of 420 km and falls, the spread F observed at 19:30–21:00 IST. During the recovery phase of magnetic storm, $h'F$ enhanced and generated ionospheric irregularities between 03:00 and 06:30 IST. From Figure 5, it can be seen that IMF B_z is in strong southward direction and AL reached its maximum negative value -1300 nT. Thus, IMF B_z component, Dst index, and AL indices are playing a role in enhancement of the $h'F$ and generation of ionospheric irregularities on the following night. The equatorial ionospheric height $h'F$ was increased when the IMF B_z turned southward. At the same time, Dst and AL indices showed higher geomagnetic activity, which is conducive condition for generation of ionospheric irregularities over the equatorial ionosphere. Biktash (2004) presented the intensity of the electric fields and currents at the polar region as well as the magnetospheric ring current intensity, which are strongly dependent on the variations of IMF. They suggested that magnetospheric ring current cannot directly penetrate into the equatorial ionosphere because of which difficulties emerge in explaining its relation to the scintillation activities. Based on the typical examples as discussed above, we suggest that in spite of many storm events in category I, we did not observe suppression of ESF irregularities to 100%, but favorable conditions were existed for the onset of spread F that resulted into spread F , which is in contrast to the Aarons criteria. Similarly, in category II type storms, it is also noticed that though ESF irregularities were supposed to be generated, we find many events that were found to be under inhibition of ESF irregularities. Also, as per the category III storms, the results showed mixed responses on the ESF occurrence. So based on these results, it is realized that ESF occurrence is not always following the Aarons criteria.

Now we will discuss the role of seasons on the ESF occurrence and their signatures in geomagnetic storms. Su et al. (2007) have suggested that transequatorial meridional wind-induced instability can be more effective in suppressing the growth of RT instability during the solstice season in a high solar activity. The percentage occurrence of spread F is known for its dependence on the solar cycle activity as reported by several authors (Abdu et al., 1985; Candido et al., 2011; Rastogi, 1980). From Figure 6, geomagnetic storms in the category I, PRE height suppression is observed only during summer season (average height noticed ~ 270 km; Figure 6e) but not in equinox and winter (Figures 6b and 6h) seasons. The percentage occurrence of spread F varies in equinox between 20 and 30% (Figure 6c), in summer 25% (Figure 6f), and 15% observed in winter (Figure 6i). It is noticed from the figure that the percentage occurrence of ESF during equinox is higher at 20:00 IST (30%); after that, it got reduced to up to 20%. The maximum $h'F$ enhancement is observed at 19:00 IST. During the summer season, $h'F$ is reduced in the evening hours at 19:00 IST, and the percentage occurrence is found to be at 25%. During summer, usually postsunset spread F is not observed. So the suppression of height during summer cannot really be attributed to geomagnetic storms. On the other hand, during winter season, the percentage occurrence of spread F is found to be weak between at 19:00 and 22:00 IST, but after that, it increased to 25%. We found that PRE in the electric field is one of main factors for all the cases to develop the conditions for generating the plasma bubbles. Somayajulu et al. (1991) investigated the spread- F occurrence during nonoccurrence period of spread F during the several magnetic storms. They found in their study that the abnormal height rise of the F layer of ionosphere during the early morning hours is associated with an eastward electric field. They also observed that the RT instability growth rates were consistent with occurrence or nonoccurrence of spread F .

As we have seen, Figure 7 represents the seasonal variation of spread- F occurrence in category II magnetic storms condition. During the postmidnight hours, in the recovery phase of storms, the maximum percentage occurrence of spread F is noticed at 70% in the summer season as compared to the other seasons where winter and equinox seasons are having percentage occurrence of spread F at 50% and 25%, respectively. From the figure, interesting thing to note during equinox is that spread F generated during the premidnight hours is found to continue till morning hours without any fresh generation of irregularities in the presunrise hours. On the other hand, during the winter season, spread- F occurrence between 01:00–04:00 IST and 05:00–06:30 IST are not related to the postsunset hour spread F , but they could be generated freshly at that instant of time. From the Figures 7h and 7i, one can see the postmidnight F -layer height enhancement at 05:00 IST where the average height went up to 430 km. Though the spread F starts occurring at 01:00 IST with percentage occurrence of 20% and continue till 04:00 IST with nearly similar trend, suddenly, presunrise spread F started occurring as soon as height rise is noticed (Figure 7h) at 05:00–06:30 IST and percentage occurrence

raised to 50%. During postmidnight hours, the generation or suppression of spread F may be associated with the trans-equatorial meridional wind due to auroral activity. Reddy et al. (1990) reported that large secondary electric fields could be setup at auroral and subauroral latitudes by enhancing the conductivities, electric fields, auroral electrojets, and field-aligned currents, which can suppress the primary convection electric field during the recovery phase of magnetic storms or substorms electric fields, which can influence the equatorial ionosphere. Another possibility is that in the inner magnetosphere on the nightside, secondary polarization electric fields can be generated and injected into the low-latitude ionosphere. This polarization electric field is opposite to the magnetospheric convection electric field, or during the postmidnight hours, it will be in the eastward direction.

It is seen that spread F is directly dependent on the strength of the PRE that occurs just around the sunset. However, the PRE itself depends on longitudinal variation of the flux tube-integrated conductivity (Abdu et al., 1981; Batista et al., 1986; Bowman & Mortimer, 2003). Previous workers have focused on the generation mechanism of ESF irregularities and its relationship to the Es layer under quiet times (Abdu et al., 2003; Carrasco et al., 2005, 2007; Stephan et al., 2002). Abdu et al. (2003) presented relationship between Es layer, PRE vertical drifts, and ESF. They reported that large PRE amplitudes are associated with disruption of Es layer, and smaller PRE amplitudes may or may not be associated with presence of Es layer because in the presence of Es layer, PRE amplitude also decreases under the DDEF condition.

Our observations and statistical analysis as shown in Figure 8 suggest good relationship between low occurrence of low-latitude Es layer over Hyderabad during evening hours and morning hour PRE over an equatorial station over Tirunelveli during geomagnetic storms under the categories I and II. In Figures 8a–8d, it is seen that when Es layer is present or h'Es value enhanced, the same time virtual height of the F layer got reduced and the percentage occurrence of spread F also got reduced over the equatorial station at Tirunelveli. However, when Es-layer disruption occurs or h'Es value reduced at the low-latitude, the same time h'F enhanced and ionospheric irregularities generate over the equatorial region. We can see from the figure that during the time of disruption of Es layer, evening hour PRE got enhanced at ~19:30 IST resulting in increase of percentage occurrence of spread F to ~25%. It is seen that if Es-layer disruption does not occur, the percentage occurrence of spread F can get reduced. Figures 8e–8h show the relationship between Es layer and morning hour height enhancement or spread- F occurrence. The base height of the Es layer or disruption of the Es layer starts at ~05:00 IST, and at the same time, virtual height of the F layer also starts to enhance and reaches its maximum mean value at ~370 km at ~05:30 IST, and the percentage occurrence of ionospheric irregularities is enhanced to ~38%. When the Es layer is present and its base height is located at higher altitude, at the same time, virtual height of the F layer goes down or percentage occurrence of spread F gets reduced. Accordingly, in the categories I and II, occurrence of Es layer at the low-latitude station at Hyderabad and equatorial spread- F occurrence at the Tirunelveli in the recovery phases of storms show the anticorrelation. As per the analysis, during the magnetic storms, the presence of Es layer at low-latitude station at Hyderabad could be influencing (diminishing) the spread- F occurrence at the equatorial station at Tirunelveli due to changes in E -region integrated Pederson conductivity. The presence of Es layer in the evening hour can modify the longitudinal/local time gradient in the E -region integrated Pederson conductivity that can affect the intensity of PRE development (Carrasco et al., 2005). Stephan et al. (2002) modeled that the growth rate of R-T instability decreases in the presence of Es layers. There are several reports that suggest the existence of coupling between the postsunset occurrence and nonoccurrence of spread- F and Es-layer absence/presence at low-latitude crest region (Bowman & Mortimer, 2003). Accordingly, several works have been made to find the possible relations between the evening hour PRE with Es layer in the conjugate magnetic field line E region (Abdu et al., 2003; Carrasco et al., 2005, 2007; Stephan et al., 2002). Abdu et al. (2013) suggested that Es layers at low latitude are strongly modified by magnetospheric electric fields depending upon the direction of penetration electric fields. According to them, if westward penetration occurs, it can cause production of Es layers at low latitude, while eastward penetration can cause disruption of Es layers at low latitude. Using ionosonde observations at SHAR, Joshi et al. (2013), on the other hand, investigated the role of low-latitude Es layers on the generation of ESF irregularities over India under geomagnetic quiet conditions and suggested that the presence/absence of low-latitude Es layers are indeed capable of modifying the occurrence of plasma irregularities. Li et al. (2006) suggested that Es layers at low latitude caused inhibition of GPS L-band scintillations on the two of the storms they have investigated. They suggested that causes for the inhibition could be due to strong presence of low-latitude Es layers. So the results presented in

our paper also suggest that PRE could have been affected by *E*-region processes. Recently, Zhou et al. (2017) suggested that occurrence of midlatitude Es layers is also influenced by geomagnetic storms. They surmised that storm-induced equatorward winds could modify the local winds and wind shears that can affect the Es layers. While many of these studies have investigated the role of low-latitude Es layers in the postsunset hours, the results presented here show the role of Es layers during postsunset and postmidnight hours. It is known that large-scale wave structures in the bottomside of the *F* layer can influence the day-to-day variability of the equatorial spread *F*. However, the source of these large-scale wave structures are again linked to the *E* region at low latitudes through the polarization electric field, which is generated by the Hall polarization process acting on an altitude modulated Es layers at low latitudes and mapped to the bottom side of the *F* layer along the geomagnetic field lines (Tsunoda, 2005, 2006). So the analysis and results presented in this paper suggest that low-latitude Es layers could be playing vital role even during geomagnetic storms and we have to consider these effects while evaluating the Aarons criteria.

5. Conclusions

In this paper, an attempt has been made to examine the local time response of the geomagnetic storms over Indian sector using 73 intense and moderate geomagnetic storms on the nighttime ionospheric irregularities during the years from 2007 to 2015 in the solar cycles 23 and 24 based on Aarons criteria. The results suggest that despite many storm events in category I, suppression of ESF irregularities was noticed, which is contrary to the Aarons criteria. Instead, ESF irregularities were present on many storm events. Similarly, in category II type storms, it is also noticed that the ESF irregularities were not only generated but also suppressed on many events. Also, as per the category III storms, the results showed mixed response on the ESF occurrence. So based on these results, it is realized that ESF occurrence is not always following the Aarons criteria.

To examine further whether any preferential seasons may follow the above criteria, the role of different seasons on the Aarons criteria is also examined by separating the storm events into seasons. The results suggest that while equinox season seems to partially follow the Aarons criteria, other seasons do not follow. So these results suggest that there is no consistent pattern emerged in the favor of the Aarons criteria and one needs to look for other parameters during the magnetic storms as occurrence of ionospheric irregularities is affected not only by the strength of ring current but also by other processes such as the local neutral winds, low-latitude Es layers, solar wind conditions, and high-latitude storm parameters.

Finally, the occurrence characteristics of the ESF irregularities and their relationship to low-latitude Es layers in Aarons criteria are examined as it is known that low-latitude Es layers can affect the equatorial ionosphere by modifications in the field line-integrated conductivity profiles and reduction of PRE height. Statistically, our observations show that there is a 40% reduction in the occurrence of Es layers at Hyderabad in both categories I and II during the onset of ESF irregularities, which is significant. Based on the statistical and morphological results as present here, we suggest that we have to look for other background influencing sources such as the role of low-latitude Es layers in suppressing/generating plasma irregularities under geomagnetic storms when Aarons criteria fail.

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