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Key Points:
- Rate of change of eastward electric field plays role in formation of F_3 layer
- Unusual increase in F_3 occurrence during extended solar minimum is reported
- Postnoon formation of F_3 in absence of eastward electric field is observed

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Peculiar features of ionospheric F_3 layer during prolonged solar minimum (2007–2009)

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Abstract We present the seasonal and local time occurrence of ionospheric F_3 layer over Tirunelveli (geographic longitude 77.8°E, geographic latitude 8.7°N, dip 0.7°) during extremely low and prolonged solar activity period (2007–2009). Canadian Advanced Digital Ionosonde observations from this station are used in the present study. We find that the occurrence of F_3 layer is nearly 3 times higher during 2009 (∼ 48%) as compared to that during 2007 (∼ 16%). The increase of this order just within the low solar activity period is unusual. In earlier studies similar increase in F_3 occurrence has been reported when solar activity changes from high ($F_{10.7}=182$) to low ($F_{10.7}=72$). The other important feature is the presence of postnoon F_3 layers which are observed dominantly during summer solstice of 2009. Such occurrence of postnoon F_3 layers was nearly absent during summer solstice of the previous solar minimum (1996) over nearby dip equatorial station Trivandrum. We take equatorial electrojet (EEJ) as a proxy for eastward electric field. It is noticed that the EEJ strength and the maximum rate of change of EEJ are higher for F_3 days as compared to those on non-F_3 days. We find that the peak occurrence of prenoon F_3 layer closely coincides with the time of maximum rate of change of EEJ. It is in general accordance with the theory proposed by Balan et al. (1998) that suggests the formation of F_3 through vertically upward $\mathbf{E} \times \mathbf{B}$ drift in presence of equatorward neutral wind. The present study reveals that the rate of change of eastward electric field (dE/dt) as well plays an important role in the formation of F_3 layer.

1. Introduction

The phenomenon of F_3 layer is known for more than half a century from ground based ionosonde observations as a stratification of F_2 layer [*Sen*, 1949; *Ratcliffe*, 1951; *Skinner et al.*, 1954], and also from topside sounding measurements as ionization ledges [*Sayers et al.*, 1962; *Lockwood and Nelms*, 1964; *Raghavarao and Sivaraman*, 1974; *Sharma and Raghavarao*, 1989]. For a long time, the stratification of F_2 layer (or the ledge) remained unexplained. Through modeling studies, *Huang* [1974] suggested that the upward drift, plasma diffusion, and high recombination rate might be involved in the bifurcation of F_2 layer. Using the Sheffield University Plasmasphere Ionosphere Model, the formation of a new layer was proposed, which was initially termed as *G* layer [*Balan and Bailey*, 1995; *Bailey et al.*, 1997]. Later, it was renamed to "F_3 layer" as no new ionization production process was involved in the formation of this layer but it was a consequence of the stratification of F_2 layer due to equatorial plasma dynamics. *Balan et al.* [1998] explained the physical mechanism involved in the formation of the F_3 layer by giving observational evidences from equatorial station Fortaleza (4°S, 38°W, dip 9°). These authors observed that usually the F_3 layer is generated during prenoon hours near the dip equator due to the special geometry of the magnetic field. The Earth's magnetic field is nearly horizontal at the dip equator, which results in vertically upward movement of the *F* region plasma in presence of eastward electric field. If the upward movement of F_2 is faster, then a new layer develops between F_1 and F_2 due to photochemical processes. Thus, the initial F_2 layer drifts upward to form the F_3 layer and the new layer appears as F_2. However, equatorward neutral wind is required to reduce the diffusion of the uplifted plasma along magnetic field lines. The $\mathbf{E} \times \mathbf{B}$ drift and neutral wind both play crucial roles in the formation of F_3 layer.

In earlier studies, it is shown that the occurrence of F_3 layer is dependent on magnetic latitude [*Jenkins et al.*, 1997]. The authors suggest that at magnetic equator, the neutral wind produces a smaller vertical movement of plasma as compared to off equatorial stations, which yields weaker formation of F_3 layer at

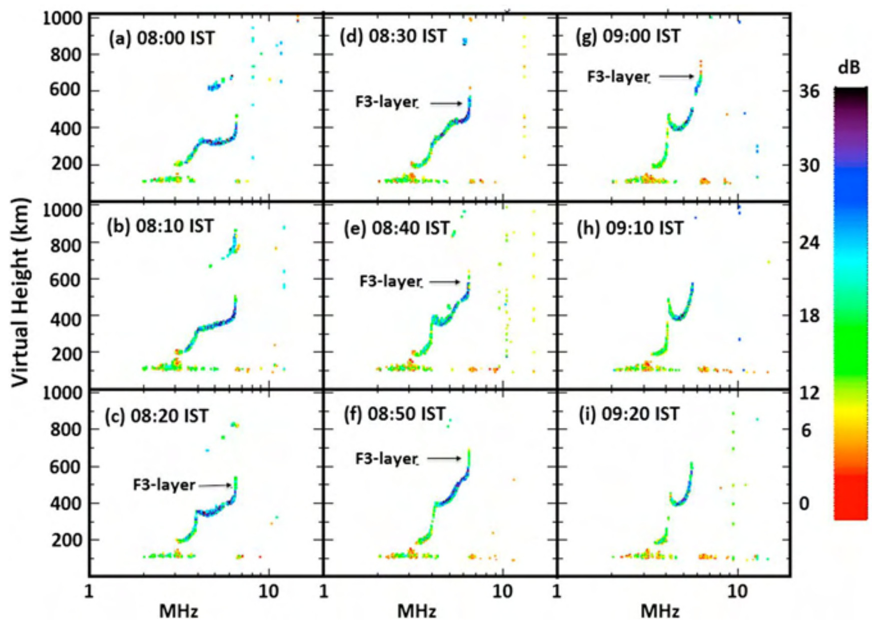

Figure 1. Sequence of formation of the F_3 layer at Tirunelveli, on 20 September 2009.

dip equator. Further studies [*Batista et al.*, 2002; *Lynn et al.*, 2000; *Uemoto et al.*, 2007a; *Rama Rao et al.*, 2005] have confirmed the latitudinal dependence of F_3 layer. *Balan et al.* [1998] studied seasonal variation of F_3 layer and reported that their occurrence is prevalent during summer solstice, unlike winter solstice where F_3 layer is less frequent. This is confirmed through different independent studies [*Balan et al.*, 1998; *Batista et al.*, 2002; *Rama Rao et al.*, 2005]. Besides the theoretical and the ground-based studies, the F_3 layer is also observed as topside ledges using topside radio sounding [*Depuev and Pulinets*, 2001]. The results show that F_3 layer in the topside ionosphere can exist as topside ledge both during daytime and nighttime, and such ledges cannot be observed using ground-based sounders as its electron density is lower than that of the F_2 layer below. Although F_3 layer is mostly a quiet time phenomenon, it has been observed under magnetically disturbed conditions as well [*Paznukhov et al.*, 2007; *Zhao et al.*, 2005]. *Balan et al.* [2008] have reported an observation, which shows the reappearance of the F_3 layer during postnoon, that resulted from the downward movement of the *F* layer plasma due to the presence of westward electric field, linked with the geomagnetic activity on 7–11 November 2004.

Recently, it is shown that the height of F_3 layer varies linearly with radar derived $\mathbf{E} \times \mathbf{B}$ drift from the daytime 150 km echoes observed at an Indian low-latitude station [*Pavan Chaitanya et al.*, 2013]. Model studies have revealed the importance of the vertical velocity, which depends on the vertical $\mathbf{E} \times \mathbf{B}$ drift, magnetic meridional neutral wind speed, and the magnetic dip angle at any given location [*Balan et al.*, 2000]. Although all studies point toward the necessity of the vertically upward $\mathbf{E} \times \mathbf{B}$ drift for the formation of the F_3 layer, their formation is prevalent during summer solstice when the ambient eastward electric field is weaker.

It has been found that the background ionospheric conditions were much different during extended solar minimum period of solar cycle 24 as compared to the previous solar minimum [*Solomon et al.*, 2013; *Liu et al.*, 2011, 2012]. As the F_3 layer is predominantly a low solar activity phenomenon [*Batista et al.*, 2002; *Uemoto et al.*, 2007a; *Rama Rao et al.*, 2005], the extended low solar activity period (2007–2009) gives us ample opportunity to investigate the variability of F_3 layer occurrence during this peculiar period. *Anderson et al.* [2002] and *Alken and Maus* [2010] have shown that the EEJ can be used as a proxy for the vertical $\mathbf{E} \times \mathbf{B}$ drift. The F_3 layer and the EEJ are both manifestations of the zonal electric field, but the relationship between them is not yet studied. Hence, we make an attempt to study the possible relationship between the two phenomena. The postnoon occurrences of F_3 layer (with no prenoon occurrence) are observed in earlier studies on some occasions [*Balan et al.*, 1998, 2000]. However, the formation mechanism for these F_3 layers is believed to be associated with the same physical mechanism as that for the

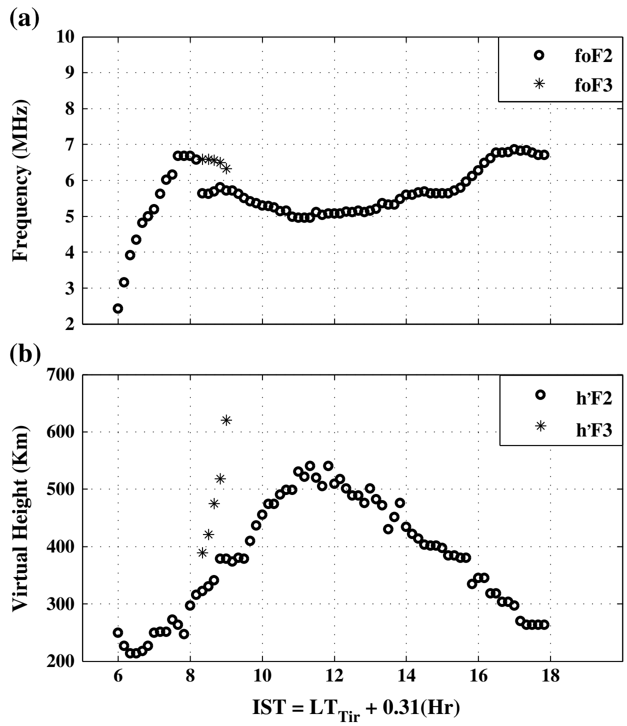

Figure 2. Variation of (a) f_oF_2 and f_oF_3 and (b) $h'F_2$ and $h'F_3$, respectively, for 20 September 2009.

morning time F_3 (i.e., due to upward movement of plasma). On the contrary, present observations reveal that there is considerable occurrence of F_3 layer only during postnoon period, which is not associated with the eastward electric field.

In present study, we investigate the local time variation of F_3 layer in different seasons during prolonged minimum period of 2007–2009. The possible linkage between EEJ and formation of F_3 layer is examined. The difference in the prenoon and postnoon formation of F_3 layer is proposed. The data used and the selection criteria for the events are described in section 2. The results are presented and discussed in section 3. The present work is concluded in section 4.

2. Data Used and F_3 Layer Selection

Here we use data recorded by digital ionosonde, CADI (Canadian Advanced Digital Ionosonde), at equatorial station Tirunelveli (geographic longitude 77.8°E, geographic latitude 8.7°N, dip 0.7°). Standard ionograms are recorded at 15 min interval although occasional ionograms of 5/10 min resolution are also available. The ionograms are visually scanned to find the occurrence of the F_3 layer, and the corresponding ionospheric parameters (e.g., f_oF_3, $h'F_3$, f_oF_2, and $h'F_2$) are manually scaled. In the present study, the days with $Ap \geq 18$ are considered as magnetically disturbed and they are excluded from the analysis. In addition, ionosonde observations from Trivandrum (geographic longitude 77°E, geographic latitude 8.5°N, dip 0.5°) during summer solstice of previous solar minimum (June–August 1996) are utilized. Ground magnetic field observations of minute resolution recorded at Tirunelveli and Alibag (geographic latitude 18.6°N, geographic longitude 72.9°E, dip 25.5°) are used to calculate the EEJ strength (ΔH) for the period 2007–2009.

Figures 1a–1i show a series of ionograms for 20 September 2009 where Figures 1a and 1b show the presence of F_1 and F_2 layers but no F_3 layer. The next ionogram, Figure 1c, shows the presence of three distinct layers; the bottom one being F_1 , middle one as F_2, and the topmost layer being the F_3 layer. So the F_3 layer is identified as the topmost layer in the ionograms when both F_1 and F_2 layers are present. The presence of the F_3 layer can be seen from 8:20 to 9.00 h IST (Figures 1c–1g) after which it is not seen in the ionograms. The time variation of (a) f_oF_2 and f_oF_3 with corresponding (b) $h'F_2$ and $h'F_3$ are shown in Figure 2 for 20 September 2009. It should be noted that at the time of onset of F_3 layer, the f_oF_3 seems more like a continuation of the old F_2 layer, whereas f_oF_2 shows a large jump indicating that it is a new layer, which is formed below F_3 layer (or old F_2 layer). Figure 2b represents the same scenario in height of F_2 and F_3 layers. A clear difference in altitudes for both the layers can be seen here. The old F_2 layer is lifted upward rapidly through $\mathbf{E} \times \mathbf{B}$ drift, and a new layer is formed to fill the gap between F_1 and uplifted F_2 layer (now seen as F_3 layer). At higher altitudes ionization is less; hence, f_oF_3 gradually decreases due to recombination and diffusion. Eventually, f_oF_3 becomes less than f_oF_2, and F_3 layer cannot be seen in ground-based ionograms. It should be noted that this particular trend is a feature of prenoon F_3 layers. The postnoon F_3 layers may show different feature, which is discussed in section 3.2.

For better temporal picture of the F_3 layer occurrence, a given day is divided into bins of 15 min duration each, which gives 96 cells per day. Then we check for the presence of the F_3 layer in the ionograms for

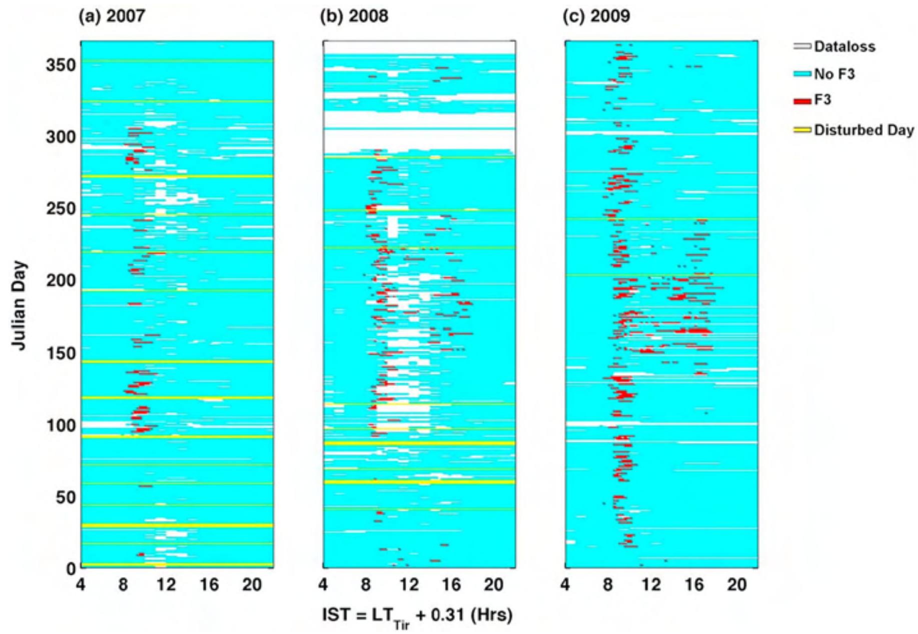

Figure 3. Occurrence of F_3 layer (red) as a function of IST during (a) 2007, (b) 2008, and (c) 2009. Disturbed days ($Ap \geq 18$) and data loss are shown by yellow and white colors, respectively.

each 15 min duration. If F_3 layer is observed for a bin of 15 min, then that cell is marked as a cell with F_3 layer. Occasionally, when there are ionograms with 5–10 min duration, a 15 min interval may correspond to multiple ionograms. In that case, if we have at least one occurrence of the F_3 layer during that 15 min interval, then the corresponding cell is considered as a cell with F_3 layer. Here the figures are shown in IST (= UT + 5.5 h). The local time of Tirunelveli corresponds to IST − 0.31 h. The results of F_3 are presented and discussed in the next section.

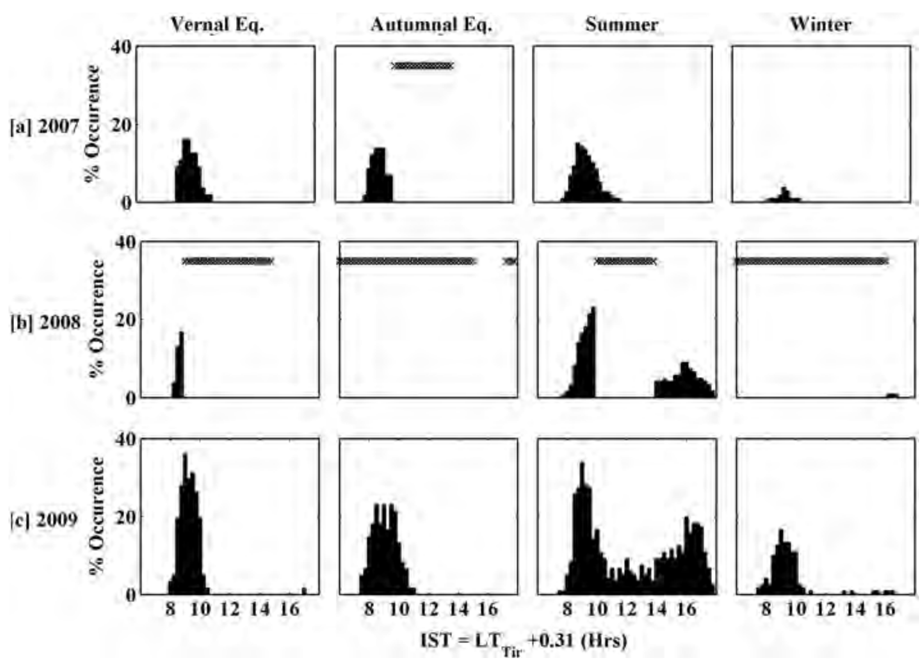

Figure 4. Seasonal local time percentage occurrence of F_3 layer is shown for (a) 2007, (b) 2008, and (c) 2009. The cross symbols indicate the data loss on more than 25% in corresponding 15 min time bin.

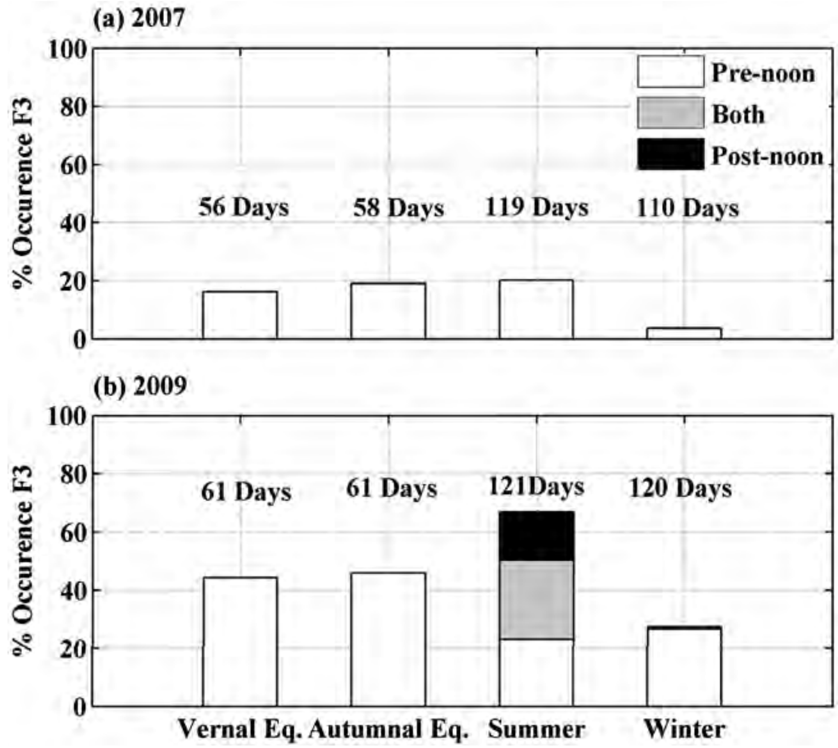

Figure 5. Percentage of number of days with F_3 for each season during (a) 2007 and (b) 2009. The total number of magnetically quiet days per season is mentioned over each bar corresponding to each season.

3. Results and Discussion

3.1. Seasonal Variation of F_3

A graphical representation of F_3 layer occurrence with 15 min resolution is shown in Figure 3 for years 2007–2009. Each red patch for 15 min interval represents the presence of F_3 layer, whereas the cells in cyan represent the absence of the F_3 layer for that period. Similarly, white and yellow patches represent the data loss and magnetically disturbed days, respectively. It is noted that F_3 layer is seen during 6–18 h IST. Thus, hereafter we consider this time period to investigate the occurrence of F_3. For each season, we compute the percentage occurrence of F_3 for every 15 min bin during 6–18 h IST. While doing this exercise, we confirm that each bin contains F_3 information for at least 75% of magnetically quiet days. The estimated percentage occurrence of F_3 is plotted as a function of IST and shown in Figure 4 for vernal equinox (March–April), autumnal equinox (September–October), summer solstice (May–August), and winter solstice (November–February) of 2007–2009. The bins, where data loss exceeds 25%, are shown by cross marks. In 2008, the data loss of more than 25% is encountered nearly for all the seasons; hence, it is excluded in the present study. A similar picture in terms of percentage of number of days with F_3 layer is shown in Figure 5, where the top and bottom represent 2007 and 2009, respectively. A day with F_3 occurrence having duration $\geq$ 30 min is considered as a day with F_3. The number of quiet days in each season is mentioned over the corresponding bar in Figure 5. It should be noted that F_3 layers are observed in the postnoon period during summer solstice of 2009. Thus, we compute the percentage occurrence of F_3 separately for categories (i) prenoon, (ii) postnoon, and (iii) both prenoon and postnoon. For the present study, the duration 6–12 IST is considered as prenoon period, whereas the duration 12–18 IST is considered as postnoon period. The major observational features based on Figures 4 and 5 are as follows:

1. The occurrence of F_3 layer is significantly higher during 2009 (~48%) as compared to 2007 (~16%). Such 3 times increase simply within low solar activity ($F_{10.7} = 73 \pm 6$ to 70 ± 3) is uncommon and hence forms the peculiar observational feature of the present study.
2. The percentage occurrence of F_3 shows maximum (minimum) during summer (winter) solstice for both 2007 and 2009, which is in general agreement with model predictions by *Balan et al.* [1998].

Table 1. Gives Average F_2-layer Frequency ($< f_0F_2 >$), Average F_3-layer Frequency ($< f_0F_3 >$), Average Peak EEJ Strength, and Maximum Rate of Change of Average EEJ for Different Seasons During 2007 and 2009

Year	Season	$\langle f_oF_2 \rangle$ MHz	$\langle f_oF_3 \rangle$ MHz	$\langle$EEJ$\rangle$ nT	$\frac{d\langle EEJ \rangle}{dt}\|_{max}$ nT/h
	Vernal equinox	7.17 ± 0.48	7.84 ± 0.55	51.24 ± 13.29	23.56
	Autumnal equinox	6.58 ± 0.41	7.02 ± 0.25	51.81 ± 13.73	21.03
2007	Summer	6.04 ± 0.61	6.75 ± 0.66	46.81 ± 18.37	20.50
	Winter	6.78 ± 0.55	7.52 ± 0.50	42.37 ± 19.61	23.60
	Vernal equinox	6.23 ± 0.45	6.93 ± 0.47	44.95 ± 11.23	19.42
	Autumnal equinox	6.27 ± 0.60	7.09 ± 0.59	59.17 ± 20.42	25.60
2009	Summer	5.73 ± 0.31	6.49 ± 0.52	31.90 ± 19.07	13.84
	Winter	6.34 ± 0.96	6.70 ± 0.75	40.95 ± 13.29	19.53

3. The probable time of occurrence of prenoon F_3 layer is found to be around 8–11 h IST for all the seasons of 2007 and 2009.
4. Interestingly, the occurrence of F_3 in postnoon period (without prenoon F_3) are solely observed during summer during 14–18 h IST. The occurrence of these F_3 layers is found to increase from no occurrence during 2007 to 17% during 2009. It is the second important observational feature noticed in the present study.

The F_3 layer occurrence has been investigated by various independent studies at different equatorial and low-latitude stations by using ground-based ionograms [*Balan et al.*, 1998; *Rama Rao et al.*, 2005; *Sreeja et al.*, 2010; *Zhao et al.*, 2011a; *Zhu et al.*, 2013] as well as by satellite observations by looking at the ionization ledges [*Uemoto et al.*, 2004; *Zhao et al.*, 2011b]. The seasonal variation observed in present study is in general agreement with the earlier observations with some differences. *Zhao et al.* [2011a] observed F_3 layers in both prenoon and postnoon periods during all seasons at Jicamarca (geographic longitude 283.2°E, geographic latitude 12.0°S, dip 1.3–0.4°), an equatorial station. These authors have reported significant occurrence of F_3 during postsunset hours at Jicamarca unlike Tirunelveli where hardly any F_3s are seen during postsunset hours. In their study it is found that unlike daytime occurrence of F_3, which is anticorrelated with solar activity, the postsunset occurrence of F_3 clearly increases with increasing solar activity. *Zhao et al.* [2011a] also showed the effect of the magnetic declination on the formation of the postsunset F_3 layer. The combined effect of the prereversal enhancement of the eastward electric field, meridional and zonal neutral winds, and geomagnetic configuration of Jicamarca allows the postsunset F_3 layer to be observed more frequently at this location. A global picture of the occurrence of the F_3 layer was reported by *Zhao et al.* [2011b] using FORMOSAT-3/COSMIC electron density data. The highest occurrence of F_3 layer was found to be around dip latitude 7–8°/−7 to −8° for Northern/Southern Hemispheres, and it was more pronounced during summer months at 10:00 to 14:00 LT. The layer was also found to show a clear longitudinal dependence during summer.

The solar activity dependence is well established from various studies [*Balan et al.*, 1998; *Batista et al.*, 2002; *Rama Rao et al.*, 2005] that show enhanced F_3 occurrence during low solar activity as compared to that during high solar activity period. *Sreeja et al.* [2010] have shown the yearly F_3 layer occurrence for a full solar cycle (1996–2006) over Trivandrum, which is close to the present observational station Tirunelveli. This study indicates that the F_3 layer occurrence approximately changes from ∼5% to ∼15% during high ($F_{10.7} = 182 \pm 30$) to low ($F_{10.7} = 72 \pm 5$) solar activity period. There are studies, which indicate that F_3 occurrence is smaller at equatorial station as compared to stations away from equator [*Batista et al.*, 2002; *Lynn et al.*, 2000; *Uemoto et al.*, 2007b; *Rama Rao et al.*, 2005]. The above mentioned brief summary of F_3 related studies reveal that solar flux and magnetic latitude both play an important role in the formation of F_3 layer.

It should be noted that 2007–2009 falls under low solar activity and the average sunspot number changed from 7.5 ± 8.5 to 3.1 ± 5.6 during 2007 to 2009, respectively. Recently, *Yadav et al.* [2014] have shown that inclination angle at Tirunelveli changed from 1.25 to 1.75 during this period. Here we notice that during 2007 to 2009 the F_3 occurrence changes from approximately 16% to 48%, respectively. The observed increase is major (nearly 3 times) and it cannot be attributed solely to change in solar flux and inclination during 2007–2009. In order to understand this puzzling observation, we computed the average f_oF_2 and f_oF_3 for F_3 days of each season during 2007 and 2009, which are mentioned in Table 1. It is noticed that

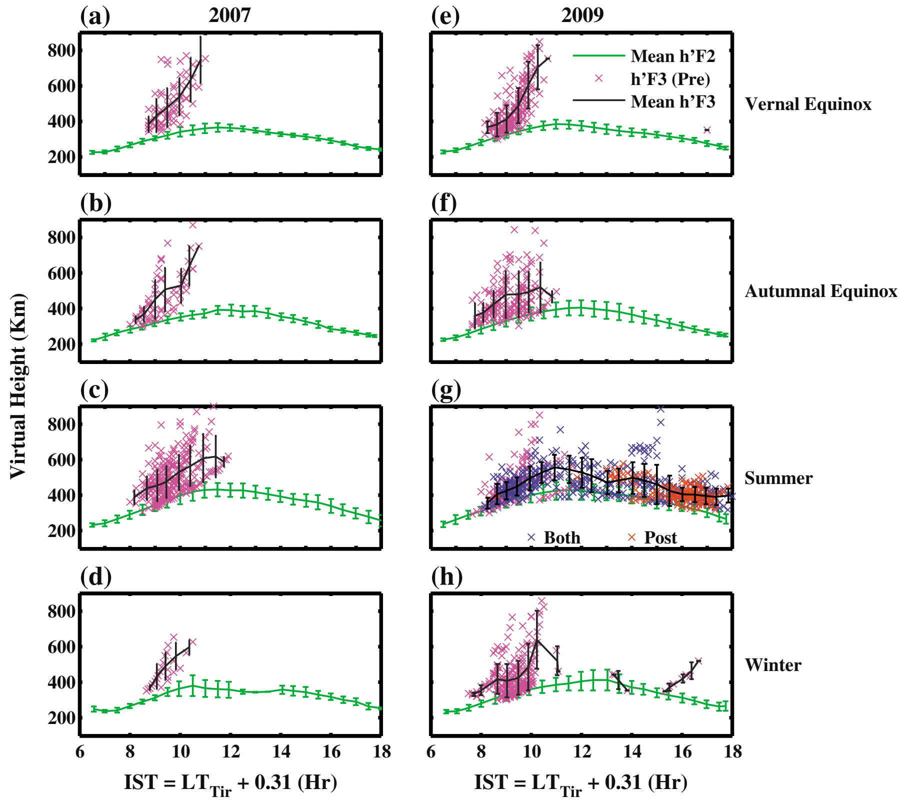

Figure 6. (a–h) Seasonal local time mass plots of height of F_3 layer and F_2 layer on days with F_3 during 2007 and 2009 are shown. The green line with error bar represents the average variation of $h'F_2$ for the respective seasons. The black line with error bar represents the average variation of the $h'F_3$, whereas the magenta cross represents the actual $h'F_3$ values for prenoon category. The red and blue crosses shown in Figure 6g show the $h'F_3$ for categories (i) postnoon and (ii) both prenoon and postnoon, respectively.

the average f_oF_2 and f_oF_3 both are considerably low during 2009 as compared to 2007. As the background electron density is lesser during 2009, it would require less upward forcing to accelerate the plasma to higher altitudes as compared to 2007, where ambient ionization is relatively more denser. Apart from the electromagnetic forces, frictional forces resulting from neutral collisions are important as well. Recent studies have shown that thermosphere was contracted during 2008–2009 due to decrease in EUV irradiance as compared to the preceded solar minima [*Solomon et al.*, 2013; *Liu et al.*, 2011]. Although decrease in EUV irradiance was small, it resulted in noticeable difference in thermospheric densities and temperatures during 2008–2009 as compared to the last solar minimum. As the background ionization, neutral densities and temperatures are significantly low during 2009, the collisional forces must be less operative during 2009 as compared to 2007 and hence aid the vertical transport of plasma to higher altitudes. Thus, 3 times increase in the F_3 occurrence observed during 2009 is attributed to reduced background ionization, neutral density, and temperatures resulting from prolonged solar minimum conditions that aid the formation of F_3.

Another key feature is the presence of F_3 layer during postnoon hours. The year 2009 shows the presence of F_3 layers in the postnoon hours, whereas 2007 shows complete absence of such F_3 layers. Also, the postnoon occurrence of F_3 layer is confined to only summer months, and hence, they are studied separately and discussed in the next section.

3.2. Prenoon and Postnoon F_3 Layer Characteristics

As discussed in section 2, the prenoon formation of F_3 layer is linked with the combined effect of vertically upward $\mathbf{E} \times \mathbf{B}$ drift and equatorward neutral wind. However, the formation of postnoon F_3 layer is not well understood. Here we point out the observational differences in the prenoon and postnoon F_3 characteristics during 2007–2009. Figure 6 shows average variation of $h'F_2$ and $h'F_3$ as a function of IST for F_3 days of each season separately for 2007 and 2009. The green line represents the average variation of $h'F_2$

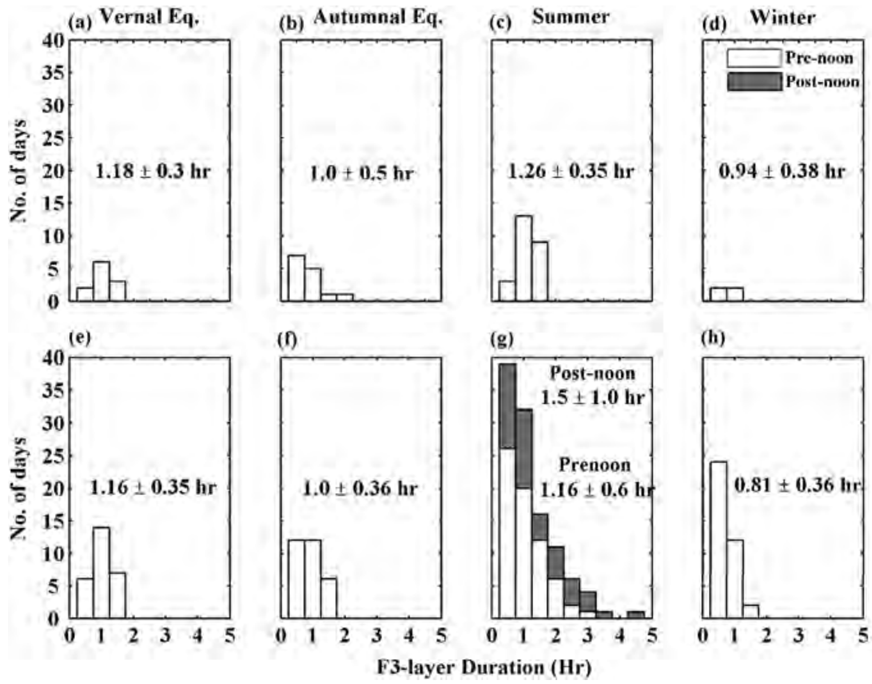

Figure 7. Number of F_3 days with their corresponding duration. The average duration for each season is mentioned in each subplot with their standard deviation.

with error bars, whereas the solid black ones represent the average variation of $h'F_3$ with error bars. The cross represents the actual value of $h'F_3$ for the corresponding season. In Figure 6 it is seen that for prenoon hours $h'F_3$ shows increasing trend with time, indicating upward movement of the layer, which is the primary requirement for the formation of F_3 layer [*Balan et al.*, 1998]. The postnoon F_3 layers are seen mainly during summer solstice 2009. Their height variation as a function of time is shown in Figure 6g for three categories, namely, (i) prenoon (magenta), (ii) postnoon (red), and (iii) both prenoon and postnoon (blue). It is noted that the F_3 layers observed during postnoon period are mainly associated with downward movement of $h'F_3$, in contrast to prenoon F_3 layers, which move upward in altitude. We have also looked into the rate of change of F_3 layer height, which indicates that fewer F_3 layers are formed due to upward movement of *F* region plasma in the postnoon period. These cases fall under the category for which F_3 is observed for both prenoon and postnoon periods. Such formation of the F_3 layer can be associated with double hump-type eastward electric field as discussed by *Balan et al.* [2000], where the physical mechanism involved in the formation is same as that for prenoon F_3.

Based on the present understanding, the existence of postnoon F_3 layers can be attributed to (i) reappearance of prenoon time F_3 layers due to decrease in f_oF_2 or (ii) The fresh formation of F_3 in the postnoon period due to rapid upward movement of *F* region plasma resulting from eastward electric field, in presence of favorable wind conditions. Both the above mentioned processes can be understood through existing model. However, the 17% occurrence of F_3 layer seen particularly during postnoon period (with no prenoon occurrence) of summer 2009 are associated with the absence of eastward electric field. In order to examine whether such postnoon F_3 layers are seen during summer solstice of previous solar minimum or not, we have used ionosonde data from nearby station Trivandrum during summer solstice (June–August) of 1996. It was found that out of 73 quiet days, the F_3 layer was found to have occurred during the prenoon hours for ~36% of days, whereas postnoon occurrence was only 1% which is negligible. Thus, it confirms that postnoon F_3 layers seen during 2008–2009 are peculiar feature of the extended minimum of solar cycle 24. The physical mechanism of occurrence of F_3 layer in postnoon period in absence of upward drift cannot be explained based on the present models.

We also estimate the average time duration of F_3 occurrence for prenoon and postnoon periods. Figure 7 shows the number of days as a function of F_3 duration. Figures 7 (top and bottom) correspond to year 2007

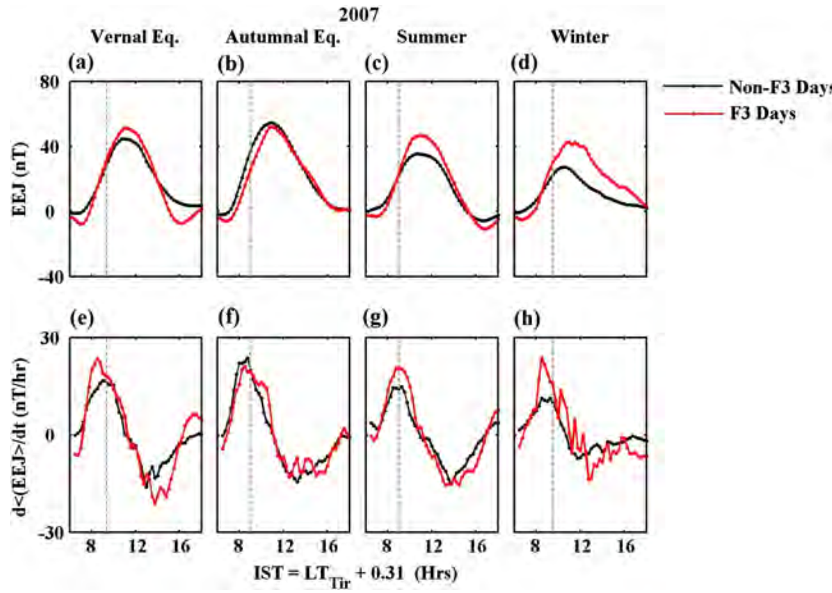

Figure 8. Comparison of equatorial electrojet (EEJ) on F_3 and non-F_3 days for 2007 as a function of IST. The red curve represents the days with F_3 occurring only during prenoon hours. The black curve represents the days without F_3. The black dotted line shows the time of maximum occurrence of the F_3 layer for each season. (a–d) The 15 min average EEJ strength for each season and (e–h) the corresponding rate of change in EEJ.

and 2009, respectively. The average time duration of F_3 layer is mentioned in each subplot with its standard deviation. It can be seen that most of the prenoon F_3 layers sustain for nearly 1 h, whereas the postnoon F_3 layers during summer solstice 2009 are found to possess longer durations. The average duration of F_3 for prenoon and postnoon periods during summer 2009 are 1.16 ± 0.6 and 1.5 ± 1.0, respectively.

The other factor that plays an important role in the formation of F_3 layer is meridional neutral wind, which assists to reduce the diffusion of *F* region plasma along geomagnetic field lines. In general, the meridional component of neutral wind is strongly equatorward (poleward) during prenoon hours of summer (winter) solstice. The smaller occurrence of F_3 layer during winter solstice is attributed to the presence the strong poleward neutral wind [*Balan et al.*, 1998].

3.3. Possible Relationship Between the F_3 Layer and the EEJ

We know that eastward electric field plays a crucial role in the formation of F_3 layer. Likewise, the EEJ, observed at *E* region heights as well, are controlled by zonal electric fields. These two phenomena are observed at different heights, and hence, their dynamics are attributed to eastward electric field at that altitude. *Anderson et al.* [2002] suggest that EEJ can be used as proxy for eastward electric field in the *F* region. Here we examine the possible linkage between occurrence of F_3 layers and EEJ. Here we use the magnetic field observations recorded at 1 min interval from Alibag and Tirunelveli to get the estimates of EEJ [*Chandra et al.*, 2000]. We compute 15 min average of EEJ for (i) F_3 days and (ii) non-F_3 days of each season during 2007 and 2009. The average EEJ (⟨EEJ⟩) and their time rate change are shown in Figures 8a–8d and Figures 8e–8h, respectively, for four seasons of 2007. A similar plot is displayed in Figure 9 for 2009. Particularly, summer 2009 is dominated by occurrence of postnoon F_3 layers, and hence, average EEJ and their time rate change of EEJ are shown separately for days with prenoon and postnoon F_3 layers. The vertical dashed line corresponds to the time of maximum occurrence of F_3 during that season. Similarly, the vertical dash-dotted line shown in Figure 9g represents the time of maximum occurrence for the postnoon F_3 layers during summer of 2009. The maximum average EEJ and maximum rate of change of EEJ for each season of 2007 and 2009 are mentioned in Table 1.

The temporal variation of average EEJ and the corresponding time rate of change indicate that the F_3 layers are observed during ascending phase of EEJ. It is noticed that maximum average EEJ and their time rate change are higher for days with F_3 as compared to those without F_3 layers for all the seasons except for autumnal (vernal) equinox of 2007 (2009). The higher EEJ represents the higher vertically upward movement

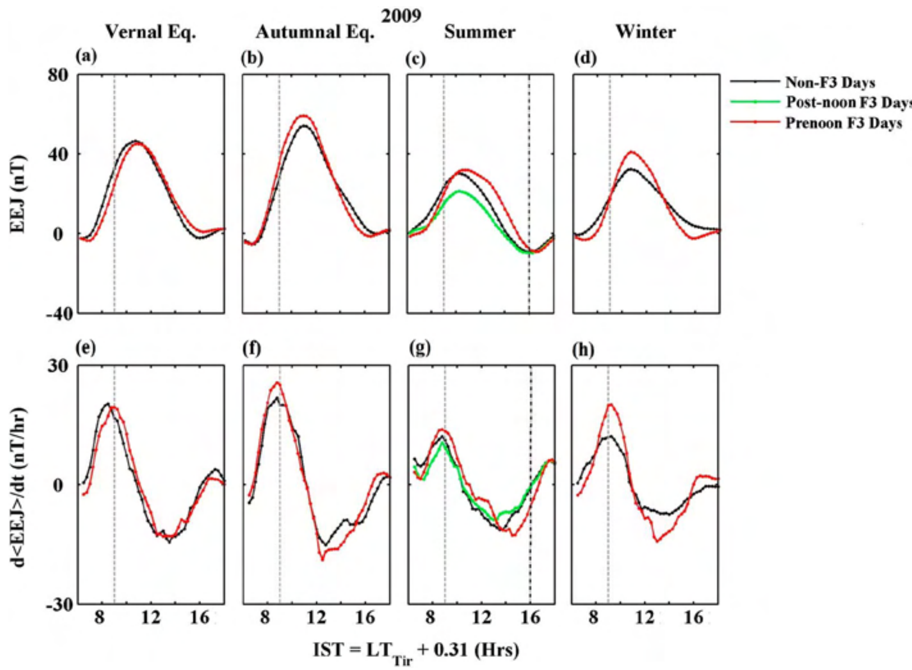

Figure 9. (a–h) Comparison of equatorial electrojet (EEJ) on F_3 and non-F_3 days for 2009 as a function of IST. The green curve in Figure 9g represents the days with F_3 layer during the postnoon hours only. The vertical black dotted line shows the time of maximum occurrence of the F_3 layer for each season. The vertical dash-dotted line represents the time of maximum occurrence for the postnoon F_3 layers during the summer of 2009. Figures 9a–9d show the 15 min averaged EEJ strength for each season and Figures 9e–9h represent the corresponding rate of change in EEJ.

of *F* region through **E** × **B** drifts. The most prominent feature of Figures 8 and 9 is that the time of maximum occurrence of the F_3 layer closely matches with the time when the rate of change of EEJ is maximum. The days of summer solstice on which F_3 layers are observed strictly during postnoon hours are shown by green curve in Figure 9g. It is clearly seen that for these days the maximum average EEJ and its time rate change both are smaller as compared to other two categories. It suggests that the slower upward movement of *F* layer inhibited the formation of F_3 during prenoon hours for these days. The minimum average rate of change of EEJ indicates how rapidly the layer is moving vertically downward. It should be noted that the minimum average EEJ does not show distinct difference for days with postnoon and prenoon F_3 layers. However, minimum rate of change of EEJ is found to be marginally smaller for days with postnoon F_3 as compared to days with prenoon F_3 and without F_3 layer. The EEJ variation also suggests the absence of eastward electric field during postnoon hours, for the days when F_3 layers are observed during postnoon period only (with no prenoon F_3).

Examination of EEJ and F_3 occurrence yields that the maximum rate of change of eastward electric field that indicates the acceleration of *F* layer plays a crucial role in the formation of F_3 layers during prenoon hours. It is in agreement with the models proposed by *Huang* [1974] and *Balan et al.* [1998] which support the formation of F_3 when F_2 layer is rapidly lifted upward to higher altitudes. It may be mentioned here that the most distinct and strongest F_3 layer was observed when the upward drift underwent the most rapid change during the eastward penetration electric field event on 9 November 2004 [*Balan et al.*, 2008].

Recently, *Pavan Chaitanya et al.* [2013] have shown a linear relationship between the F_3 layer height and the MST radar derived **E** × **B** drift from the daytime 150 km echoes observed at Indian low-latitude station Gadanki (dip latitude 6.6°N) during 2008–2009. These authors have observed that no F_3 layers are formed when the prenoon **E** × **B** drift is less than 10 m/s. However, this threshold upward drift cannot be considered as sufficient condition because the F_3 layer was not seen on many occasions even though the upward drift was above the threshold value. *Balan et al.* [2000] have discussed the importance of the threshold vertical velocity, which depends on the vertical **E** × **B** drift, magnetic meridional neutral wind speed, and the magnetic dip angle at any given location. At times, the layer may be absent even if there is sufficiently strong

E × **B** drift. This may be due to the reason that although the drift may be strong enough, the rate of increase of the vertical drift may not be fast enough to create suitable conditions for the formation of the layer which is evident from our results from Figures 8 and 9.

Observational and modeling studies of F_3 have pointed out the role of upward drift in the formation of F_3. However, peak occurrence of F_3 is mainly seen during summer solstice, when ambient eastward electric field is weaker. Looking at Figures 8 and 9, it can be questioned that the peak EEJ during the vernal and the autumnal equinoxes are considerably higher than those for the summer solstice for both 2007 and 2009. Hence, the corresponding vertical **E** × **B** drift must be higher during the equinoxes than in summer. Similar trends are well known from Jicamarca incoherent scatter radar observations [*Fejer et al.*, 1991]. *Patra et al.* [2012] have also shown a similar trend of the vertical drifts in the Indian longitude using **E** × **B** drifts calculated from daytime 150 km echoes obtained by the Gadanki MST radar. Thus, we expect higher occurrence of F_3 layer during both equinoxes as compared to that during summer solstice. However, present observations show that pre-noon time occurrence of F_3 is nearly the same for equinoctial and summer period. It could be related to the presence of favorable winds during summer solstice. Hence, although EEJ strength and their rate of change is smaller during summer, the F_3 layer occurrence is maximum during summer as compared to other seasons. On the other hand, wind conditions are not favorable for the formation of F_3 during winter solstice. If we examine winter 2009 shown in Figures 8h and 9h, significantly higher eastward electric field and its rate of change are found to be present for days with prenoon F_3.

As discussed in section 3.2 the postnoon F_3 layers show descending pattern in altitude unlike prenoon F_3 layers. It should also be noted that the days with only postnoon F_3 show presence of weaker eastward electric field during prenoon as evident from EEJ variation. This suggests that during those days the *F* layer plasma was not lifted to higher altitudes during prenoon hours, which explains the absence of F_3 during prenoon for those days. Here puzzle is that the formation of postnoon F_3 layers without upward movement of plasma and absence of such F_3 layers during summer of previous solar minimum. The answer to this puzzle probably lies in the background ionospheric conditions that are considerably modified during the extended solar minimum of 2008–2009. Certainly, modeling efforts are needed for the better understanding of formation of F_3 layers in postnoon periods.

4. Conclusion

We present the local time and seasonal variation of occurrence of F_3 layers over dip equatorial station Tirunelveli in Indian longitude during the extended solar minimum period of solar cycle 24 (2007–2009). We report peculiar observational features of F_3 layer during this period. Also, we have examined the possible relation between EEJ and occurrence of F_3 layer. The major conclusions of the present study are listed below.

1. The occurrence of F_3 layer is substantially higher during 2009 (48%) as compared to 2007 (16%). Such major increase just within low solar activity period is uncommon.
2. The postnoon F_3 layers are solely observed during summer solstice during 14–18 h IST. The occurrence of these postnoon F_3 layers increases from 0% during 2007 to 17% during 2009.
3. Above mentioned two observations are peculiar features of F_3 layer over Tirunelveli during the extended solar minimum period of solar cycle-24 and they were not seen during previous solar minimum. These peculiar features are attributed to modified background ionospheric conditions like ambient electron density, neutral density, and temperature during observational period that have resulted from extended solar minimum as reported by earlier studies [*Solomon et al.*, 2013; *Liu et al.*, 2011, 2012]. However, it will be worthwhile to investigate whether such peculiar features of F_3 occurrence are observed at other longitudes or not.
4. The seasonal variation of occurrence of F_3 presented here are in general accordance with the model proposed by *Balan et al.* [1998] for the formation of F_3 layers based on **E** × **B** drifts in presence of favorable meridional winds. However, the formation of F_3 layer observed during only postnoon period of summer 2009, in absence of eastward electric field to assist the upward movement of *F* region plasma is an unanswered question. Modeling efforts are needed for the better understanding of such phenomena.
5. We establish the link between F_3 occurrence and rate of change of average EEJ for the first time. We assume EEJ as a proxy for eastward electric field. It is found that maximum EEJ and maximum rate of change of EEJ both play a crucial role in the formation of F_3 layer. The peak occurrence of F_3 layer matches well with the time of maximum rate of change of EEJ for a given season.

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References

Alken, P., and S. Maus (2010), Relationship between the ionospheric eastward electric field and the equatorial electrojet, *Geophys. Res. Lett.*, *37*, L04104, doi:10.1029/2009GL041989.

Anderson, D., A. Anghel, K. Yumoto, M. Ishitsuka, and E. Kudeki (2002), Estimating daytime vertical E×B drift velocities in the equatorial F-region using ground-based magnetometer observations, *Geophys. Res. Lett.*, *29*(12), 37-1–37-4, doi:10.1029/2001GL014562.

Bailey, G. J., N. Balan, and Y. Z. Su (1997), The sheffield university plasmasphere ionosphere model: A review, *J. Atmos. Sol. Terr. Phys.*, *59*, 1541–1552.

Balan, N., and G. J. Bailey (1995), Equatorial plasma fountain and its effects: Possibility of an additional layer, *J. Geophys. Res.*, *100*, 21,421–21,432, doi:10.1029/95JA01555.

Balan, N., I. S. Batista, M. A. Abdu, J. MacDougall, and G. J. Bailey (1998), Physical mechanism and statistics of occurrence of an additional layer in the equatorial ionosphere, *J. Geophys. Res.*, *103*, 29,169–29,181, doi:10.1029/98JA02823.

Balan, N., I. S. Batista, M. A. Abdu, G. J. Bailey, S. Watanabe, J. MacDougall, and J. H. A. Sobral (2000), Variability of an additional layer in the equatorial ionosphere over Fortaleza, *J. Geophys. Res.*, *105*, 10,603–10,613, doi:10.1029/1999JA000020.

Balan, N., S. V. Thampi, K. Lynn, Y. Otsuka, H. Alleyne, S. Watanabe, M. A. Abdu, and B. G. Fejer (2008), F_3 layer during penetration electric field, *J. Geophys. Res.*, *113*, A00A07, doi:10.1029/2008JA013206.

Batista, I. S., M. A. Abdu, J. McDougall, and J. R. Souza (2002), Long term trends in the frequency of occurrence of the F_3 layer over Fortaleza, *J. Atmos. Sol. Terr. Phys.*, *64*, 1409–1412.

Chandra, H., H. S. S. Sinha, and R. G. Rastogi (2000), Equatorial electrojet studies from rocket and ground measurements, *Earth Planets Space*, *52*, 111–120.

Depuev, V. H., and S. A. Pulinets (2001), Intercosmos-19 observations of an additional topside ionization layer: The F_3 layer, *Adv. Space Res.*, *27*, 1289–1292, doi:10.1016/S0273-1177(01)00205-8.

Fejer, B. G., E. R. de Paula, S. A. Gonzales, and R. F. Woodman (1991), Average vertical and zonal F region plasma drifts over Jicamarca, *J. Geophys. Res.*, *96*, 13,901–13,906, doi:10.1029/91JA01171.

Huang, C. M. (1974), Certain behavior of the ionospheric F_2 region at low latitudes, *Radio Sci.*, *9*, 519–532.

Jenkins, B., G. J. Bailey, M. A. Abdu, I. S. Batista, and N. Balan (1997), Observations and model calculations of an additional layer in the topside ionosphere above Fortaleza, Brazil, *Ann. Geophys.*, *15*, 753–759, doi:10.1007/s00585-997-0753-3.

Liu, L., Y. Chen, H. Le, V. I. Kurkin, N. M. Polekh, and C.-C. Lee (2011), The ionosphere under extremely prolonged low solar activity, *J. Geophys. Res.*, *116*, A04320, doi:10.1029/2010JA016296.

Liu, L., J. Yang, H. Le, Y. Chen, W. Wan, and C.-C. Lee (2012), Comparative study of the equatorial ionosphere over Jicamarca during recent two solar minima, *J. Geophys. Res.*, *117*, A01315, doi:10.1029/2011JA017215.

Lockwood, G. E. K., and G. L. Nelms (1964), Topside sounder observations of the equatorial anomaly in the 75° W longitude zone, *J. Atmos. Sol. Terr. Phys.*, *26*, 569–570.

Lynn, K. J. W., T. J. Harris, and M. Sjarifudin (2000), Stratification of the F_2 layer observed over Southeast Asia, *J. Geophys. Res.*, *105*, 27,147–27,156, doi:10.1029/2000JA900056.

Patra, A. K., P. P. Chaitanya, N. Mizutani, Y. Otsuka, T. Yokoyama, and M. Yamamoto (2012), A comparative study of equatorial daytime vertical E×B drift in the Indian and Indonesian sectors based on 150 km echoes, *J. Geophys. Res.*, *117*, A11312, doi:10.1029/2012JA018053.

Pavan Chaitanya, P., A. K. Patra, N. Balan, and S. V. B. Rao (2013), First simultaneous observations of F_3 layer and E×B drift in Indian sector and modeling, *J. Geophys. Res. Space Physics*, *118*, 3527–3539, doi:10.1002/jgra.50298.

Paznukhov, V. V., B. W. Reinisch, P. Song, X. Huang, T. W. Bullett, and O. Veliz (2007), Formation of an F_3 layer in the equatorial ionosphere: A result from strong IMF changes, *J. Atmos. Sol. Terr. Phys.*, *69*, 1292–1304, doi:10.1016/j.jastp.2006.08.019.

Raghavarao, R., and M. R. Sivaraman (1974), Ionization ledges in the equatorial ionosphere, *Nature*, *249*, 331–332, doi:10.1038/249331a0.

Rama Rao, P. V. S., K. Niranjan, D. S. V. V. D. Prasad, P. S. Brahmanandam, and S. Gopikrishna (2005), Features of additional stratification in ionospheric F_2 layer observed for half a solar cycle over Indian low latitudes, *J. Geophys. Res.*, *110*, A04307, doi:10.1029/2004JA010646.

Ratcliffe, J. A. (1951), Some regularities in the F_2 region of the ionosphere, *J. Geophys. Res.*, *56*, 487–507.

Sayers, J., P. Rothwell, and J. H. Wager (1962), Evidence for a further ionospheric ledge above the F_2-region, *Nature*, *195*, 1143–1145, doi:10.1038/1951143a0.

Sen, H. Y. (1949), Stratification of the F_2-layer of the ionosphere over Singapore, *J. Geophys. Res.*, *54*, 363–366.

Sharma, P., and R. Raghavarao (1989), Simultaneous occurrence of ionization ledge and counter electrojet in the equatorial ionosphere: Observational evidence and its implications, *Can. J. Phys.*, *67*, 166.

Skinner, N. J., R. A. Brown, and R. W. Wright (1954), Multiple stratification of the F layer at Ibadan, *J. Atmos. Terr. Phys.*, *5*, 92–100.

Solomon, S. C., L. Qian, and A. G. Burns (2013), The anomalous ionosphere between solar cycles 23 and 24, *J. Geophys. Res. Space Physics*, *118*, 6524–6535, doi:10.1002/jgra.50561.

Sreeja, V., N. Balan, S. Ravindran, T. K. Pant, R. Sridharan, and G. J. Bailey (2010), Features of the F_3 layer occurrence over the equatorial location of Trivandrum, *Ann. Geophys.*, *28*, 1741–1747, doi:10.5194/angeo-28-1741-2010.

Uemoto, J., T. Ono, A. Kumamoto, and M. Iizima (2004), Ionization ledge structures observed in the equatorial anomaly region by using PPS system on-board the Ohzora (EXOS-C) satellite, *Earth Planets Space*, *56*(7), e21–e24.

Uemoto, J., T. Ono, T. Maruyama, S. Saito, M. Iizima, and A. Kumamoto (2007a), Magnetic conjugate observation of the F_3 layer using the SEALION ionosonde network, *Geophys. Res. Lett.*, *34*, L02110, doi:10.1029/2006GL028783.

Uemoto, J., T. Maruyama, T. Ono, S. Saito, M. Iizima, and A. Kumamoto (2007b), Observations and model calculations of the F_3 layer in the Southeast Asian equatorial ionosphere, *J. Geophys. Res.*, *116*, A03311, doi:10.1029/2010JA016086.

Yadav, V., B. Kakad, C. Nayak, G. Surve, S. Sripathi, and K. Emperumel (2014), Occurrence of blanketing Es-layer (Esb) over equatorial region during the peculiar minimum of solar cycle-24, *Ann. Geophys.*, *32*, 553–562, doi:10.5194/angeo-32-553-2014.

Zhao, B., W. Wan, and L. Liu (2005), Responses of equatorial anomaly to the October–November 2003 superstorms, *Ann. Geophys.*, *23*, 693–706, doi:10.5194/angeo-23-693-2005.

Zhao, B., W. Wan, B. Reinisch, X. Yue, H. Le, J. Liu, and B. Xiong (2011a), Features of the F_3 layer in the low-latitude ionosphere at sunset, *J. Geophys. Res.*, *116*, A01313, doi:10.1029/2010JA016111.

Zhao, B., W. Wan, X. Yue, L. Liu, Z. Ren, M. He, and J. Liu (2011b), Global characteristics of occurrence of an additional layer in the ionosphere observed by COSMIC/FORMOSAT-3, *Geophys. Res. Lett.*, *38*, L02101, doi:10.1029/2010GL045744.

Zhu, J., B. Zhao, W. Wan, and B. Ning (2013), An investigation of the formation patterns of the ionospheric F_3 layer in low and equatorial latitudes, *J. Atmos. Sol. Terr. Phys.*, *102*, 48–58, doi:10.1016/j.jastp.2013.04.015.

