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

C. K. Nayak$^1$, V. Yadav$^1$, B. Kakad$^1$, S. Sripathi$^1$, K. Emperumal$^2$, T. K. Pant$^3$, A. Bhattacharyya$^1$, and Shuanggen Jin$^4$

$^1$Indian Institute of Geomagnetism, Navi Mumbai, India, $^2$Equatorial Geophysical Research Laboratory, Indian Institute of Geomagnetism, Tirunelveli, India, $^3$Space Physics Laboratory, Vikram Sarabhai Space Centre, Trivandrum, India, $^4$Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai, China

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 ($\sim 48\%$) as compared to that during 2007 ($\sim 16\%$). 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 ($d\mathbf{E}/dt$) 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 Sivarman, 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 $F_3$ 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.

The $F_3$ layer 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 $F_1$ 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 [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 $E \times B$ 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 $E \times B$ 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 $E \times B$ 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 $F_1$ 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 $E \times B$ 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...
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., $f_{oF_2}$, $h'F_2$, $f_{oF_3}$, and $h'F_3$) 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 ($\Delta H$) 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) $f_o F_2$ and $f_o F_3$ and 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 $f_o F_3$ seems more like a continuation of the old $F_2$ layer, whereas $f_o F_2$ 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 $E \times B$ 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, $f_o F_3$ gradually decreases due to recombination and diffusion. Eventually, $f_o F_3$ becomes less than $f_o F_2$, 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
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.

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.
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 ($\sim$48%) as compared to 2007 ($\sim$16%). Such 3 times increase simply within low solar activity ($F_{10.7} = 73 \pm 6$ to $70 \pm 3$) 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].
that inclination angle at Tirunelveli changed from 1.25 to 1.75 during this period. Here we notice that during 2007 to 2009, the occurrence of $F_3$ 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 $F_3$ s 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 $f_{op}F_2$ and $f_{op}F_3$ for $F_3$ days of each season during 2007 and 2009, which are mentioned in Table 1. It is noticed that

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

<table>
<thead>
<tr>
<th>Year</th>
<th>Season</th>
<th>$&lt; f_{op}F_2 &gt;$ MHz</th>
<th>$&lt; f_{op}F_3 &gt;$ MHz</th>
<th>(EEJ) nT</th>
<th>d(EEJ)/dt max nT/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>Vernal equinox</td>
<td>7.17 ± 0.48</td>
<td>7.84 ± 0.55</td>
<td>51.24 ± 13.29</td>
<td>23.56</td>
</tr>
<tr>
<td></td>
<td>Autumnal equinox</td>
<td>6.58 ± 0.41</td>
<td>7.02 ± 0.25</td>
<td>51.81 ± 13.73</td>
<td>21.03</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>6.04 ± 0.61</td>
<td>6.75 ± 0.66</td>
<td>46.81 ± 18.37</td>
<td>20.50</td>
</tr>
<tr>
<td></td>
<td>Winter</td>
<td>6.78 ± 0.55</td>
<td>7.52 ± 0.50</td>
<td>42.37 ± 19.61</td>
<td>23.60</td>
</tr>
<tr>
<td>2009</td>
<td>Vernal equinox</td>
<td>6.23 ± 0.45</td>
<td>6.93 ± 0.47</td>
<td>44.95 ± 11.23</td>
<td>19.42</td>
</tr>
<tr>
<td></td>
<td>Autumnal equinox</td>
<td>6.27 ± 0.60</td>
<td>7.09 ± 0.59</td>
<td>59.17 ± 20.42</td>
<td>25.60</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>5.73 ± 0.31</td>
<td>6.49 ± 0.52</td>
<td>31.90 ± 19.07</td>
<td>13.84</td>
</tr>
<tr>
<td></td>
<td>Winter</td>
<td>6.34 ± 0.96</td>
<td>6.70 ± 0.75</td>
<td>40.95 ± 13.29</td>
<td>19.53</td>
</tr>
</tbody>
</table>
the average $f_{\text{eq}}F_2$ and $f_{\text{eq}}F_3$ 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 $E \times B$ 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 $f_cF_2$ 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.
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 $1.16 \pm 0.6$ and $1.5 \pm 1.0$, 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 of 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 ($\langle EEJ \rangle$) 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 $E \times B$ 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 $E \times B$ 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 $E \times B$ 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 $E \times B$ 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 \( E \times B \) 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 \( E \times B \) 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.

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 \( F_3 \) 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 \( E \times B \) 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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