Features of the $F_3$ layer in the low-latitude ionosphere at sunset

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The $F_3$ layer is a common feature within $\pm 10^\circ$ of the magnetic equatorial ionosphere in the daytime. According to Balan et al. (1998) the $F_3$ layer occurs mainly during the morning-noon period due to the combined effect of the upward $\mathbf{E} \times \mathbf{B}$ drift and the neutral wind that provides upward plasma drifts at and above the $F_2$ layer. The $F_3$ layer occurrence rate is higher in summer and decreases with increasing solar activity. In this study, the characteristic of the sunset $F_3$ layer is first investigated using a solar cycle of ionosonde data (1995–2010) from the magnetic equatorial station at Jicamarca, and compared with the features derived from the four subtropical stations at Sao Luis, Fortaleza, Kwajalein, and Vanimo. Evidence shows that the local time distribution of the occurrence of the $F_3$ layer can extend to the postsunset time (1800–2100 local time). The sunset $F_3$ layer has a strong seasonal dependence occurring mainly during the summertime. Unlike the daytime $F_3$ layer, the occurrence of the sunset $F_3$ layer clearly increases and the virtual height of the bottom side of the $F_3$ layer statistically increases from 620 to 1000 km with increasing solar activity. In addition, the occurrence of the sunset $F_3$ layer at the other stations is much less than that at Jicamarca. These features of the dependence on the season, solar activity, and latitude are clearly related to the geomagnetic control of the evening prereversal enhancement of the equatorial zonal electric field and geomagnetic configuration.


1. Introduction

The revelation of multilayer structure in the $F_2$ region over the equatorial ionosphere can be traced back to the middle of the last century. Ground-based ionosonde measurements show that the high-frequency end of the virtual height-frequency ($h' - f$) ionogram records a “spur” which moves to higher frequencies during the morning-noon sector [e.g., Sen, 1949; Ratcliffe, 1951; Skinner et al., 1954]. Sayers et al. [1963] detected the topside ledges in the equatorial topside ionosphere using a Langmuir probe onboard the Ariel I satellite. Such ledges were later detected by the topside sounding technique and revealed as cusps in the topside ionograms at low latitudes after the launch of the Alouette-ISIS program [e.g., Lockwood and Nelms, 1964; Raghavarao and Sivaraman, 1974; Sharma and Raghavarao, 1989].

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ionosonde measurements in Southeast Asia show that the transitory layer was seen as an $F_2$ layer close to the magnetic equator but invariably as an $F_1$ layer farther from the magnetic equator. These observations suggest that the distortion in the equatorial electron density profile, associated with a movement toward the base of the $F_2$ layer as magnetic field lines, descended with increasing latitude. Fagundes et al. [2007] reported stratification of the $F_2$ layer over an equatorial anomaly crest location in Brazil, which was mainly considered as the result of the propagation of atmospheric gravity waves (AGWs) often observed in the middle latitudes [Heisler, 1962].

The study on the stratification of $F_2$ layer at the topside ionosphere was also in progress. Uemoto et al. [2004, 2006] performed a statistical analysis of the topside ledges in the equatorial ionosphere using the Ohzora (EXOS-C) and ISIS II satellite. They concluded that the characteristics of the $F_3$ layer and topside ledges are similar, except for the seasonal dependence of the occurrence probabilities. Their results also show that the ionization ledge is observable at almost all local time (LT) sectors except the period from 0300 to 0800 LT. However, Depue and Pulinets [2001], using the data from the Intercosmos 19 satellite, reported the first observations of ionization ledges at midnight and early morning hours (0400 LT) at 165° longitude. Thampi et al. [2005, 2007] also discussed the possibility of a link between the $F_3$ layer and topside ledges through the total electron content (TEC) measured by low Earth orbiting satellites.

From these investigations, it is known that the $F_3$ layer can be observed under geomagnetically quiet conditions. The critical frequency becomes greater than that of the $F_2$ layer during daytime (0800–1600 LT) within about ±10° magnetic latitudes. The $F_3$ layer appears with higher occurrence and lasts longer on the summer side of the geomagnetic equator during low solar activity periods. Rama Rao et al. [2005] point out that the altitude of the $F_3$ layer is very high at the magnetic equator (600–700 km) compared with that at subtropical stations Wairaka and SHAR (around 500 km). It can also be detected by topside sounders as topside ledges although the two concepts are not completely equivalent.

In this paper we report a type of the $F_3$ layer produced by the $E \times B$ prereversal enhancement (PRE), which was not fully discussed in previous work [e.g., Balan et al., 1998]. A statistical result with respect to the seasonal and solar activity dependence of the sunset $F_3$ layer is given on the basis of more than a solar cycle (1995–2010) of ionogram data recorded at Jicamarca (dip latitude ~0.5°N). A comparative study has also been carried out with ionograms recorded at four subtropical stations, Sao Luis (2.0°S), Kwajalein (3.8°N), Fortaleza (6.6°S), and Vanimo (11.2°S). The results are expected to enhance our knowledge about the characteristics of the $F$ layer stratification phenomenon on equatorial aeronomy, although it has been investigated for years.

### 2. Data Sources

In this study, ionogram data recorded at five subtropical and equatorial stations (Jicamarca, Sao Luis, Fortaleza, Kwajalein, and Vanimo) are used. The geographic locations, magnetic inclinations, declinations, and data coverage of the stations are listed in Table 1. Geomagnetic information is calculated by International Geomagnetic Reference Field (IGRF) 2010. Measurements at Jicamarca, Sao Luis, Fortaleza, and Kwajalein are taken from the University of Massachusetts Lowell digital ionosonde database [Reinisch et al., 2004; Khmyrov et al., 2008] with ionogram temporal resolution of 15, 10, and 5 min. Note that the ionosonde at Jicamarca during 1995–2000 was a DPS-1 [Reinisch et al., 2009], running most of the time with a 30 min ionogram cadence. Measurements at Vanimo were performed every 15 min and were obtained from the Ionospheric Prediction Service (IPS) clean ionogram data available at http://www.ips.gov.au/World_Data_Centre.

### 3. Results

#### 3.1. Features of the Sunset $F_3$ Layer at Jicamarca

The typical $F_3$ layer is a cusp structure occurring at the high-frequency end of the trace recorded in the ionogram during daytime periods. The stratification of the $F_2$ layer on the days of occurrence started around 0800 LT and occasionally extended as late as 1600 LT [Balan et al., 1998; Rama Rao et al., 2005]. However, there is usually an evening PRE of the eastward electric field in the dusk sector which occurs simultaneously in the equatorial $E$ and $F$ regions [Heeis et al., 1974]. This upward $E \times B$ drift raises the ionization peak and plasma converges in the topside ionosphere and then forms the $F_3$ layer which could be detected by ground-based ionosondes for a short period when its peak density is greater than that of the $F_2$ layer. One such set of observations is presented in Figure 1, which displays some sample ionograms recorded at Jicamarca on 21 November 1995, 9 February 1999, and 14 January 2002 corresponding to different solar activity. The geomagnetic conditions during the three events were quiet with maximum $Kp$ index not exceeding 2. The ionograms recorded at 30 min intervals show some distortions at the high-frequency end starting at around 1700 LT. The distortions developed into a clear “cusp,” and an additional trace appears at the high-frequency end at around 1900 LT. The trace remained distorted until the whole $F$ layer started to descend at 2100 LT. Note that on 9 February 1999 there was a strong spread-$F$ after 2030 LT which made the $F_3$ trace difficult to identify.

<table>
<thead>
<tr>
<th>Station</th>
<th>Latitude (deg)</th>
<th>Longitude (deg)</th>
<th>Magnetic Dip Latitude (deg)</th>
<th>Magnetic Dip (deg)</th>
<th>Data Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jicamarca</td>
<td>−12.0</td>
<td>283.2</td>
<td>0.7−0.2</td>
<td>1.3−0.4</td>
<td>1995.1–2009.12</td>
</tr>
<tr>
<td>Sao Luis</td>
<td>−2.6</td>
<td>315.8</td>
<td>−2.0</td>
<td>−4.0</td>
<td>2006.5–2006.12, 2010.1–2010.4</td>
</tr>
<tr>
<td>Kwajalein</td>
<td>9.0</td>
<td>167.2</td>
<td>3.8</td>
<td>7.6</td>
<td>2006.7–2007.6</td>
</tr>
<tr>
<td>Fortaleza</td>
<td>−3.8</td>
<td>322.0</td>
<td>−6.6</td>
<td>−13.0</td>
<td>2007.3–2007.9, 2009.10–2010.2</td>
</tr>
<tr>
<td>Vanimo</td>
<td>−2.7</td>
<td>141.3</td>
<td>−11.2</td>
<td>−21.7</td>
<td>2006.7–2007.6</td>
</tr>
</tbody>
</table>

Table 1. Location of the Ionosondes Used in the Study
Figure 2 shows the monthly occurrence probability of the $F_3$ layer versus local time at Jicamarca during the low, middle, and high solar activity years 2006, 1999, and 2002, respectively. The monthly occurrence probability refers to the percentage of days of available data when stratification of the $F_2$ layer appears. As illustrated in Figure 2 the higher occurrence probability of the $F_3$ layer appears at two local time bands, the morning–noon period 0900–1300 LT and the afternoon–sunset period 1600–2000 LT, which have a clearly seasonal dependence. In summer, the $F_3$ layer occurrence in the afternoon–sunset band is higher than that of the morning–noon band, while at equinox, the situation is the reverse. In winter, occurrence probabilities at both local time bands are very low. Another noteworthy feature is that the occurrence probability of the $F_3$ layer near sunset local time has clear solar activity dependence. In the following section, statistical results are given according to the Jicamarca data during 1995–2010.

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Figure 2. Histograms showing the percent occurrence of the $F_3$ layer during 0700–2100 LT over Jicamarca in 1999, 2002, and 2006, years of different solar activity.
which display a linear dependence on the solar flux as revealed by Fejer et al. [1991]. Actually, the solar activity dependence can also be found in the altitude of the daytime $F_3$ layer with a model simulation at the June solstice corresponding to 1100 LT at 4°N magnetic latitude at the longitude of Fortaleza [Balan et al., 1998]. The visible virtual height of the $F_3$ peak increases from 500 to 600 km as $F_{10.7}$ changes from 95 to 194. In comparison, the virtual height of the $F_3$ peak during the daytime varies from about 430 km in June to about 625 km in January at subtropical regions [Balan et al., 1998], which should be attributed to the seasonal variation of the wind-lifting effect.

There is no one-to-one correspondence between the height of the sunset $F_3$ layer and the $Kp$ index. However, sufficiently strong magnetic activity can induce a distinct additional layer during the sunset period such as was the case on 23 September 1999 and also on 30 October 2003. The mechanism responsible for the storm time $F_3$ layer is similar to that in quiet periods but with a much faster formation due to the rapid uplift of the $F$ layer by an upward $E \times B$ drift resulting from an eastward penetrating electric field [e.g., Zhao et al., 2005; Paznukhov et al., 2007; Balan et al., 2008]. Such an example from a theoretical model is presented in detail by Lin et al. [2009a, 2009b].

### 3.3. Occurrences of the $F_3$ Layer at Five Stations During Low Solar Activity

The morning-noon ionosphere becomes broad and intense with increasing solar activity, while the corresponding driving mechanism such as $E \times B$ drift and neutral wind for $F_3$ layer formation remains more or less constant. Thus, the upward force arising from drift and wind becomes less

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**Figure 3.** Day-to-day variations of the occurrence of the $F_3$ layer recorded at Jicamarca during 1995–2010. The virtual height of the $F_3$ layer for $Kp < 3$ (green circles) and $Kp \geq 3$ (red circles) when best seen is shown, as is the maximum $Kp$ (squares) during which the $F_3$ layer appeared. The data coverage is denoted as black horizontal bar.
plasma to the topside altitude region undergoes a drift increases from the layer is the \( F \) layer usually becomes weak and invisible because of the \( F \) layer drifts upward, because of the absence of the \( F \) layer for want of a concise description. As illustrated \( F \) layer during solar maximum \( F \) layer and \( F \) layer may not be layer occurs most frequently (>75%) in \( Rama Rao et al. \) drift in winter associated with less \( \times \) \( E \) \( B \) layer). \( F \) layer in winter and attributed it to \( B \) \( F \) \[1998\] suggested that \( F \) layer, which could rise above the \( Rama Rao et al. \) \( \times \) \( B \) 

Figure 4. Relationship between the virtual height of the \( F_3 \) layer when best seen and solar flux during 1995–2010 for \( Kp < 3 \). The solid line shows the linear fitting line of the data.

efficient to raise the morning \( F_2 \) plasma to the topside altitude to form an \( F_2 \) layer during solar maximum [Balan et al., 1998]. Then the occurrence of the \( F_2 \) layer is higher during periods of low solar activity than under periods of high solar activity as revealed by long-term observational ionogram data [Batista et al., 2002; Rama Rao et al., 2005]. Considering the availability, integrity, and quality of the ionograms, data from July 2006 to June 2007 at Jicamarca, Kwajalein, and Vanimo, data from May to December 2006 and January to April 2010 at Sao Luis, and data from March to September 2007 and October 2009 to February 2010 at Fortaleza were chosen. The average \( F_0.7 \) cm solar flux indices during the above three periods are 77.6, 80.0, and 75.8 solar flux units (sfu) (1 sfu = \( 10^{-22} \text{ Wm}^{-2} \text{ Hz}^{-1} \)).

[14] Figure 5 shows the monthly occurrence probability of the \( F_3 \) layer versus local time at five stations. The occurrence probability refers to the percentage of days of available data when stratification of the \( F_2 \) layer appears. According to Lynn et al. [2000], the stratification was recognized in terms of a kink in the profile of the \( F_3 \) layer, which could rise above the peak of the background \( F_2 \) layer (\( F_3 \) layer) or remain below the peak depending on the latitude of observation (\( F_{1.5} \) layer). In this paper the \( F_{1.5}/F_3 \) phenomenon is generally designated as an \( F_3 \) layer for want of a concise description. As illustrated in Figure 5, the \( F_3 \) layer occurs most frequently (>75%) in summer, that is December–February at Fortaleza and Vanimo, and June–July at Kwajalein, during 0930–1400 LT. Furthermore, the layer occurs earlier in summer than in other periods; the layer also lasts longest in summer from morning to presunset. The \( F_2 \) layer occurs least frequently (<20%) in winter except at Fortaleza in July and at Kwajalein in January, when the occurrence can exceed 40% at some intervals during daytime. Balan et al. [1998] discussed the possibility of the higher occurrence of the \( F_3 \) layer in winter and attributed it to the strong upward \( E \times B \) drift in winter associated with less poleward wind, which was confirmed by the SUPIM model. Figure 5 shows that the characteristics of the \( F_3 \) layer appearing at Jicamarca near the magnetic equator are different from those at subtropical stations Fortaleza, Kwajalein, and Vanimo. The \( F_3 \) layer of Jicamarca has lower occurrence probability (<30%) during the daytime and higher occurrence probability during the sunset period. The occurrence probability, as well as its duration, decreases with the increase in dip latitude, which implies a geomagnetic control of the sunset \( F_3 \) layer.

4. Discussion

[15] The model result of Balan and Bailey [1995] shows that the \( F_3 \) layer starts to form during the morning hours when the upward \( E \times B \) drift increases. Once formed, the peak concentration of the \( F_3 \) layer remains greater than that of the \( F_2 \) layer for a short period of time before noon when the drift is large. The layer then weakens but continues to exist for more than 10 hours at the equator. However, the possibility of detection for the \( F_3 \) layer depends on the magnitude of the upward \( E \times B \) drift as the plasma at the topside ionosphere will diffuse downward along the geomagnetic field lines to higher latitudes due to the field-aligned pressure gradient and gravity forces. Without a sustaining upward plasma flux, the \( F_3 \) layer usually becomes weak and invisible because of the shielding effect of the \( F_2 \) layer (\( NmF_2 \geq NmF_3 \)) and disappears on the ionograms in the morning–noon period. On the other hand, interhemispheric wind blowing from the summer hemisphere to the winter hemisphere acts to raise the plasma at the upwind latitudes near the magnetic equator helping to maintain the diffused plasma at high altitude. As a result, the peak value of the \( F_3 \) layer exceeds that of the \( F_2 \) layer and hence enhances the possibility of the \( F_3 \) layer in the ionogram. This mechanism adequately explains the high occurrence of the \( F_3 \) layer observations at Fortaleza, Kwajalein, and Vanimo in summer, and the low occurrence at Jicamarca. Similar observational results were also obtained at other magnetic equatorial stations [Jenkins et al., 1997; Rama Rao et al., 2005; Uemoto et al., 2007].

[16] Although the neutral wind controls where and when the \( F_3 \) layer appears with higher probability, the main driving force for the formation and maintenance of the \( F_3 \) layer is the upward \( E \times B \) drift velocity. The strength and direction of the equatorial zonal electric field undergoes large day-to-day variability. Thus, the appearance of the \( F_3 \) layer may not be presented as described in the model studies. Fejer et al. [1991] give the average pattern of the equatorial \( F \) region drift, which shows that the upward \( E \times B \) drift increases from morning hours to noon, during which the \( F_3 \) layer can be best seen. Another period during which the \( F \) region undergoes a quick ascent is around dusk when PRE of the eastward electric field develops. Balan et al. [1998] suggested that although the driving force undergoes a large and sudden upward strengthening during the evening hours, formation of another layer at lower altitudes is unlikely to occur during when the \( F_2 \) layer drifts upward, because of the absence of the production of ionization. Our results fail to support the above assumption. As shown in Figures 2 and 3, the amount of the sunset \( F_3 \) layer during the high solar activity and summer is significant. The sunset \( F_3 \) layer may appear when the magnitude of the PRE of the eastward electric field is strong.
enough. Note that the dusk upward drift develops from 1600 LT and peaks at 1900 LT while the production of ionization still exists at the high altitudes of the $F_2$ region.

[17] The occurrence of the sunset $F_3$ layer was shown to be location-dependent, as illustrated in Figure 5. At Kwajalein and Vanimo, sunset $F_3$ was hardly observed at middle and low solar activity (data absent during high solar activity). One possible reason is that the PRE has a longitude variation. Kil et al. [2009] derived a global PRE map (vertical ion velocity within $\pm 5^\circ$ dip latitudes at 1730–1930 LT during 1999–2002) using the drift data measured by ROCSAT-1 at 600 km [Su et al., 2006]. As shown by Su et al. [2006, Figure 6], strong upward drift (>30 m s$^{-1}$) was measured at longitude ranges 45°W–75°W in summer months. In comparison, at longitude 120°E–180°E, where Kwajalein and Vanimo are located, the drift is small (8–24 m s$^{-1}$). The PRE is weak at these longitudes unable to produce the sunset $F_3$ layer. At Fortaleza and Sao Luis, 40° east of Jicamarca, a distinctive sunset $F_3$ layer was also seldom observed at dusk in summer.

[18] We propose that this regional difference may be related to the configuration of the geomagnetic field. Figure 6 (top) shows the average virtual height changes $\Delta h'F$ at Sao Luis, Jicamarca, and Kwajalein, superimposed within a summer month’s data during 2002 (black dots, solid line) and 2004 (shaded dots, dashed line). At Sao Luis we added data in November because of less data in December. There were no data during 2002 for Kwajalein. Figure 6 (bottom) displays the drift derived from $\Delta h'F/\Delta t$ at Sao Luis, Jicamarca, and Kwajalein. The $\Delta h'F/\Delta t$ reflects the vertical movement of the base of the layer and can be used to estimate ionosonde vertical plasma drifts [Oyekola, 2006; Oyekola et al., 2008]. In an earlier study comparing coincident incoherent scatter and ionosonde $F$ region vertical plasma drifts, Batista et al. [1986] showed that the reversal times after sunset derived

Figure 5. Occurrence probability of the $F_3$ layer at Vanimo, Fortaleza, Kwajalein, Sao Luis, and Jicamarca during low solar activity. The dip latitude and the solar terminator around sunset (thick line) at 300 km are shown.
electric field and the equatorward wind allow the $F_3$ layer to be observed more frequently at Jicamarca than at the Sao Luis longitude, which has a large magnetic declination of $-18^\circ$.

[20] The occurrence of sunset $F_3$ layers also shows a large day-to-day variability. Part of the variability of PRE can be attributed to forcing from lower altitudes. Evidence has shown that the thermospheric and electrodynamic conditions of the ionosphere in the afternoon may affect the intensity of the postsunset $\mathbf{E} \times \mathbf{B}$ drift velocity. Large, sudden increases of 52–117 km in the $h'F$ were observed in the postsunset sector (1800–2000 LT) on eight geomagnetically quiet days ($Ap \leq 5$) during 1957–1969. The perturbations were characterized by postnoon enhancements of the equatorial electrojet (EEJ) and an accompanying intensification of the equatorial ionization anomaly (EIA) before evening. Sastri [1998] attributed the phenomenon to the modifications of the equatorial thermospheric zonal winds and a flux tube integrated Pedersen conductivity distribution favorable to a very effective $F$ region dynamo. A similar case was investigated by Zhao et al. [2008] for the East Asian region, which suggests that planetary waves modulating the semidiurnal tide might be responsible for the corresponding anomaly enhancement of EIA in the postsunset period. Basu et al. [2009] revealed the fact that a counter-electrojet (CEJ) event in the afternoon may contribute to the inhibition of EIA. The cause of the day-to-day variability of the $\mathbf{E} \times \mathbf{B}$ drift corresponding to the PRE remains unresolved as the information regarding altitude, latitude, longitude, and local time variations of the ion drifts, the neutral winds, and the electric fields are only starting to become available. Future observational initiatives from the ground and space are designed to specifically address these issues.

[21] Thampi et al. [2007] have discussed the relationship between the $F_3$ layer and topside ledges. The simultaneous occurrence of the ledges in latitude TEC variation and $F_3$ layer in the ground ionograms suggests that topside ledges are upward propagating $F_3$ layers. A potential relationship between the topside ledge and bottomside $F_3$ layer was also pointed out by Uemoto et al. [2006] who analyzed the topside ionograms of 19 and 430 passages obtained from the Ohzora and ISIS II satellites. They also found that the topside ledges can appear from the evening to slightly after midnight and occur mostly in equinox. This nighttime ionization ledge is possibly caused by the large daytime upward vertical drifts, or probably attributed to the large PRE drift around sunset during moderate and high solar activity according to our investigation. Although the local time dependence of the ionization ledge, as well as the observed dip latitude range, is consistent with those of the $F_3$ layer reported by Balan et al. [1998], this does not prove that the topside ledges can form independently of an $F_3$ layer. If the topside ionization ledge is caused by the upward movement of the ionospheric plasma driven by the zonal electric fields, a diurnal variation should be observed in the altitude parameter. The topside ledge should undergo a downward drift at night. However, the results of Uemoto et al. [2006] show that the altitude variations of the ionization ledge were largely scattered. The study by Yizengaw et al. [2009] may provide a clue in understanding the above inconsistency. They found that very strong EIAs in the postmidnight (0100–0500 LT) sector during magnetically quiet periods are common which should
be caused by a reversed vertically upward drift observed from the ROCSAT-1 measurement.

5. Summary

[22] In this study we have shown, from five stations at subtropical and equatorial areas, the seasonal, local time, and geomagnetic latitude variations of the F3 layer occurrence. The main conclusions are as follows. High occurrence of the sunset F3 layer should be distinguished from the traditional morning-noon F3 layer feature. The occurrence of sunset F3 layers, longitude, which appear mainly at Jicamarca, is clearly dependent on the magnetic latitude as well as longitude. It also has a strong seasonal dependence which occurs mainly during November–February. Unlike the daytime F3 layer, occurrences of the sunset F3 layer clearly increase with increasing solar activity. It is suggested that PRE of a zonal electric field associated with an equatorward wind contributes mostly to the F3 layer formation. Statistical analyses for other areas are needed in future studies to clarify longitude and magnetic latitude dependence of the occurrence probability of the sunset F3 layer.

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Figure 7. Effective neutral wind velocity (equatorward positive) at 500 km altitude at Jicamarca (solid line) and Sao Luis (dashed line).


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