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Study of the F3 and StF4 Layers at Tucumán Near the Southern Crest of the Equatorial Ionization Anomaly in Western South America

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Key Points:

- The first time the seasonal and solar activity variations of F3 and StF4 layers at low-latitude region were reported
- F3 and StF4 layers have a dependence on solar activity
- The solar cycle dependence of StF4 layer at low-latitude region is consistent with the one obtained at equatorial region

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Abstract The present investigation reports for the first time seasonal and solar activity variations of F3 and StF4 layers at the low-latitude station of Tucumán (26.9°S, 65.4°W; dip latitude 13.9°S), Argentina, by considering ionograms recorded from 2007 to 2015 by an Advanced Ionospheric Sounder-Istituto Nazionale di Geofisica e Vulcanologia (AIS-INGV) digital ionosonde. Occurrences of F3 and StF4 layers are found to be higher during summer months, while they are almost nil in winter. Moreover, occurrences of F3 and StF4 layers show a solar activity dependence with higher values during high solar activity. The solar activity dependence of F3 over Tucumán is similar to that reported earlier for the low-latitude station of São José dos Campos, Brazil (dip latitude 14.1°S), but different than that reported for the near-equatorial station of Palmas (dip latitude 6.6°S), Brazil. On the other hand, the solar cycle dependence of StF4 layer is consistent with the one obtained at Palmas. This highlights the complex nature of electrodynamics characterizing the ionosphere from the magnetic equatorial to low latitudes. Moreover, as shown in previous studies, the StF4 layer is always preceded and followed by the F3 layer, and it shows a shorter lifetime than that of the F3 layer. During the considered period, 1812 days were analyzed and the F3 layer was found in 370 days (20.4%), while the StF4 layer was found in 41 days (2.3%). This means that the StF4 stratification is seen during 11% of F3 layer days.

1. Introduction

One of the interesting aspects of the ionospheric electrodynamics day-to-day variability is the multiple stratification that can characterize the ionospheric *F* region. In this sense, Bailey (1948) presented experimental evidences of the *F* layer tendency to present multiple stratifications. Investigating the F2 layer stratification near the magnetic equator at Singapore, Sen (1949) reported a triple F2 layer stratification and named it as F′2, F″2, and F2. For a couple of decades, the study of *F* region multiple stratifications has been focused on the formation of the F3 layer at magnetic equatorial and low-latitude regions (Balan & Bailey, 1995; Balan et al., 1997, 1998, 2000, 2008; Batista et al., 2000, 2002, 2003, 2017; Fagundes et al., 2007, 2011; Jenkins et al., 1997; Karpachev et al., 2012, 2013; Klimenko et al., 2011; Klimenko, Klimenko, & Karpachev, 2012; Klimenko, Zhao, et al., 2012; Lynn et al., 2000; Mridula & Pant, 2015; Paznukhov et al., 2007; Sreeja et al., 2009, 2010; Uemoto et al., 2006, 2011; Zhao et al., 2014). Using satellite observations, Zhao, Wan, Yue, et al. (2011) presented a statistical study of the location of the F3 layer occurrence on a global scale. Zhang et al. (2016) instead, using incoherent scatter radar measurements over Jicamarca (12°S, 283.2°E), presented a study about the equatorial plasma drift enhancement near sunrise, which was named as sunrise enhancement, and they highlighted a possible connection between it and the F3 layer appearance.

Several studies were made to better understand the behavior and physical mechanisms of the F3 layer formation. Among these, Balan et al. (1998) proposed a mechanism based on a joint action of the daytime $\mathbf{E} \times \mathbf{B}$ plasma drift and thermospheric meridional winds. However, it has been reported that F3 layer occurrence characteristics at low latitudes (according to Uemoto et al., 2011; Zhu et al., 2013, when mentioning as low-latitude regions, we mean northern and southern magnetic latitude bands between 7.5° and 25.0°), and near EIA (equatorial ionization anomaly) crests regions (about dip latitude ±17°) (Balan & Bailey, 1996;

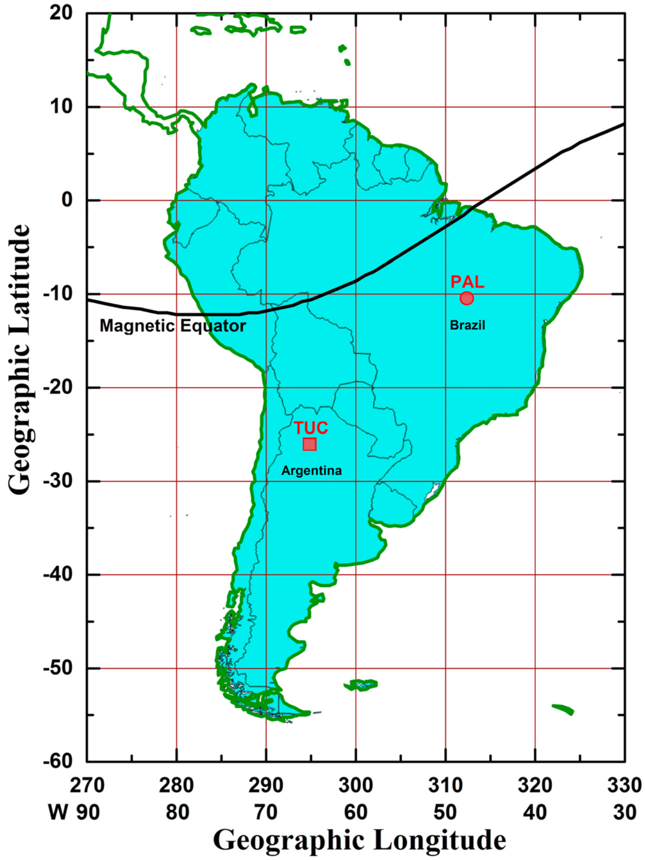

Figure 1. South American map showing the Tucumán (TUC, red square) and Palmas (PAL, red circle) locations. The black curve represents the magnetic equator.

Bittencourt et al., 2007), are different from those recorded at regions around the magnetic equator (Fagundes et al., 2007, 2011; Klimenko et al., 2011; Klimenko, Klimenko, & Karpachev, 2012; Klimenko, Zhao, et al., 2012; Uemoto et al., 2007, 2011; Zhao et al., 2014). In order to account for these differences, other F3 layer triggering factors such as planetary waves, medium-scale traveling ionospheric disturbances (MSTID), and gravity waves (GWs) were proposed, in addition to that by Balan et al. (1998). In this context, Vasil'yev (1967) reported the important role of internal GWs in the formation of the F2 layer stratifications at low latitudes and near EIA crests regions. Fagundes et al. (2007) reported that GWs with vertical wavelengths greater than the vertical extent of the *F* region can create favorable conditions for the F3 layer formation. Klimenko et al. (2011), Klimenko, Klimenko, and Karpachev (2012), and Klimenko, Zhao, et al. (2012) proposed that a nonuniform electric field can generate a nonuniform vertical $\mathbf{E} \times \mathbf{B}$ plasma drift that can give rise to the formation of additional *F* layer stratifications.

Batista et al. (2017) studied the F3 layer characteristics during quiet and disturbed periods, using Digisonde observations from two conjugate Brazilian locations at the north and south of the magnetic equator. They found that the F3 layer occurrence is higher in the Southern Hemisphere (97%) than in the Northern Hemisphere (4%) during December solstice, while it is higher in the Northern Hemisphere (82%) than in the Southern Hemisphere (16%) during June solstice. They have also found that in the equinoctial month of March, the F3 layer occurrence is low in both hemispheres (4% north and 7% south).

Tardelli and Fagundes (2015) observed for the first time an StF4 layer in the American sector during a study focused on the F3 layer occurrence at the near-equatorial ionospheric station of Palmas (10.3°S, 48.3°W; dip latitude 6.6°S), Brazil (according to Uemoto et al., 2011; Zhu et al., 2013, when mentioning as near-equatorial regions, we mean northern and southern magnetic latitude bands between 2.5° and 7.5°). Following that study, Tardelli et al. (2016) investigated the seasonal and solar cycle features of F3 and StF4 layers at Palmas using ionosonde observations recorded from 2002 to 2006 (from high solar activity (HSA) to low solar activity (LSA)). They reported that (a) out of 857 analyzed days, F3 and StF4 layers were found in 542 days (63%) and 78 days (9%), respectively; (b) the F3 layer presents a semiannual variation with a main maximum during local summer and a secondary maximum during local winter; and (c) the StF4 layer occurrence presents an annual variation with a local winter maximum. They further reported that the StF4 layer frequency of occurrence has a dependence on the solar activity.

Since the StF4 layer was initially found near the magnetic equator, it is interesting to investigate whether this fourth stratification of the *F* layer is also a low-latitude feature. The study that will be described in this paper is based on ionograms recorded at Tucumán (26.9°S, 65.4°W; dip latitude 13.9°S), Argentina, close to the southern crest of EIA (Figure 1). Since 2007, several works based on Tucumán ionograms have been done, but this paper represents the first study focused on *F* layer multiple stratifications. Specifically, this paper reports and discusses F3 and StF4 layers occurrences and their seasonal and solar cycle dependence.

2. Data and Method

The study is based on ionograms recorded at Tucumán (TUC) by an Advanced Ionospheric Sounder-Istituto Nazionale di Geofisica e Vulcanologia (AIS-INGV) ionosonde (Pezzopane et al., 2007; Zuccheretti et al., 2003) from 2007 to 2015, a time window going from LSA to HSA (see Figure 5a for corresponding values of the solar flux index $F_{10.7}$). The AIS-INGV ionosonde operates by transmitting radio wave pulses from 1 to 20 MHz with a peak power of 250 W in linear conditions. Pulses have a length of 30 μs, which gives a height resolution of about ±5 km (Arokiasamy et al., 2002; Zuccheretti et al., 2003). TUC ionograms can be downloaded from

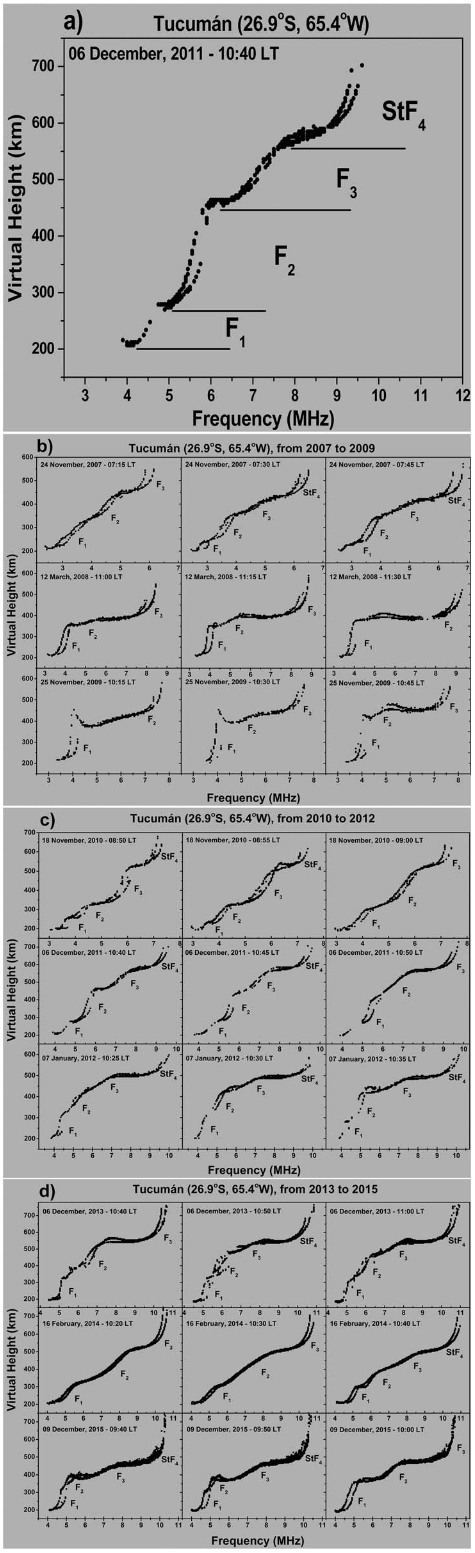

Figure 2. (a) Ionogram showing the *F* layer multiple stratification at Tucumán, with the presence of the F1, F2, F3, and StF4 layers on 6 December 2011 at 10:40 local time (LT). Examples of ionograms showing F3 and StF4 layers recorded at Tucumán in (b) November 2007, March 2008, and November 2009; (c) November 2010, December 2011, and January 2012; and (d) December 2013, February 2014, and December 2015.

the electronic Space Weather upper atmosphere database (http://www.eswua.ingv.it/) (Romano et al., 2008). It is important to mention that, during the considered period, the ionograms were obtained with different sounding repetition rates: 5, 10, or 15 min. Figure 1 shows the location of TUC (low-latitude region) and also that of Palmas (PAL, near-equatorial region), where the StF4 layer was observed in the American sector for the first time (Tardelli & Fagundes, 2015). Besides showing the location of TUC, Figure 1 shows also the location of PAL, because similarities and differences of F3 and StF4 occurrences as recorded at both low-latitude and near-equatorial regions in the South America sector will be discussed. Since the appearance of *F* layer stratifications is mostly a daytime phenomenon (Balan et al., 1998; Batista et al., 2002; Tardelli & Fagundes, 2015; Tardelli et al., 2016), ionograms recorded at TUC from 7 to 17 local time were considered.

During the F3 layer formation, an inflection characterizing the F2 layer takes place, thus dividing it into two new layers; the layer immediately above the F1 layer is named F2, while the highest one is named as F3 layer (Balan et al., 1998). Similarly to the F3 layer formation, the StF4 layer appears between two layers already well established (either between F1 and F2 or F2 and F3); thus, the remaining layers above are renamed with higher classifications than the layers below. Figure 2a clarifies about the F3 and StF4 formation, and Figures 2b–2d report several ionograms characterized by the triple and quadruple stratifications, recorded at TUC from 2007 to 2015.

3. Results

Figures 3a–3c show the day-to-day variability of F3 and StF4 layers occurrences, and the corresponding time duration, for three different years (2008, 2011, and 2014) representative of LSA, medium solar activity (MSA), and HSA. Thick blue bars indicate the occurrence of the F3 layer, thick red bars indicate the presence of the StF4 layer, thin black lines indicate no F3/StF4, and thin white lines indicate lack of data. It can be observed that all StF4 cases are always preceded and followed by the apperance of the F3 layer, with the lifetime of the StF4 layer, varying from 10 to 30 min, by far shorter than that of the F3 layer.

F3 and StF4 layers were studied from 2007 to 2015, and the number of days with data during 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, and 2015 were 117, 269, 279, 247, 208, 213, 47, 315, and 117, respectively. The statistical analysis performed from 2007 to 2015 showed that the days characterized by the percentage of occurrence are obtained from number of days with data and number of days with F3 and StF4. The percentage of occurrence of F3 is given by 15.4% (2007), 10.8% (2008), 5.4% (2009), 18.2% (2010), 22.1% (2011), 15.5% (2012), 85.1% (2013), 30.8% (2014), and 40.2% (2015) and percentage of occurrence of StF4 are 0.9% (2007), 0% (2008), 0% (2009), 2% (2010), 4.3% (2011), 0.5% (2012), 8.5% (2013), 4.1% (2014), and 6.8% (2015). Tables 1 and 2 summarize in detail monthly and annual variabilities of F3 and StF4 layers.

3.1. F3 and StF4 Seasonal Variation

Figures 4a and 4b show monthly occurrence characteristics of the F3 layer as recorded at TUC. Specifically, Figure 4a shows the monthly

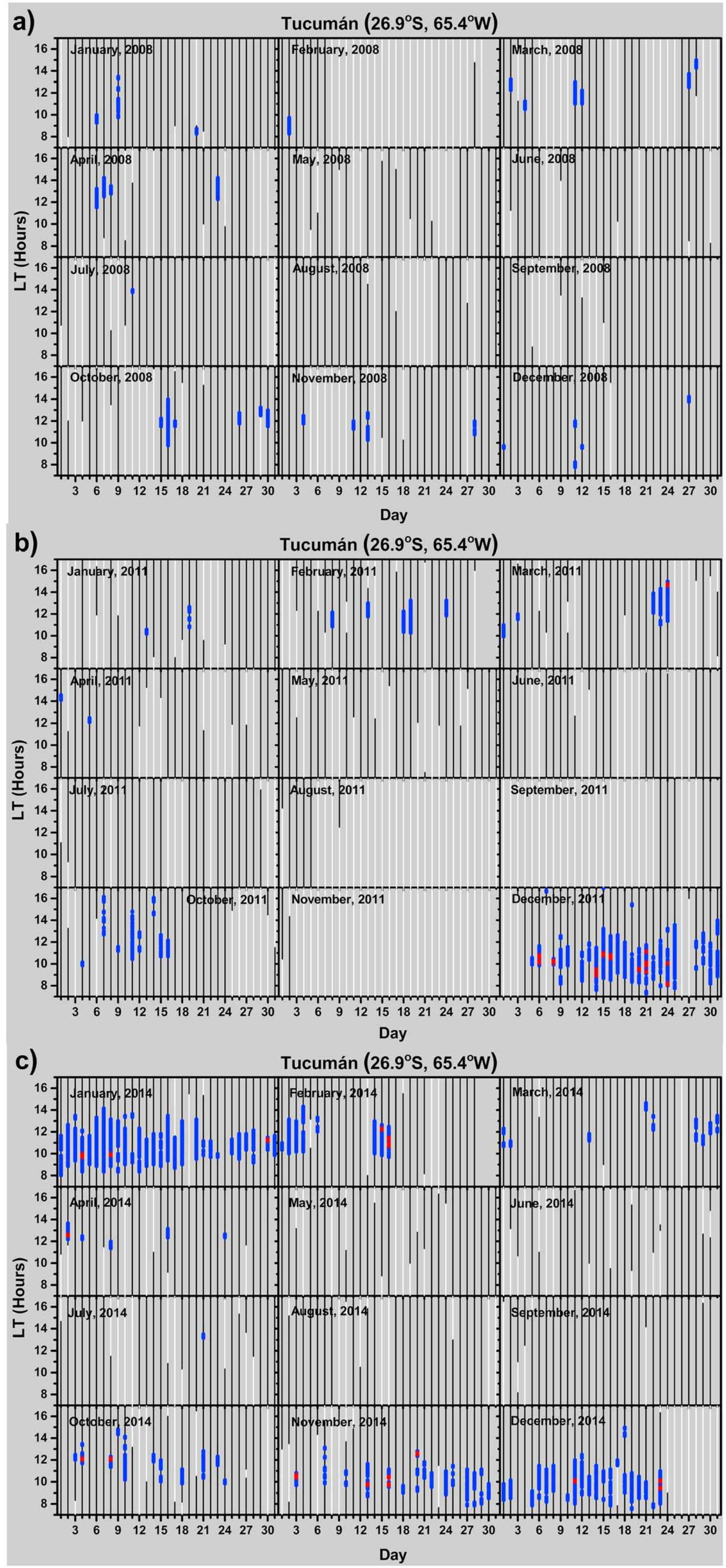

Figure 3. Day-to-day variability of F3 and StF4 layers occurrences for all months of (a) 2008, (b) 2011, and (c) 2014 as representative of period of low solar activity, medium solar activity, and high solar activity, respectively. Blue bars, red bars, thin black lines, and thin white lines indicate the occurrence of the F3 layer, the occurrence of the StF4 layer, no F3/StF4 layers, and no data, respectively. LT = local time.

Table 1
Seasonal Variations of the Monthly F3 and StF4 Layers Occurrence, From 2007 to 2010

			F3 layer occurrence				StF4 layer occurrence			
Year	Month	Number of days with data	Number of days	Duration in hours	Percentage of occurrence	Percentage of annual frequency	Number of days	Duration in hours	Percentage of occurrence	Percentage of annual frequency
2007	August	12	2	0.8	16.7	15.4	0	0	0	0.9
	September	28	2	0.8	7.1		0	0	0	
	October	27	4	7.8	14.8		0	0	0	
	November	28	3	3.8	10.7		1	0.5	3.6	
	December	22	7	7.8	31.8		0	0	0	
	Total	117	18	21	—	—	1	0.5	—	—
2008	January	30	3	3.3	10	10.8	0	0	0	0
	February	8	1	1.5	12.5		0	0	0	
	March	16	6	7	37.5		0	0	0	
	April	23	4	6.3	17.4		0	0	0	
	May	21	0	0	0		0	0	0	
	June	24	0	0	0		0	0	0	
	July	26	1	0.3	3.8		0	0	0	
	August	24	0	0	0		0	0	0	
	September	23	0	0	0		0	0	0	
	October	22	6	8.8	27.3		0	0	0	
	November	22	4	4.3	18.2		0	0	0	
	December	30	4	2	13.3		0	0	0	
	Total	269	29	26.5	—	—	0	0	—	—
2009	January	18	0	0	0	5.4	0	0	0	0
	February	22	0	0	0		0	0	0	
	March	22	2	2.6	9.1		0	0	0	
	April	25	1	0.5	4		0	0	0	
	May	28	0	0	0		0	0	0	
	June	26	0	0	0		0	0	0	
	July	29	0	0	0		0	0	0	
	August	26	0	0	0		0	0	0	
	September	26	0	0	0		0	0	0	
	October	23	4	7	17.4		0	0	0	
	November	16	4	3.3	25		0	0	0	
	December	18	4	1.5	22.2		0	0	0	
	Total	279	15	14.9	—	—	0	0	—	—
2010	January	22	3	2	13.6	18.2	0	0	0	2
	February	18	8	7.3	44.4		0	0	0	
	March	28	12	15	42.9		1	0.3	3.6	
	April	26	2	0.5	7.7		0	0	0	
	May	24	0	0	0		0	0	0	
	June	24	0	0	0		0	0	0	
	July	22	0	0	0		0	0	0	
	August	22	0	0	0		0	0	0	
	September	16	1	0.6	6.3		0	0	0	
	October	13	5	10.2	38.5		0	0	0	
	November	19	12	26.1	63.2		4	0.9	21.1	
	December	13	2	1	15.4		0	0	0	
	Total	247	45	62.7	—	—	5	1.2	—	—

percentage of days for which the F3 layer occurred, while Figure 4b shows the monthly percentage time duration of the F3 layer. Percentages of Figures 4a and 4b are, respectively, calculated by dividing the monthly number of days and the monthly number of hours, with occurrence of the F3 layer and the F3/StF4 layers, by the total monthly number of days and hours with observations. Both analyses show an annual variation of the F3 layer, with a maximum during summertime (November–January) and a minimum during wintertime (June–August).

Table 2
Seasonal Variations of the Monthly F3 and StF4 Layers Occurrence, From 2011 to 2015

			F3 layer occurrence				StF4 layer occurrence			
Year	Month	Number of days with data	Number of days	Duration in hours	Percentage of occurrence	Percentage of annual frequency	Number of days	Duration in hours	Percentage of occurrence	Percentage of annual frequency
2011	January	20	2	1.3	10	22.1	0	0	0	4.3
	February	22	5	8.9	22.7		0	0	0	
	March	24	5	9.8	20.8		1	0.2	4.2	
	April	20	2	0.9	10		0	0	0	
	May	20	0	0	0		0	0	0	
	June	19	0	0	0		0	0	0	
	July	23	0	0	0		0	0	0	
	August	4	0	0	0		0	0	0	
	September	5	0	0	0		0	0	0	
	October	23	8	10.1	34.8		0	0	0	
	November	2	0	0	0		0	0	0	
	December	26	24	54.4	92.3		8	2.5	30.8	
	Total	208	46	85.4	—	—	9	2.7	—	—
2012	January	24	19	46.5	79.2	15.5	1	0.3	4.2	0.5
	February	27	9	10.8	33.3		0	0	0	
	March	20	1	1.6	5		0	0	0	
	April	21	2	0.6	9.5		0	0	0	
	May	22	0	0	0		0	0	0	
	June	21	0	0	0		0	0	0	
	July	21	0	0	0		0	0	0	
	August	26	0	0	0		0	0	0	
	September	23	0	0	0		0	0	0	
	October	8	2	2.6	25		0	0	0	
	Total	213	33	62.1	—	—	1	0.3	—	—
2013	February	1	0	0	0	85.1	0	0	0	8.5
	March	1	0	0	0		0	0	0	
	October	9	6	8.2	66.7		0	0	0	
	November	9	9	14.5	100		1	0.2	11.1	
	December	27	25	47.7	92.6		3	0.8	11.1	
	Total	47	40	70.4	—	—	4	1	—	—
2014	January	30	28	73.7	93.3	30.8	3	0.7	10	4.1
	February	25	8	17.7	32		2	0.7	8	
	March	30	9	6.8	30		0	0	0	
	April	28	5	3.5	17.9		0	0	0	
	May	26	0	0	0		0	0	0	
	June	22	0	0	0		0	0	0	
	July	26	1	0.3	3.8		0	0	0	
	August	25	0	0	0		0	0	0	
	September	27	0	0	0		0	0	0	
	October	28	11	10.7	39.3		2	0.3	7.1	
	November	25	15	19	60		4	1	16	
	December	23	20	35.3	87		2	0.5	8.7	
	Total	315	97	167	—	—	13	3.2	—	—
2015	August	22	0	0	0	40.2	0	0	0	6.8
	September	26	0	0	0		0	0	0	
	October	24	10	16.7	41.7		2	0.7	8.3	
	November	30	22	50.5	73.3		3	0.5	10	
	December	15	15	36	100		3	0.8	20	
	Total	117	47	103.2	—	—	8	2	—	—

Figures 4c and 4d show the same analysis for the StF4 layer. It can be seen from these figures that the StF4 layer is absent during 6 months (from April to September). Both the monthly percentage of days and the monthly percentage time duration show a clear StF4 annual variation, with a maximum during summertime (November–January) and a minimum from April to September, similar to that characterizing the F3 layer.

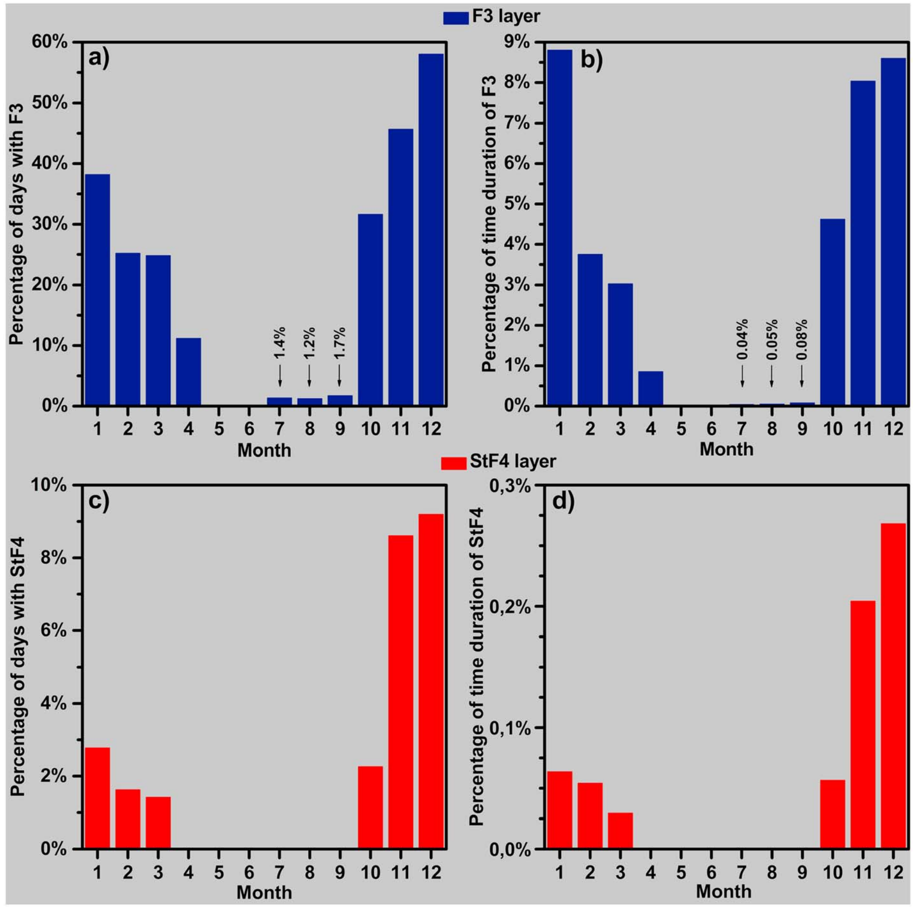

Figure 4. Seasonal characteristics of (a and b) the F3 layer (blue bars) and (c and d) the StF4 layer (red bars). Monthly percentages were calculated using the number of days of each month with occurrence of the F3 layer or the StF4 layer and the total number of days per month with observations, combining data from 2007 to 2015.

3.2. Solar Cycle Dependence of F3 and StF4 Occurrences

Figure 5 presents the occurrence of F3 and StF4 during the whole considered period (2007–2015), characterized by a LSA-MSA-HSA. Variations of the solar flux index $F_{10.7}$ are shown in Figure 5a, while the total number of days with F3 and StF4 layers in each month is highlighted in Figure 5b. Both F3 and StF4 layers show a clear solar cycle dependence with a maximum during HSA and a minimum during LSA. It is worth noting that during the very LSA characterizing years 2008 and 2009 there is no formation of the StF4 layer.

4. Discussion

F3 layer characteristics have been studied during quiet and disturbed periods from the equatorial region (according to Uemoto et al., 2011; Zhu et al., 2013, when talking about the equatorial region, we mean the magnetic latitude band between 2.5°N and 2.5°S) to low latitudes in many sectors (American, Indian, and Chinese). From previous studies, the physical mechanism behind the F3 layer generation at equatorial/near-equatorial regions has been well understood (Balan et al., 1998), which is a joint action of the daytime $\mathbf{E} \times \mathbf{B}$ plasma drift and thermospheric meridional winds. The F2 peak is uplifted by the $\mathbf{E} \times \mathbf{B}$ action to higher altitudes, and the subsequent diffusion along magnetic field lines is prevented if an equatorward neutral wind is present; this gives rise to the formation of the F3 layer, while the F2 layer appears at lower altitudes due to the usual photochemical and dynamical processes. Uemoto et al. (2007, 2011) tried to improve the mechanism proposed by Balan et al. (1998) by including the field-aligned diffusion of plasma. They claimed that the magnetic latitudinal dependence of the F3 layer is caused not only by the merdional neutral wind but also by the field-aligned diffusion. Pavan Chaitanya et al. (2013) highlighted the limitations of the

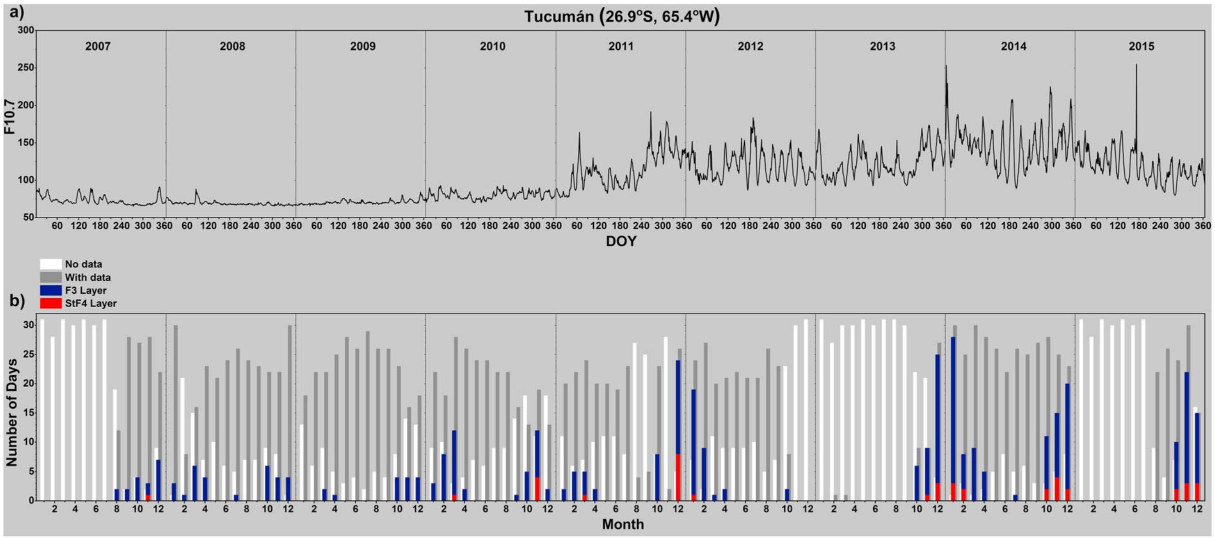

Figure 5. (a) Solar flux index $F_{10.7}$ from 2007 to 2015. (b) Monthly number of days with F3 layer (blue bars), monthly number of days with StF4 layer (red bars), number of days with available data (gray bars), and days with no data (white bars), from 2007 to 2015. DOY = day of year.

available wind models to reproduce the F3 layer observations, underlining the requirement for neutral wind measurements. Using ionosonde observations at Thiruvananthapuram (dip latitude 0.5°N), India, Mridula and Pant (2015) have shown that the coupling between the equatorial thermospheric zonal wind and an enhanced ionospheric density at low altitudes can trigger the F3 layer formation through the ion-drag process. Nevertheless, at low latitudes the F3 layer generation process is still under debate, since many factors as MSTIDs, GWs, and nonuniform electric fields (which means nonuniform vertical $\mathbf{E} \times \mathbf{B}$ plasma drift) can play an important role (Fagundes et al., 2007; Klimenko et al., 2011; Klimenko, Klimenko, & Karpachev, 2012; Klimenko, Zhao, et al., 2012; Nayak et al., 2014). More specifically, the magnetic latitude dependence of *F* layer multiple stratifications is still an open question (Uemoto et al., 2011; Zhu et al., 2013). The purpose of this study is to give an additional contribution to this issue, presenting the F3 and StF4 layers day-to-day, seasonal, and solar cycle variations obtained for the low-latitude station of TUC. Moreover, studies on F3 and StF4 layers as recorded at PAL were pioneering investigations (Tardelli et al., 2016; Tardelli & Fagundes, 2015). Therefore, comparing the F3/StF4 layer day-to-day and seasonal variations, recorded in the South American sector at TUC (low-latitude region) and PAL (near-equatorial region), is of interest to better understand the *F* layer multiple stratification mechanism from equatorial to low latitudes.

Concerning the occurrence percentages, the analysis carried out for Tucumán shows that out of 1,812 analyzed days, the F3 layer is found in 370 days (20.4%), while the StF4 layer is observed in 41 days (2.3%), despite that the observed period of PAL (from 2002 to 2006, near-equatorial region) and TUC (from 2007 to 2015, low latitude) is different. These results suggest that the occurrence percentages at low latitude are lower than at PAL, which are 63% and 9%, respectively (Tardelli et al., 2016). This confirms what was found by Thampi et al. (2007); namely, the highest occurrence of *F* layer multiple stratifications appears at dip latitude ±8° (a few degrees within the EIA) and reinforces the idea that the F3/StF4 formation mechanism at low latitudes may be different than that at equatorial/near-equatorial latitudes, or that the mechanism proposed by Balan et al. (1998) is less efficient at low latitudes, and GWs become more significant as a F3/StF4 formation mechanism (Fagundes et al., 2007). Another possible mechanism that can be suggested is that the winter anomaly was given a latitudinal distribution of ionization at low latitudes, its effect would be more pronounced over TUC than over PAL. However, these hypotheses can only be evaluated using model simulations and hope that this paper motivates the modelers.

From a seasonal point of view, Figures 3–5 show that the F3 layer occurrence at TUC presents an annual variation with a maximum in summer and a minimum in winter. This annual variation was recorded also at other low-latitude stations: São José dos Campos (Brazil; dip latitude 17.6°S), Waltair (India; dip latitude 10.6°N), and

Vanimo (Papua New Guinea; dip latitude 11.2°S) (Fagundes et al., 2011; Rama Rao et al., 2005; Zhu et al., 2013). Notwithstanding, Tardelli et al. (2016) have recently reported that the F3 layer occurrence at the near-equatorial site of PAL presents a semiannual variation, with a main maximum during summertime and a secondary maximum during wintertime. This result confirmed what was previously found at other South American equatorial/near-equatorial stations, Fortaleza (Brazil; dip latitude 4.4°S), São Luis (Brazil; dip latitude 2.0°S), and Jicamarca (Peru; dip latitude 0.2°S) (Balan et al., 1998; Batista et al., 2002; Zhao, Wan, Reinisch, et al., 2011), showing that in the South American sector the F3 layer at equatorial/near-equatorial regions presents a definite semiannual seasonal variation. Balan et al. (1998) attributed the presence of the secondary winter maximum of the F3 layer occurrence to a combination of local high values of the $\mathbf{E} \times \mathbf{B}$ drift with meridional winds less poleward than expected. The confirmation that the appearance of the winter secondary maximum is, however, a local feature mainly depends on the longitudinal structure of the $\mathbf{E} \times \mathbf{B}$ drift intensity (e. g., Yizengaw et al., 2014). However, in other sectors (Asian), for instance, Trivandrum (India; dip latitude 0.5°N) and Chumphon (Thailand; dip latitude 3.2°N) show an annual variation of the F3 layer occurrence (Sreeja et al., 2010; Uemoto et al., 2011).

Taking into account the mechanism proposed by Fagundes et al. (2007) that the presence of GWs in a vertically extended *F* layer can cause the F3-F2 stratification, the F3 layer annual variation at TUC and at Waltair and Vanimo (Rama Rao et al., 2005; Zhu et al., 2013) with a maximum in summer can be ascribed to the fact that in the low-latitude South American sector the GW activity is greater in summer than in other seasons (Fagundes et al., 2011; Klausner et al., 2009). However, F3 layer semiannual variations were found at low-latitude sites in other longitudinal sectors: Sanya (China; dip latitude 12.6°N) and Chiang Mai (Thailand; dip latitude 9.0°N) (Uemoto et al., 2011; Zhu et al., 2013). This means that at low latitudes there are sectors, the ones showing an F3 layer annual variation, for which GWs significantly affect the F3 layer formation, while there are other sectors, the ones showing an F3 layer semiannual variation, for which the GW action is counterbalanced by the mechanism proposed by Balan et al. (1998).

With regard to the StF4 stratification, the results shown in the previous section confirm those of Tardelli and Fagundes (2015) and Tardelli et al. (2016) that the StF4 layer is always preceded and followed by the apperance of an F3 layer, with the corresponding lifetime, ranging from 10 to 30 min, by far shorter than that of the F3 layer. This highlights that (a) the connection between StF4 and F3 layers is strong, at both low and near-equatorial latitudes, independent of the F3 layer triggering mechanism; and (b) the StF4 layer is really a transient phenomenon. The latter is most likely due to the fact that, when the four stratifications are present, at least two of them are very close to each other in altitude (see Figure 2) and it is sufficient that a slight vertical plasma redistribution, caused by either a small variation of the zonal electric field at the base of the plasma uplift (Klimenko et al., 2011; Klimenko, Klimenko, & Karpachev, 2012; Klimenko, Zhao, et al., 2012) or a slight variation of the traveling ionospheric disturbance wavelike oscillation (Tardelli & Fagundes, 2015), to make a layer disappear and come back to a triple stratification.

Figure 5 shows that at TUC the F3 layer has a clear direct dependence on solar activity, the higher the solar activity, the greater the F3 layer occurrence. This confirms the study by Fagundes et al. (2011) for Sao Jose dos Campos, and more generally the fact that at low latitudes the relationship (F3 layer versus solar activity) is direct, while at equatorial/near-equatorial latitudes is usually reversed; that is, the F3 layer occurrence is higher for LSA than for HSA (Balan et al., 1998; Batista et al., 2002; Nayak et al., 2014; Rama Rao et al., 2005; Sreeja et al., 2010). Balan and Bailey (1995) and Balan et al. (1998) justified the reverse proportionality between the F3 layer occurrence and the solar activity at equatorial/near-equatorial latitudes saying that the morning-noon ionosphere becomes broad and intense as the solar activity increases, while the $\mathbf{E} \times \mathbf{B}$ drift and neutral winds remain more or less constant, this making the upward force insufficient to uplift the morning F2 peak to the topside altitudes to form a clear F3 layer. This suggests again that mechanisms behind the F3 layer occurrence at low latitudes and equatorial/near-equatorial latitudes cannot be the same. The direct proportionality between the F3 layer occurrence and the solar activity is an additional evidence that GWs are most likely the main triggering factor of the F3 layer formation at low latitudes. This is because, according to Klausner et al. (2009), the GW occurrence at low latitudes is more for HSA than for LSA.

The same can also be attributed for the StF4 layer occurrence recorded at TUC, which is similar like the F3 layer occurrence showing a direct proportionality with the solar activity. Tardelli and Fagundes (2015), reported for the first time the StF4 stratification in the South American sector, suggested a possible mechanism of formation wavelike oscillations caused by GWs, which is in combination with the $\mathbf{E} \times \mathbf{B}$ vertical drift. The fact that the direct proportionality between the StF4 layer occurrence and the solar activity, unlike what happens for the F3 layer, characterizes both low and near-equatorial latitudes suggests that GWs play a key role to trigger the appearance of the StF4 layer independent of the latitude.

The most striking feature characterizing the results showed in the previous section is, however, the seasonal dependence of the StF4 layer occurrence. In fact, if at TUC the StF4 occurrence presents a maximum in summer as expected, at PAL the StF4 occurrence maximum is instead recorded in winter. This is a really challenging issue to be explained. One can think that at PAL the winter anomaly could play a significant role concerning the StF4 layer formation. The winter anomaly consists of the observation of daytime maximum electron density values lower in summer than in winter. It has been suggested that this anomaly is linked to changes in the neutral composition of the atmosphere, caused by a heating of the summer hemisphere, which gives rise to a convection of lighter neutral elements toward the winter sector, which causes changes in the ratio of [ON_2] in both hemispheres (Johnson, 1964; Rishbeth & Setty, 1961; Torr & Torr, 1973). This anomaly depends significantly on solar activity and at low latitudes tends to disappear for LSA (e.g., Ezquer et al., 2014; Perna et al., 2017). Taking into account the F3 layer formation mechanism proposed by Mridula and Pant (2015), the fact that at PAL the StF4 occurrence presents a maximum for HSA in winter could be ascribed to a joint action of three factors: (1) the GW propagation, (2) an enhanced daytime ionospheric density due to the winter anomaly, and (3) a fast wind jet characteristic of the Earth's dip equator due to thermospheric zonal winds (Liu et al., 2009). Anyhow, this remains an outstanding issue that the authors will surely investigate more deeply as soon as longer time series of ionograms at PAL and TUC are available, but mostly considering different sectors.

With regard to the puzzling multiple *F* layer stratification dependence on the season, magnetic latitude, and solar activity, we want to conclude by highlighting what Karpachev et al. (2013), Klimenko, Klimenko, and Karpachev (2012), and Klimenko, Zhao, et al. (2012) have said that the simultaneous ground-based and satellites observations and comprehensive study based on both the observation and modeling are needed.

5. Conclusions

This investigation presents the daytime seasonal and solar cycle variations of the *F* layer multiple stratification (F3 and StF4), using ionograms recorded by an AIS-INGV ionosonde installed at TUC, Argentina, near the EIA southern crest in the west South American sector. Corresponding results are then compared with those reported earlier by Tardelli et al. (2016) for PAL, Brazil, a near-equatorial station. The main outcomes of the study are as follows:

1. The formation mechanisms of the F3 layer at near-equatorial and low latitudes are different. At near-equatorial latitudes the mechanism proposed by Balan and Bailey (1995) and Balan et al. (1998), based on a joint action of the daytime $\mathbf{E} \times \mathbf{B}$ plasma drift and thermospheric meridional winds, meets pretty well with the observed F3 layer occurrence. At low latitudes instead there are sectors, the ones showing an F3 layer annual variation, for which GWs significantly affect the F3 layer formation, while there are other sectors, the ones showing an F3 layer semiannual variation, for which the GW action is counterbalanced by the mechanism proposed by Balan and Bailey (1995) and Balan et al. (1998).
2. The StF4 layer occurrence recorded at TUC, as well as the one recorded at PAL, presents a direct proportionality with the solar activity, just like the F3 layer occurrence recorded at TUC and more generally at low latitudes. This suggests that the mechanism proposed by Tardelli and Fagundes (2015), that a joint action of wavelike oscillations caused by GWs and the $\mathbf{E} \times \mathbf{B}$ vertical drift, can account for the quadruple stratification independent of the latitude.
3. The StF4 stratification is always preceded and followed by the apperance of an F3 layer, with the corresponding lifetime by far shorter than that of the F3 layer. This underlines on the one hand that the connection between StF4 and F3 layers is strong, at both low and near-equatorial latitudes, independent of the F3 layer triggering mechanism, and on the other hand that the StF4 layer is really a transient phenomenon. The transience of the phenomenon is most likely due to the fact that, when the four stratifications are present, at least two of them are very close to each other in altitude and it is sufficient a slight vertical plasma redistribution, caused by either a small variation of the zonal electric field at the base of the

plasma uplift or a slight variation of the traveling ionospheric disturbance wavelike oscillation, to make a layer disappear and come back to a triple stratification.

4. At TUC the StF4 occurrence presents a maximum in summer, while at PAL unexpectedly the maximum is recorded in winter. The winter maximum recorded at PAL could be ascribed to a joint action of three factors: (1) the GW propagation, (2) an enhanced daytime ionospheric density due to the winter anomaly, and (3) a fast wind jet characteristic of the Earth's dip equator due to thermospheric zonal winds. This remains, however, an outstanding issue that needs additional investigations both at PAL and TUC, but also in different sectors.

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