AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Space Physics

RESEARCH ARTICLE
10.1002/2016JA023580

Key Points:
- A seasonal variation of the quadruple stratification (StF-4) is shown for the first time
- Quadruple stratification (StF-4) has a dependence on solar activity
- There is a strong connection between the F_3 layer and the quadruple stratification (StF-4)

Correspondence to:
A. Tardelli,
tardelli@univap.br

Citation:
Tardelli, A., P. R. Fagundes, M. Pezzopane, K. Venkatesh, and V. G. Pillat (2016), Seasonal and solar activity variations of F_3 layer and quadruple stratification (StF-4) near the equatorial region, *J. Geophys. Res. Space Physics*, *121*, 12,116–12,125, doi:10.1002/2016JA023580.

Received 12 OCT 2016
Accepted 15 NOV 2016
Accepted article online 17 NOV 2016
Published online 20 DEC 2016

Seasonal and solar activity variations of F_3 layer and quadruple stratification (StF-4) near the equatorial region

A. Tardelli[1], P. R. Fagundes[1], M. Pezzopane[2], K. Venkatesh[1], and V. G. Pillat[1]

[1]Instituto de Pesquisas e Desenvolvimento (IP&D), Universidade do Vale do Paraíba (UNIVAP), São José dos Campos, Brazil, [2]Istituto Nazionale di Geofisica e Vulcanologia (INGV), Via di Vigna Murata, Rome, Italy

Abstract The study of multiple stratification of the *F* layer has the initial records in the midtwentieth century. Since then, many studies were focused on F_3 layer. The diurnal, seasonal, and solar activity variations of the F_3 layer characteristics have been investigated by several researchers. Recently, investigations on multiple stratifications of *F* layer received an important boost after the quadruple stratification (StF-4) was observed at Palmas (10.3°S, 48.3°W; dip latitude 6.6°S—near-equatorial region), Brazil. The present study reports the latest findings related with the seasonal and solar activity characteristics of the F_3 layer and StF-4 near the equatorial region during the period from 2002 to 2006. A significant connection between StF-4 and F_3 layer has been noticed, since the StF-4 is always preceded and followed by a F_3 layer appearance. However, the F_3 layer and the StF-4 present different seasonal and solar cycle variations. At a near-equatorial station Palmas, the F_3 layer shows the maximum and minimum occurrences during summer and winter seasons, respectively. On the contrary, the StF-4 presents the maximum and minimum occurrences during winter and summer seasons, respectively. While the F_3 layer occurrence is not affected by solar cycle, the StF-4 appearance is instead more frequent during high solar activity.

1. Introduction

The ionospheric *F* layer shape and electron density peak variations depend on local time, latitude, longitude, season, solar cycle, geomagnetic activity, and electrodynamic conditions. In particular, the equatorial and low-latitude *F* layer may change its shape and peak height in a few minutes due to electric fields induced by propagation of medium-scale traveling ionospheric disturbances (MSTIDs) or thermospheric-ionospheric coupling. This *F* layer electrodynamic feature characterizing the low latitudes is one of the most remarkable ionospheric physic research fields. In addition, the combination of north-south magnetic field with daytime electric fields uplifts the *F* region at equatorial region to higher altitudes. As soon as the ionosphere reaches higher altitudes, the plasma diffuses downward to lower altitudes, and to higher latitudes, through the magnetic field lines, causing the formation of electron density crests around ±15° latitude; this phenomenon is called as the equatorial ionospheric anomaly (EIA) [*Appleton*, 1946]. Also, just after the sunset there is an intensification of $\mathbf{E} \times \mathbf{B}$ drift, which can combine with MSTIDs leading to the generation of large-scale ionospheric irregularities (plasma bubbles) [*Rishbeth*, 1971; *Heelis et al.*, 1974; *Eccles*, 1998; *Fagundes et al.*, 2009].

The study of stratification in ionospheric layers has the initial records in the midtwentieth century by *Appleton* [1927]. *Bailey* [1948] studied the geomagnetic behavior of the F_2 layer and found its tendency to present multiple stratification. *Sen* [1949] investigated the F_2 layer stratification near the magnetic equator at Singapore and reported F_2 layer triple stratification into F'_2, F''_2, and F_2. Later *Balan et al.* [1998] proposed a mechanism to understand the F_3 layer formation. This mechanism shows that the F_3 layer is formed during daytime due to dynamical and photochemical processes. The combination of the equatorial vertical plasma drift $\mathbf{E} \times \mathbf{B}$ and thermospheric meridional winds creates favorable conditions for generation of the F_3 layer [*Fagundes et al.*, 2011]. On the other hand, *Vasiliev* [1967] indicates that the internal gravity waves play an important role in the formation of the equatorial F_2 layer stratifications. In addition, *Fagundes et al.* [2007] found a strong relationship between the formation of the F_3 layer and gravity wave propagation, near the EIA crest during high solar activity period. *Klimenko et al.* [2011, 2012] proposed that a nonuniform in height zonal electric field can generate a nonuniform height vertical $\mathbf{E} \times \mathbf{B}$ plasma drift, and this can be a source of formation of the *F* layer stratification at the geomagnetic equator.

More recently, day-to-day F_3 layer occurrence have been investigated in the Brazilian, Indian, and Chinese sectors under different solar activity and geomagnetic conditions [*Balan et al.*, 1997, 1998, 2000; *Batista et al.*, 2000; *Rama Rao et al.*, 2005; *Fagundes et al.*, 2007, 2011; *Zhu et al.*, 2013]. In the Brazilian equatorial region the occurrence of F_3 layer was found to be higher during the summer and winter solstice months [*Balan et al.*, 2000; *Batista et al.*, 2000]. *Batista et al.* [2002] and *Balan et al.* [1998, 2000] studied the F_3 layer seasonal occurrence characteristics as a function of solar activity and dip latitude at Fortaleza from 1975 to 2000 when the dip latitude changed from $-1.7°$ to $-11°$, respectively. They showed that the F_3 layer has higher occurrence during January (local summer) and August (local winter) than during equinoctial months. They have also reported higher F_3 layer occurrences during low solar activity (LSA) than during high solar activity (HSA). In addition, the F_3 layer occurrence is directly proportional to the proximity of the magnetic equator.

Recently, *Tardelli and Fagundes* [2015] reported for the first time the occurrence of *F* layer quadruple stratification (StF-4) in the American sector. However, this preliminary study showed the StF-4 formation only during winter months (June, July, and August 2002). They reported that the StF-4 is preceded and followed by the F_3 layer and that the StF-4 is always characterized by a lifetime shorter than the one of the F_3 layer. They also showed that the StF-4 occurs when the *F* layer electron density peak reaches its daytime maximum, which combines with a nonuniform vertical $\mathbf{E} \times \mathbf{B}$ plasma drift due to MSTID propagation. This result agrees with the model simulations carried out by *Klimenko et al.* [2011, 2012], who proposed that a nonuniform electric field near the geomagnetic equator can create favorable conditions for the generation of multiple *F* layer stratifications (F_3 and F_4).

The present investigation reports and discusses the seasonal and solar cycle occurrences of ionospheric F_3 layer and StF-4 at Palmas (PAL; 10.3°S, 48.3°W; dip latitude 6.6°S; near-equatorial region), Brazil, covering a period from HSA to LSA.

2. Results and Discussion

The ionosphere at PAL (dip latitude 6.6°S) has been investigated using a Canadian Advanced Digital Ionosonde (CADI) digital ionosonde. The CADI operates transmitting radio wave pulses from 1 to 20 MHz with a power of 600 W. The pulses have a length of 40 μs, which gives a height resolution of ±6 km. The ionograms are obtained with a cadence of 5 min [*Grant et al.*, 1995; *MacDougall et al.*, 1997; *Fagundes et al.*, 2007, 2011].

In this study we used ionosonde observations recorded at PAL from 2002 to 2006 during the declining phase of the solar cycle 23 to investigate the F_3 layer and the StF-4 occurrence. Since the occurrence of *F* layer stratification (F_3 and StF-4) is a typical daytime phenomena we analyzed ionograms from 06:00 LT to 19:00 LT. Also, the StF-4 lifetime varies from 10 to 30 min in most of the cases, which shows that the present observation cadence of 5 min is very important in this kind of investigation.

Tardelli and Fagundes [2015] reported for the first time on the occurrence of StF-4 in the American sector, during the 2002 (winter time). In addition, they showed that the F_3 *layer is observed always before and after the occurrence of the StF-4*. However, the day-to-day and seasonal occurrence characteristics of F_3 layer and StF-4 were not addressed in that first investigation. In the present investigation, out of 857 analyzed days, 542 days (63%) are found to be characterized by the occurrence of the F_3 layer and 78 days (9%) are found to be characterized by the occurrence of StF-4. It is confirmed that the StF-4 is always preceded and followed by the F_3 layer, as it was found by *Tardelli and Fagundes* [2015]. Among the days with occurrence of F_3 layer only 14% of days there were observed with simultaneous occurrences of F_3 layer and StF-4 (for more details, see Table 1).

In order to highlight the simultaneous occurrences of F_3 layer and StF-4 along the studied period, it is shown in Figure 1 a set of ionograms displaying one case per year, where the F_3 layer and the StF-4 appear simultaneously. When the ionograms present a triple stratification the layers are named F_1, F_2, and F_3, and when the ionograms present a quadruple stratification the layers are named F_1, F_2, F_3, and StF-4 (for more details, see Figure 1).

Figure 2 shows the day-to-day F_3 layer and StF-4 occurrence for each day of the year from 2002 to 2006. The blue bars indicate the F_3 layer, the thick red bars indicate the StF-4, the thin black lines indicate no F_3/StF-4

Table 1. Seasonal Variations of the Monthly F_3 Layer and StF-4 Occurrence, During the Period From 2002 to 2006

			F_3 Layer Occurrence				StF-4 Occurrence			
Year	Month	Number of Days with Data	Number of Days	Number of Hours	Percent of Occurrence	Percent of Annual Frequency	Number of Days	Number of Hours	Percent of Occurrence	Percent of Annual Frequency
2002	April	17	1	0.42	5.9	65	0	0	0	25.3
	May	22	17	11.59	77.3		3	0.42	13.6	
	June	23	20	34	87		13	2.42	56.5	
	July	28	25	56.33	89.3		11	3.08	39.3	
	August	22	17	21.92	77.3		5	1.42	22.7	
	September	26	22	26.92	84.6		9	1.75	34.6	
	October	28	6	2.41	21.4		1	0.08	3.6	
2003	June	10	7	8.83	70	67.1	3	0.75	30	15
	July	31	21	23.75	67.7		8	1.50	25.8	
	August	10	10	22.83	100		5	2.08	50	
	September	28	20	20	71.4		2	0.33	7.1	
	October	27	10	6.33	37		1	0.08	3.7	
	November	30	17	14.75	56.7		2	0.17	6.7	
	December	31	27	52	87.1		4	0.75	12.9	
2004	January	31	26	69.17	83.9	58.1	1	0.5	3.2	0.7
	February	29	28	64.58	96.5		0	0	0	
	March	31	18	15.92	58.1		0	0	0	
	April	30	6	5.33	20		0	0	0	
	May	15	1	0.58	6.7		0	0	0	
2005	April	2	1	0.83	50	49	0	0	0	1.5
	May	28	13	10.42	46.4		1	0.42	3.6	
	June	25	3	1.84	12		1	0.17	4	
	July	25	14	13.59	56		1	0.17	4	
	August	29	9	9.17	31		0	0	0	
	September	17	4	2.58	23.5		0	0	0	
	October	24	11	22.17	45.8		0	0	0	
	November	30	23	49.83	76.7		0	0	0	
	December	28	24	115.92	85.7		0	0	0	
2006	January	15	14	57.41	93.3	71.2	1	0.08	6.7	3.8
	April	3	2	4.66	66.7		1	0.33	33.3	
	May	26	10	13.92	38.5		1	0.17	3.8	
	June	21	11	20.5	52.4		1	0.17	4.8	
	July	25	16	23.17	64		0	0	0	
	August	24	12	19.08	50		0	0	0	
	September	7	4	3.91	57.1		1	0.08	14.3	
	October	15	15	48.58	100		0	0	0	
	November	21	21	76.75	100		0	0	0	
	December	27	26	105.5	96.3		2	0.33	7.4	

stratification, and the thin white lines indicate no data. In addition, Table 1 shows more details about monthly and annual variabilities of F_3 layer and StF-4. Specifically, Figures 2a–2e show the F_3 layer and StF-4 day-to-day variability for 2002 (166 days analyzed), 2003 (167 days analyzed), 2004 (136 days analyzed), 2005 (208 days analyzed), and 2006 (184 days analyzed), respectively. The analysis showed that during 2002, 2003, 2004, 2005, and 2006 the numbers of days with F_3 layer are 108 (65%), 112 (67%), 79 (58%), 102 (49%), and 131 (71%) and the numbers of days with F_3/StF-4 are 42 (25%), *25* (15%), 1 (1%), 3 (2%), and 7 (4%), respectively. Also, it is seen from Figure 2 that all cases of StF-4 are always preceded and followed by the F_3 layer. This result reinforces the connection between StF-4 and F_3 layer as proposed by *Tardelli and*

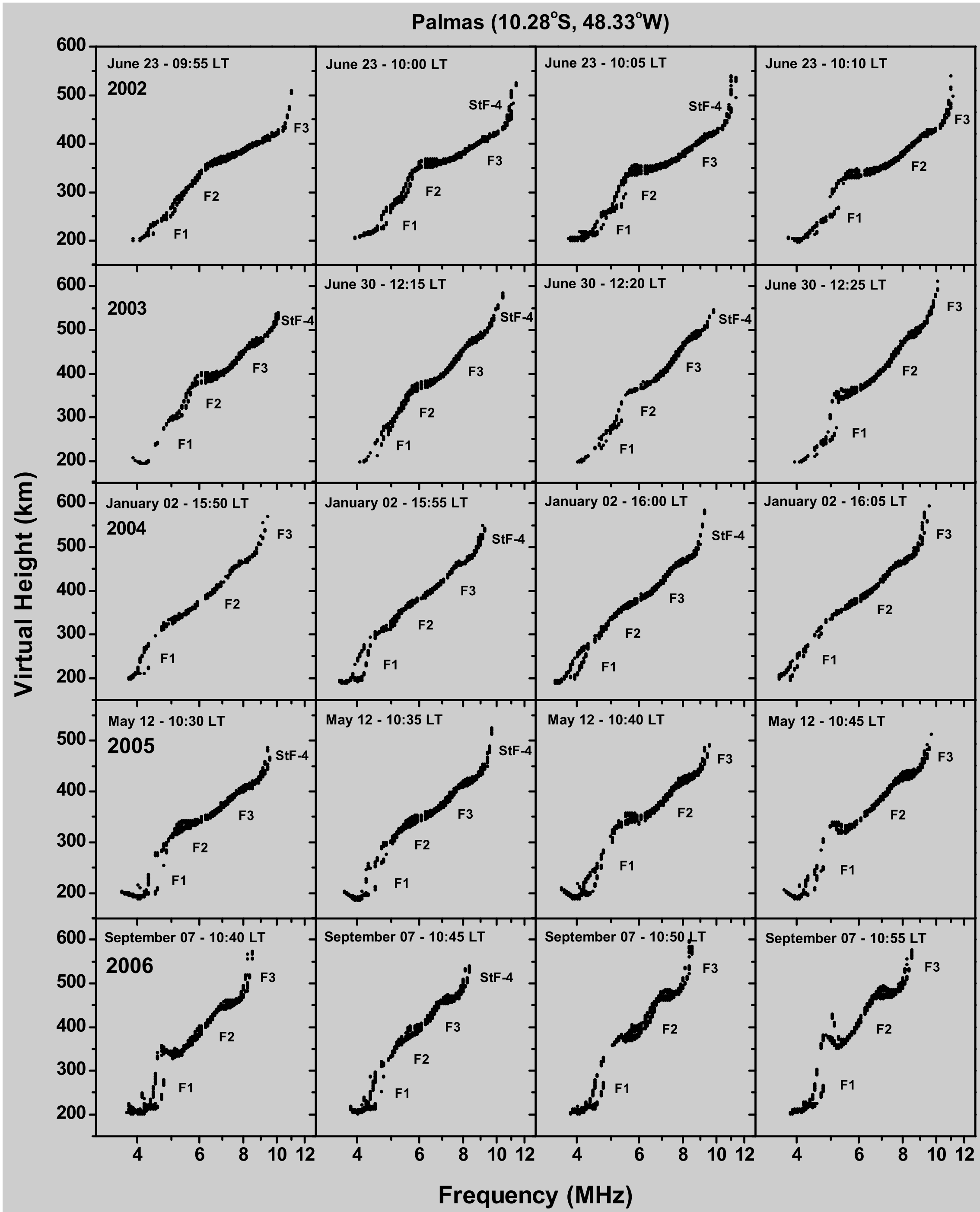


Figure 1. Set of ionograms obtained at PAL (10.3°S, dip latitude 6.6°S) in June 2002, June 2003, January 2004, May 2005, and September 2006. The ionograms show the formation of the F_3 layer and the StF-4.

Fagundes [2015]. An insight into the Figure 2 reveals that not only the occurrence of F_3 layer and StF-4 but also the duration of F_3 layer and StF-4 present a seasonal dependence.

In order to study the seasonal variations of the F_3 layer and the StF-4 all the available data from 2002 to 2006 are combined in Figure 3. The percentages are calculated by dividing the monthly number of days (Figures 3a and 3c) and the monthly number of hours (Figures 3b and 3d), with occurrence of the F_3 layer and the F_3/StF-4, respectively, by the total number of days and hours of the month with observations.

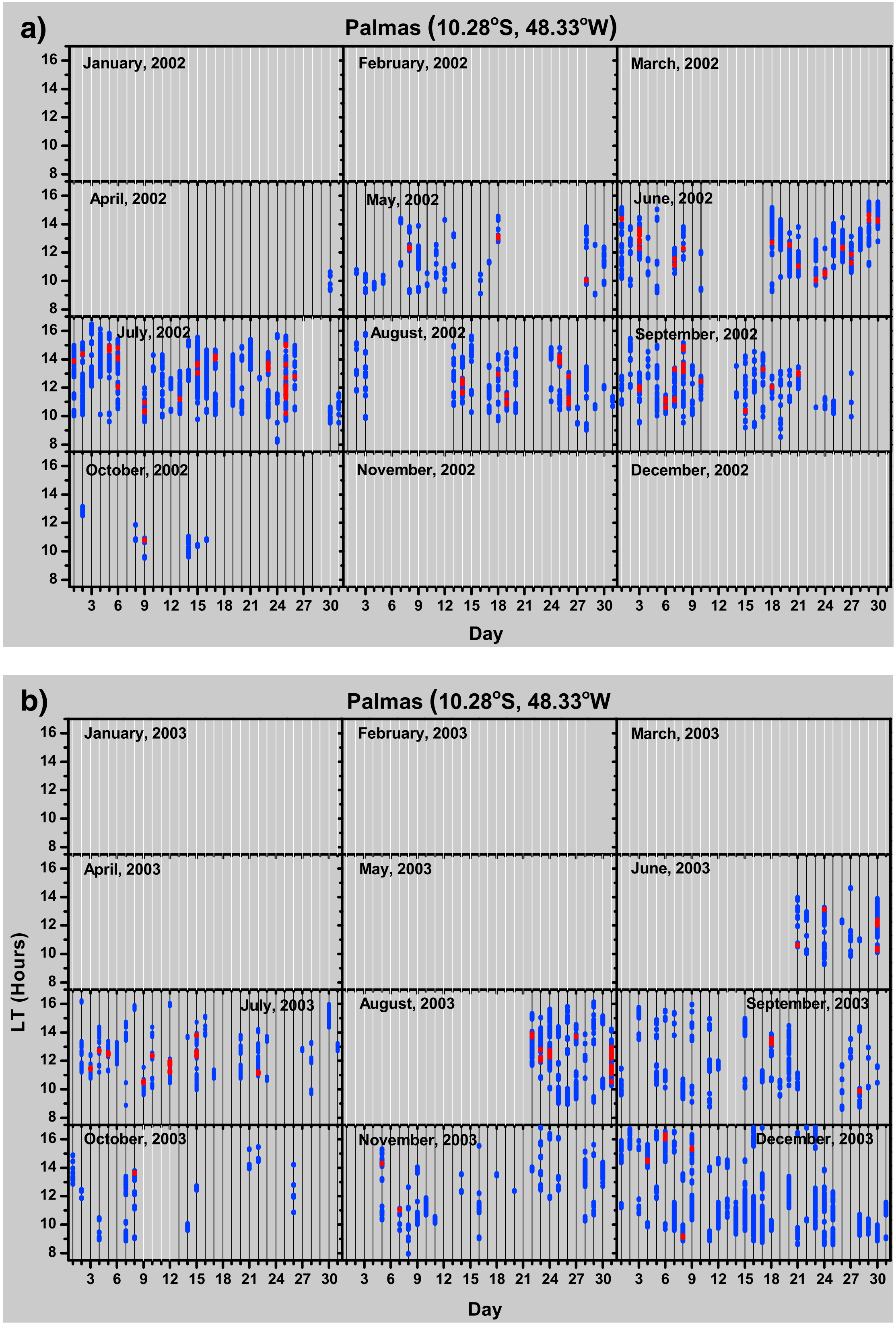
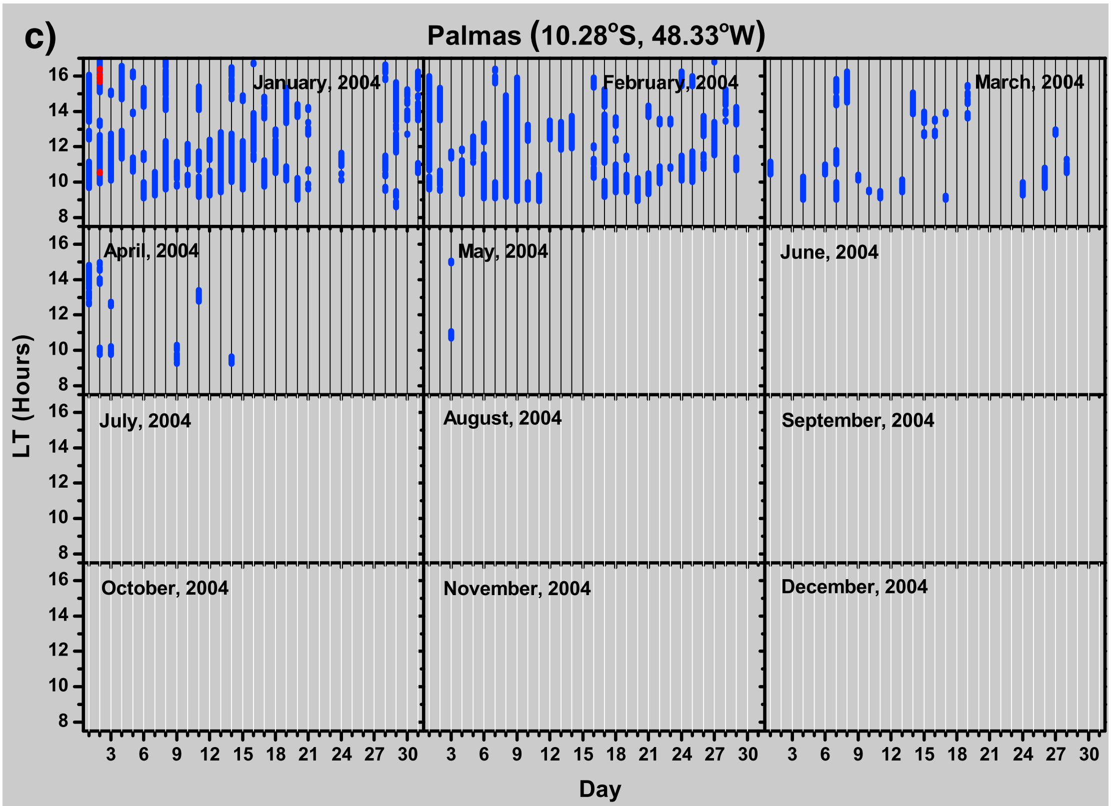


Figure 2. Day-to-day history of the F_3 layer and the StF-4 occurrences for each month from 2002 to 2006: (a) 2002, (b) 2003, (c) 2004, (d) 2005, and (e) 2006. The blue bars, red bars, thin black lines, and thin white lines indicate the occurrence of F_3 layer, the occurrence of StF-4, no F_3/StF-4 stratification, and no data, respectively.



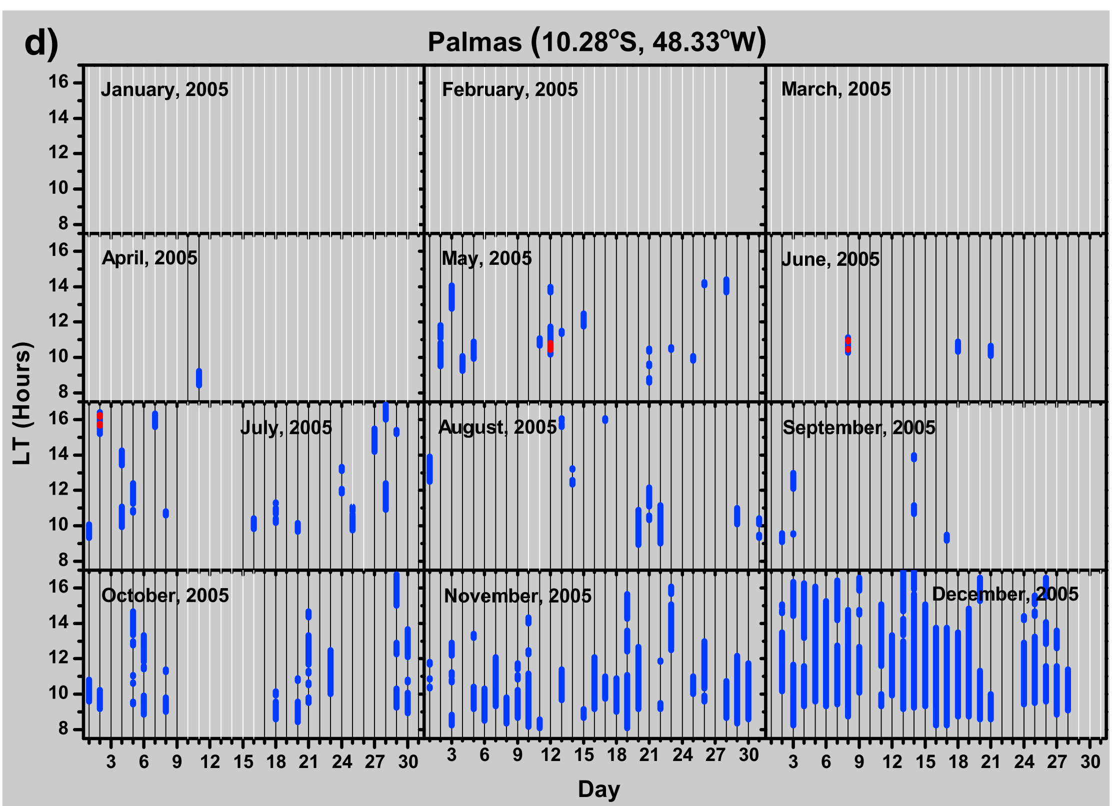


Figure 2. (continued)

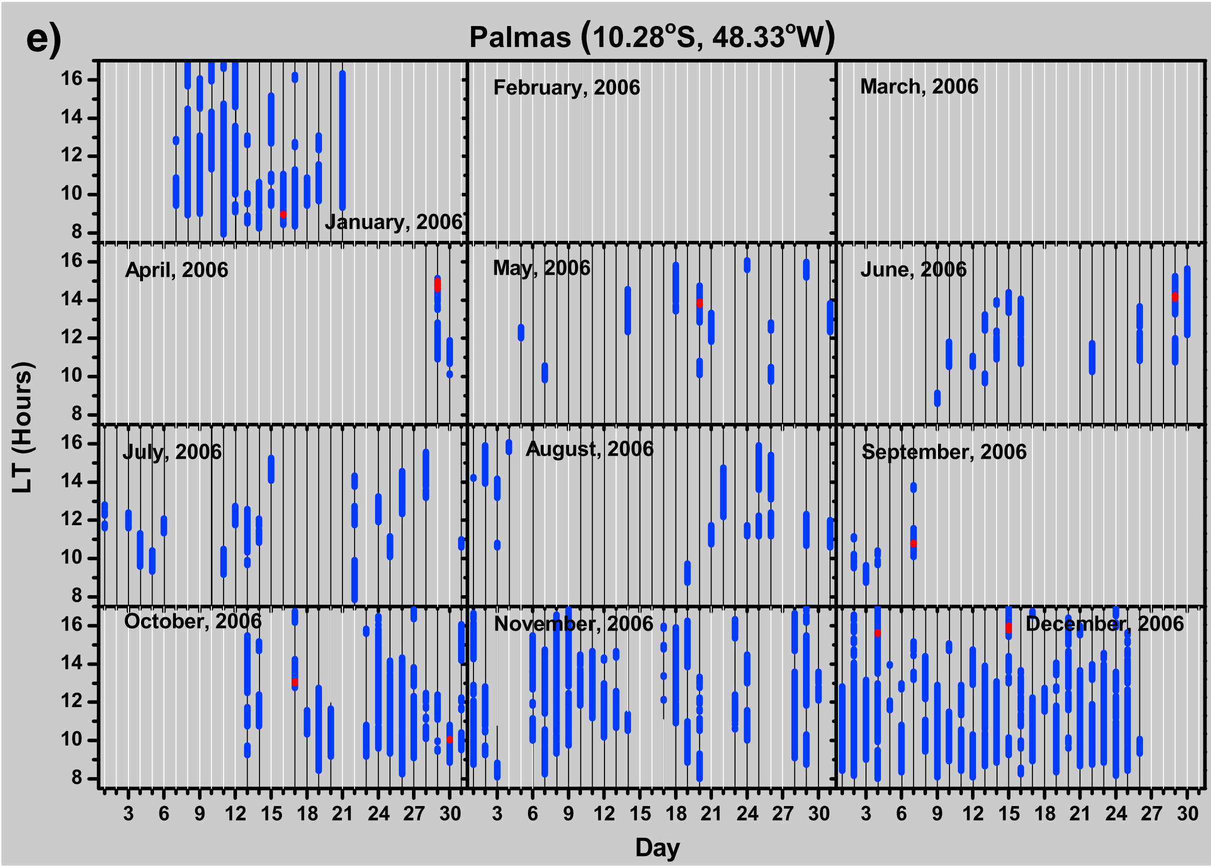


Figure 2. (continued)

Figures 3a and 3b show the monthly percentages of days with F_3 layer and monthly percentage of time duration with F_3 layer, respectively. These figures show that the F_3 layer is present during all months of the year and has a semiannual variation, more evident in the time duration plot (Figure 3b), with maxima during summer and winter time. These results agree with previous investigations carried out at Fortaleza (4°S, 38°W) by *Balan et al*. [1998, 2000] and *Batista et al*. [2000]. The monthly number of days characterized by the presence of the F_3 layer presents a summertime maximum in February, while the monthly number of hours characterized by the presence of the F_3 layer presents a summertime maximum in December. Both occurrences present a secondary wintertime maximum in July.

Figures 3c and 3d show the monthly percentages of days with StF-4 and monthly percentage of time duration with StF-4, respectively. These figures show that there are 2 months (February and March) without StF-4, and they show a clear annual variation with a wintertime maximum in June.

Figure 4 shows the solar flux $F_{10.7}$ index, during the declining phase of the solar cycle 23, from 2002 (HSA) to 2006 (LSA) along with the total number of days with StF-4 and F_3 layer per month. Even though there are several months without available data, it is possible to notice that the occurrence of the F_3 layer does not show a clear dependency on solar cycle. The analysis here described does not support that made by *Batista et al*. [2002], who investigated the formation of the F_3 layer near the equatorial region as a function of solar cycle and reported higher occurrences during LSA than during HSA. Anyhow, focusing on wintertime, Figure 4 shows an occurrence of the F_3 layer higher during HSA than during LSA.

On the other hand, at low latitude *Zhu et al*. [2013] showed that in the China sector the F_3 layer has a higher occurrence during medium solar activity than during LSA, and *Fagundes et al*. [2011] presented a study showing that in the Brazilian sector the occurrence of the F_3 layer during HSA is 11 times higher than that during LSA. *Rama Rao et al*. [2005] reported a complete absence of F_3 layer at an anomaly crest location, Ahmedabad, in the Indian sector.

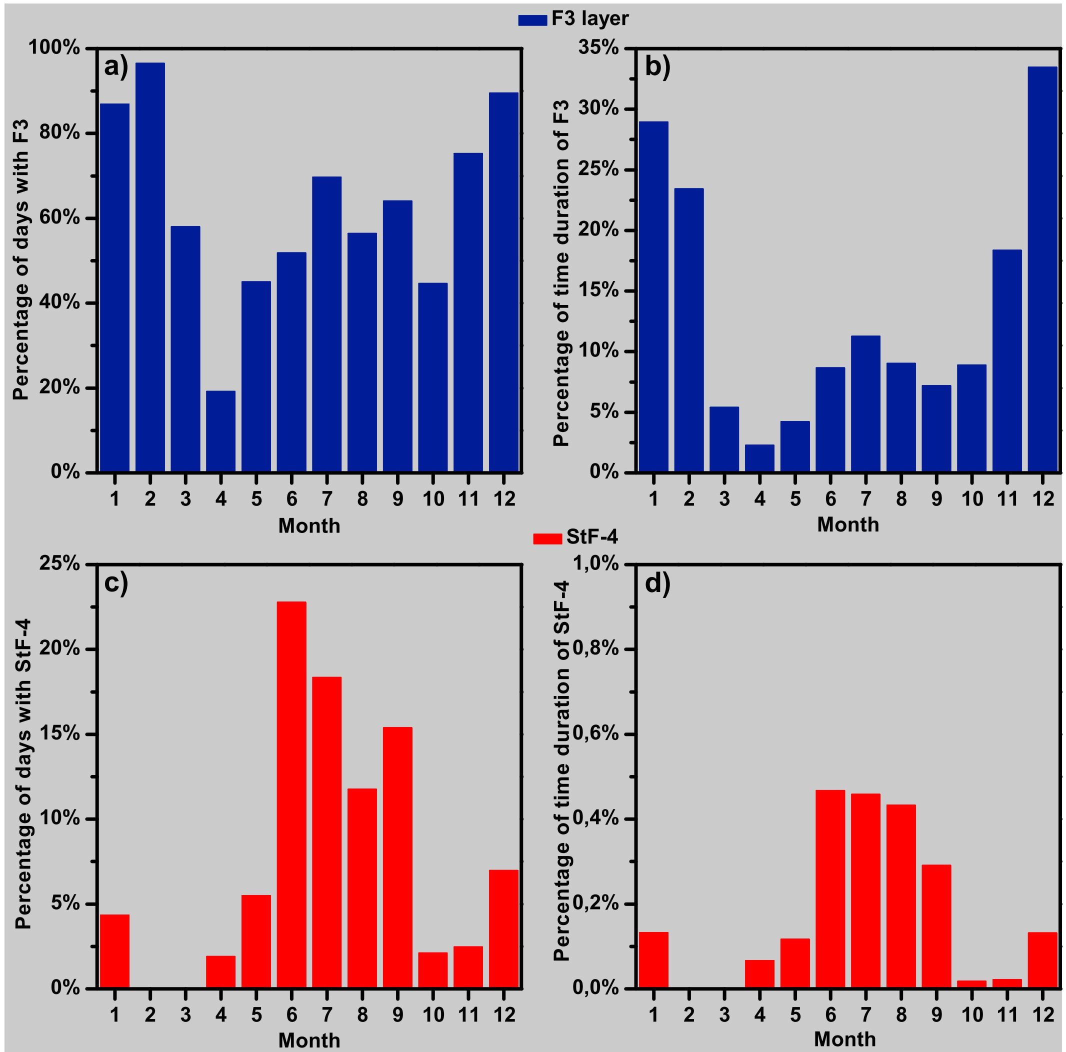


Figure 3. The seasonal characteristics of the (a and b) F_3 layer (blue bars) and the (c and d) F_3/StF-4 (red bars). The monthly percentages were calculated using the number of days with occurrence of the F_3 layer or F_3/StF-4 and the total number of days per month with observations, combining data from 2002 to 2006.

Concerning StF-4, Figure 4 shows that the corresponding occurrence has a clear solar cycle dependence with a maximum during HSA. Since StF-4 and F_3 layer have a strong relationship, it is important to highlight that both of them present a high occurrence during wintertime. Probably, the wintertime absolute maximum of occurrence of StF-4 and the wintertime secondary maximum of occurrence of the F_3 layer are in such way connected. However, to clarify the connection between the F_3 layer and the StF-4 it is needed to analyze more observations from different sectors along with model simulations which are of vital interest for further investigations.

3. Conclusion

In this study, we present ionospheric *F* layer observations during daytime, using a Canadian Advanced Digital Ionosonde (CADI) ionosonde at a near-equatorial station, PAL (10.2°S, 48.2°W; dip latitude 6.6°S), in the Brazilian sector. The main purpose of this paper is to investigate the day-to-day, seasonal, and solar cycle characteristics of the F_3 layer and the StF-4 occurrence. The salient results are summarized below:

1. Out of 857 analyzed days, the F_3 layer is found for 542 days (63%), while the StF-4 is observed for 78 days (9%);

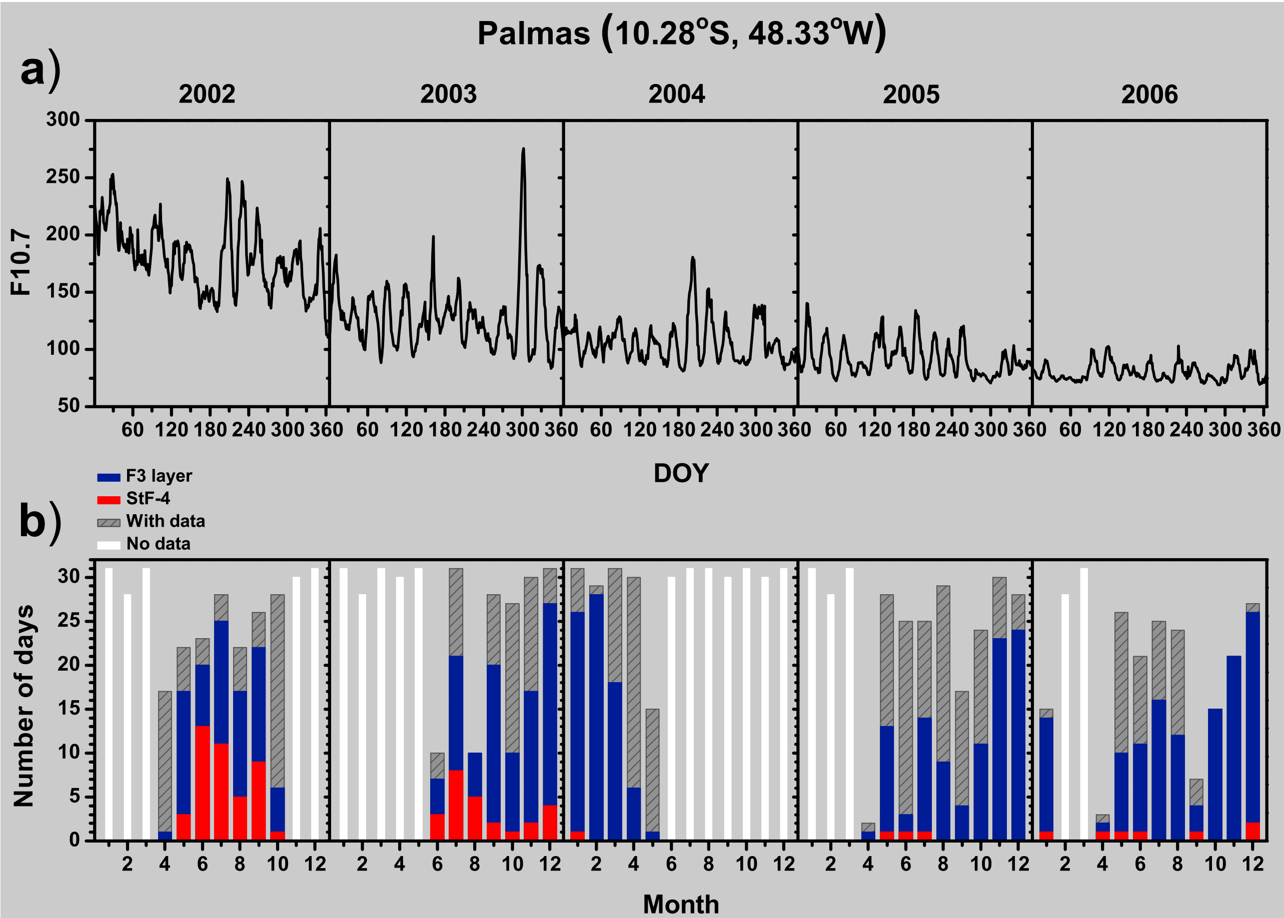


Figure 4. (a) $F_{10.7}$ index from 2002 (HSA) to 2006 (LSA). (b) Monthly number of days with StF-4 (red bars), the monthly number of days with F_3 layer (blue bars), number of days with available data (grey bars), and days with no data (white bars), from 2002 to 2006.

2. The F_3 layer is present during all months of the year and has a semiannual variation with a main maximum during summertime and a secondary maximum during wintertime. This seasonal dependence is noticed considering both the number of days and the number of hours per month;
3. The StF-4 is present all the year, except during February and March. Also, StF-4 occurrence presents an annual variation with a wintertime maximum;
4. All 78 StF-4-recorded events that were observed from 2002 to 2006 have a lifetime shorter than that of the F_3 layer, and StF-4 is always preceded and followed by the F_3 layer, showing a strong connection between the two stratifications;
5. The StF-4 occurrence presents a dependence on solar activity higher during HSA than during LSA.

Acknowledgments
We wish to express our sincere thanks to the Fundação de Amparo a Pesquisa do Estado de Sao Paulo for providing financial support through processes 2015/24791-2, 2012/08445-9, and 2013/17380-0 and to CNPq (grant 302927/2013-1) and FINEP (grant 01.100661-00) for their partial financial support. Data of ionosonde that used in this article are from the Universidade do Vale do Paraiba, Brazil (fagundes@univap.br).

References

Appleton, E. V. (1927), The existence of more than one ionised layer in the upper atmosphere, *Nature*, *120*, 330, doi:10.1038/120330a0.
Appleton, E. V. (1946), Two anomalies in the ionosphere, *Nature*, *157*, 691, doi:10.1038/157691a0.
Bailey, D. K. (1948), The geomagnetic nature of the F_2-layer longitude effect, *Terr. Magn. Atmos. Electr.*, *53*(1), 35–39, doi:10.1029/TE053i001p00035.
Balan, N., G. J. Bailey, M. A. Abdu, K. I. Oyama, P. G. Richards, J. Macdougall, and I. S. Batista (1997), Equatorial plasma fountain and its effects over three locations: Evidence for an additional layer, the F_3 layer, *J. Geophys. Res.*, *102*(A2), 2047–2056, doi:10.1029/95JA02639.
Balan, N., I. S. Batista, M. A. Abdu, J. Macdougall, and G. J. Bailey (1998), Physical mechanism and statistics of occurrence of an additional layer in the equatorial ionosphere, *J. Geophys. Res.*, *103*, 29,169–29,181, doi:10.1029/98JA02823.
Balan, N., I. S. Batista, M. A. Abdu, G. J. Bailey, S. Watanabe, J. MacDougall, and J. H. A. Sobral (2000), Variability of an additional layer in the equatorial ionosphere over Fortaleza, *J. Geophys. Res.*, *105*, 10,603–10,613, doi:10.1029/1999JA000020.
Batista, I. S., N. Balan, M. A. Abdu, J. MacDougall, and P. F. Barbosa Neto (2000), F_3 layer observations at low and equatorial latitudes in Brazil, *Geofis. Int.*, *39*(1), 57–64.

Batista, I. S., M. A. Abdu, J. MacDougall, and J. R. Souza (2002), Long term trends in the frequency of occurrence of the F_3 layer over Fortaleza, Brazil, *J. Atmos. Sol. Terr. Phys.*, *64*, 1409–1412, doi:10.1016/S1364-6826(02)00104-9.

Eccles, J. V. (1998), Modeling investigation of the evening prereversal enhancement of the zonal electric field in the equatorial ionosphere, *J. Geophys. Res.*, *103*, 26, 709–26,719, doi:10.1029/98JA02656.

Fagundes, P. R., V. Klausner, Y. Sahai, V. G. Pillat, F. Becker-Guedes, F. C. P. Bertoni, M. J. A. Bolzan, and J. R. Abalde (2007), Observations of daytime F_2-layer stratification under the southern crest of the equatorial ionization anomaly region, *J. Geophys. Res.*, *112*, A04302, doi:10.1029/2006JA011888.

Fagundes, P. R., J. R. Abalde, J. A. Bittencourt, Y. Sahai, R. G. Francisco, V. G. Pillat, and W. L. C. Lima (2009), *F* layer postsunset height rise due to electric field prereversal enhancement: 2. Traveling planetary wave ionospheric disturbances and their role on the generation of equatorial spread *F*, *J. Geophys. Res.*, *114*, A12322, doi:10.1029/2009JA014482.

Fagundes, P. R., V. Klausner, J. A. Bittencourt, Y. Sahai, and J. R. Abalde (2011), Seasonal and solar cycle dependence of F_3-layer near the southern crest of the equatorial ionospheric anomaly, *Adv. Space Res.*, *48*(3), 472–477, doi:10.1016/j.asr.2011.04.003.

Grant, I. F., J. W. MacDougall, J. M. Ruohoniemi, W. A. Bristow, G. J. Sofko, J. A. Koehler, D. Danskin, and D. Andre (1995), Comparison of plasma flow velocities determined by the ionosonde Doppler drift technique, SuperDARN radars, and patch motion, *Radio Sci.*, *30*, 1537–1549, doi:10.1029/95RS00831.

Heelis, R. A., P. C. Kendall, R. J. Moffet, D. W. Windle, and H. Rishbeth (1974), Electrical coupling of the *E*- and *F*-region and its effects on the *F*-region drifts and winds, *Planet. Space Sci.*, *22*, 743–756, doi:10.1016/0032-0633(74)90144-5.

Klimenko, M. V., V. V. Klimenko, K. G. Rastovsky, L. P. Goncharenko, Y. Sahai, P. R. Fagundes, R. de Jesus, A. J. de Abreu, and A. M. Vesnin (2011), Numerical modeling of ionospheric effects in the middle- and low-latitude *F* region during geomagnetic storm sequence of 9–14 September 2005, *Radio Sci.*, *46*, RS0D03, doi:10.1029/2010RS004590.

Klimenko, M. V., B. Zhao, A. T. Karpachev, and V. V. Klimenko (2012), Stratification of the low-latitude and near-equatorial F_2 layer, topside ionization ledge, and F_3 layer: What we know about this? A review, *Int. J. Geophys.*, 938057, doi:10.1155/2012/938057.

MacDougall, J. W., G. E. Halland, and K. Havashi (1997), *F*-region gravity waves in the central polar cap, *J. Geophys. Res.*, *102*(A7), 14,513–14,530, doi:10.1029/97JA01076.

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

Rishbeth, H. (1971), Polarization fields produced by winds in the equatorial *F* region, *Planet. Space Sci.*, *19*, 357–369, doi:10.1016/0032-0633(71)90098-5.

Sen, H. Y. (1949), Stratification of the F_2-layer of the ionosphere over Singapore, *J. Geophys. Res.*, *54*(4), 363–366, doi:10.1029/JZ054i004p00363.

Tardelli, A., and P. R. Fagundes (2015), Observations of ionospheric *F* layer quadruple stratification near equatorial region, *J. Geophys. Res. Space Physics*, *120*, 834–840, doi:10.1002/2014JA020653.

Vasiliev, K. N. (1967), Geomagnetic effect in the vertical movements of ionization in the ionosphere *F* region [Russian], *Geomagn. Aeron.*, *7*(3), 469–474.

Zhu, Z., K. Chen, J. Lan, and F. Sun (2013), F_3 layer feature under low and medium solar activity observed at a Chinese low latitude station Fuke, *Adv. Space Res.*, *53*(3), 383–390, doi:10.1016/j.asr.2013.03.031.