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Longitudinal variations of the occurrence of F3 and F4 layers within the southern EIA and their dependence on solar cycle

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Abstract

This investigation presents for the first time the seasonal and solar cycle variations of the daytime F-layer multiple stratifications (F3 and F4 layers) near the southern crest of the EIA in two different longitudinal sectors of South America. To perform the study, the ionograms recorded from 2007 to 2015 at Sao José dos Campos (23.2°S, 45.9°W), Brazil (eastern sector), and at Tucumán (26.9°S, 65.4°W), Argentina (western sector), are considered. Both sites present a frequency of occurrence of the F3 and F4 layers which is directly proportional to the solar activity, and an annual variation with a maximum in spring/summer and a minimum in autumn/winter. The main result that came out from the analysis is that the frequency of occurrence of the F3 and F4 layers is higher in the western sector than in the eastern sector, and this could be attributed to a different gravity waves activity characterizing the two longitudinal sectors.

1. Introduction

The investigations related to F-layer additional stratifications began in the mid 20′s (Appleton, 1927). Bailey (1948) studied the daytime F region and observed that the F2 layer split into two layers (F1 and F2), sometimes with the appearance of multiple stratifications. Also Sen (1949) noticed that the F layer, near the magnetic equator, could split into two (F1 and F2) or more layers (F1, F’2, F’’2, and F2).

After these early investigations, the study of the F-layer stratification has been the subject of intense research, especially in recent decades. However, its day-to-day variation as a function of latitude, longitude, season, and solar cycle, during quiet and disturbed geomagnetic activity, is still a subject of intense research and has attracted the attention of many researchers. This interest is mainly due to the generation process at the base of the phenomenon, that is closely related to both the ionospheric electrodynamics and the ionosphere-thermosphere coupling characterizing the low-latitude and equatorial regions (Balan et al.,1998; Fagundes et al., 2007; Klimenko et al., 2011, 2012a, 2012b; Nayak et al., 2014; Balan et al., 2018; Jiang et al., 2019; Mridula and Pant, 2018; Mridula et al., 2019; Tardelli et al., 2018; Venkatesh et al., 2019).

In this sense, Balan et al. (1998) proposed a mechanism to explain the F3-layer formation in the near-equatorial region. This mechanism takes into account the combination of the F-region vertical plasma drift $\mathbf{E} \times \mathbf{B}$ (where $\mathbf{E}$ is the equatorial zonal electric field and $\mathbf{B}$ the geomagnetic field) and the meridional winds blowing from the summer to the winter hemisphere. This joint action acts in a way to upward the F2 layer in height and thus create favorable conditions for the F3-layer generation during daytime. On the other hand, Uemoto et al. (2011) suggested that in the magnetic low-latitude regions, besides the neutral winds

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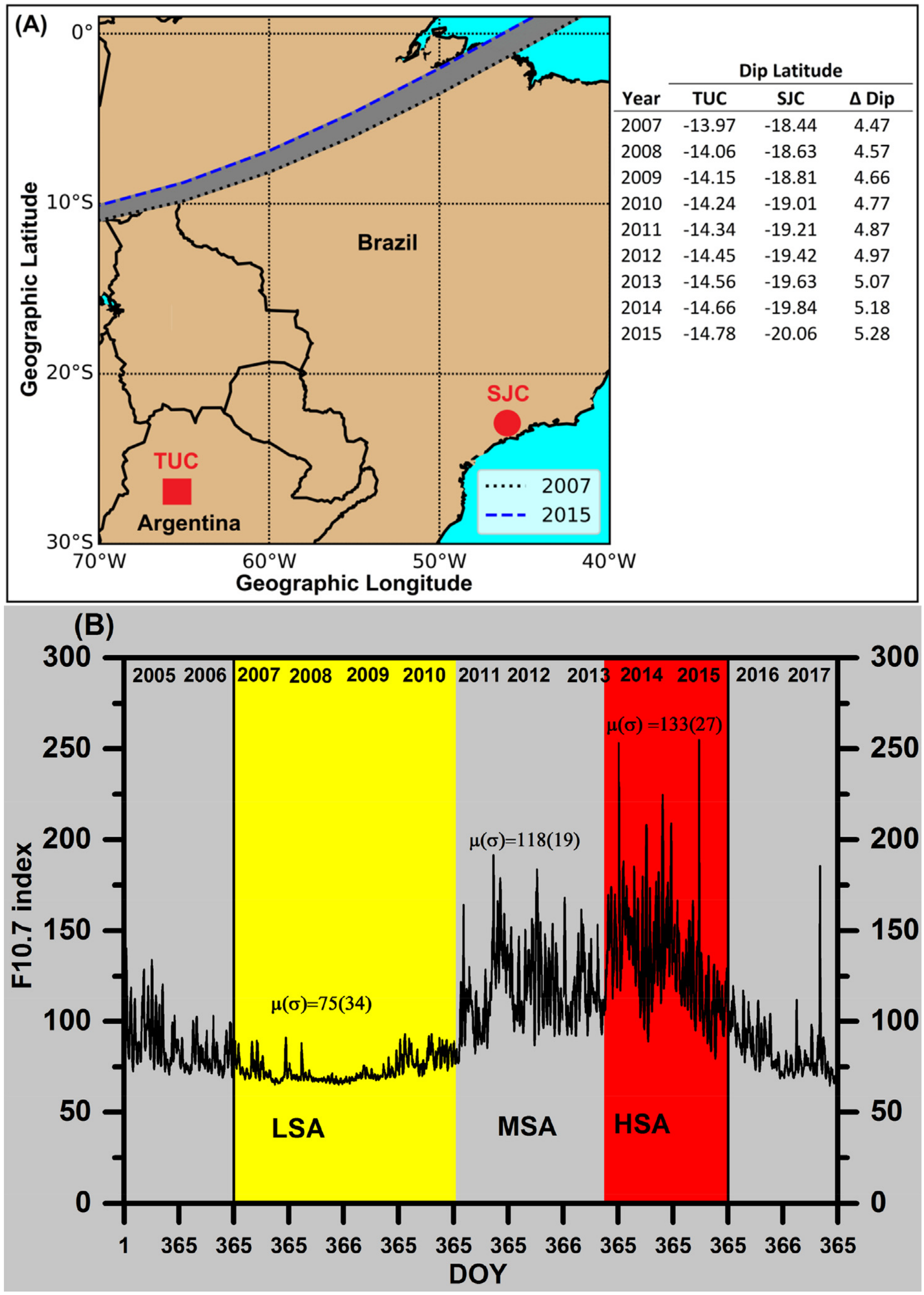

Fig. 1. (A) South American map showing the SJC (red circle) and TUC (red square) locations. The gray band represents the geomagnetic equator changes during the studied period. In the right side is presented the average annual values of the dip latitude for SJC and TUC sites, and the corresponding difference. (B) F10.7 solar flux index variation for the studied period. μ and σ represent respectively the average and the standard deviation of F10.7 for the LSA, MSA and HSA periods. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

proposed by Balan et al. (1998), also the field-aligned diffusion effects can play a role in the F3-layer formation.

Further, Rama Rao et al. (2005) and Fagundes et al. (2007, 2011) investigated the F3-layer occurrence near the equatorial ionization anomaly (EIA) crest in the Indian and Brazilian sectors, respectively. Their research has shown that there is no F3-layer formation near the EIA crest in the Indian sector, while instead in the Brazilian sector the F3 layer appears often, especially during high solar activity (HSA). There are strong evidences that medium-scale traveling ionospheric disturbances (MSTIDs) at low latitudes in the Brazilian sector are responsible for the generation of the F3 layer (Fagundes et al., 2007). In addition, Vasil'yev (1967) reported that gravity waves (GWs) have an important role in the formation of the F2-layer stratifications at low latitudes and near the EIA crest regions.

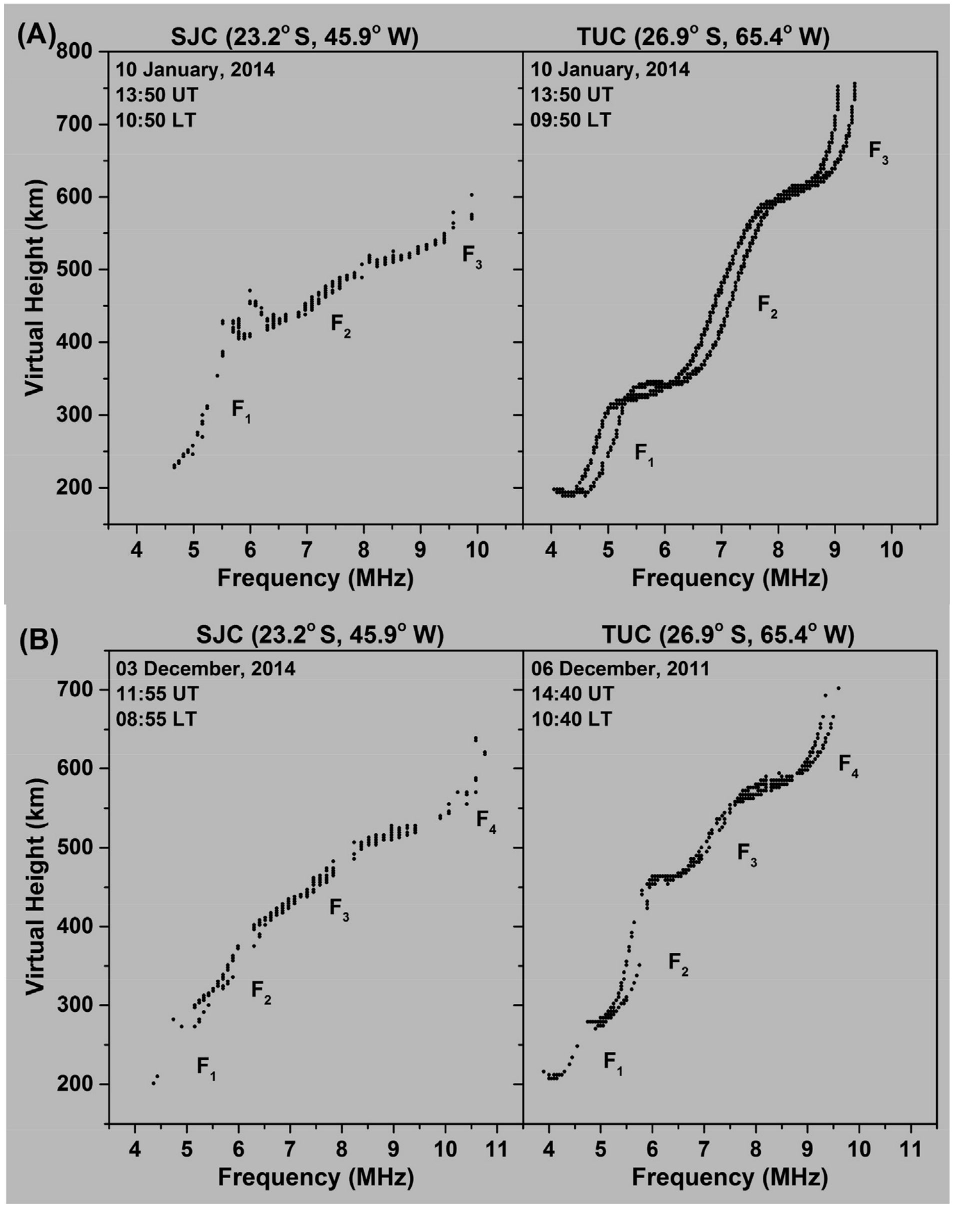

Fig. 2. (A) Ionograms showing the F1, F2, and F3 layers recorded at SJC (left panel) and at TUC (right panel), both recorded on 10 January 2013 at 13:50 UT. (B) Ionograms showing the F1, F2, F3, and StF4 layers recorded at SJC (left panel) on 03 December 2014 at 11:55 UT, and at TUC (right panel) on 06 December 2011 at 14:40 UT.

From the literature on the matter, it is evident that the F3-layer generation process is a subject still under debate, because many factors as MSTIDs, GWs and non-uniform electric fields can contribute (Fagundes et al., 2007; Klimenko et al., 2011, 2012a, 2012b, 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 F3-layer and the quadruple stratification/StF4 (hereafter F4) layer occurrence studies show that the region between the magnetic equator and the crests of the EIA is the one presenting the highest F3-layer and F4-layer occurrence (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, 2012a, 2012b; Lynn et al., 2000; Mridula & Pant, 2015; Paznukhov et al., 2007; Sreeja et al., 2009, 2010; Tardelli and Fagundes 2015; Tardelli et al., 2016, 2018; Uemoto et al., 2006, 2011; Zhao et al., 2014).

Tardelli and Fagundes (2015) reported the first observation of an F4 layer in the American sector, during the winter of 2002. The observational study was carried out near the magnetic equator (Palmas; 10.3°S; 48.3°W, hereafter PAL). In addition to this study, Tardelli et al. (2016, 2018) investigated the seasonal and solar cycle characteristics of the F3 and F4 layers at Palmas (Brazil) and Tucuman (Argentine).

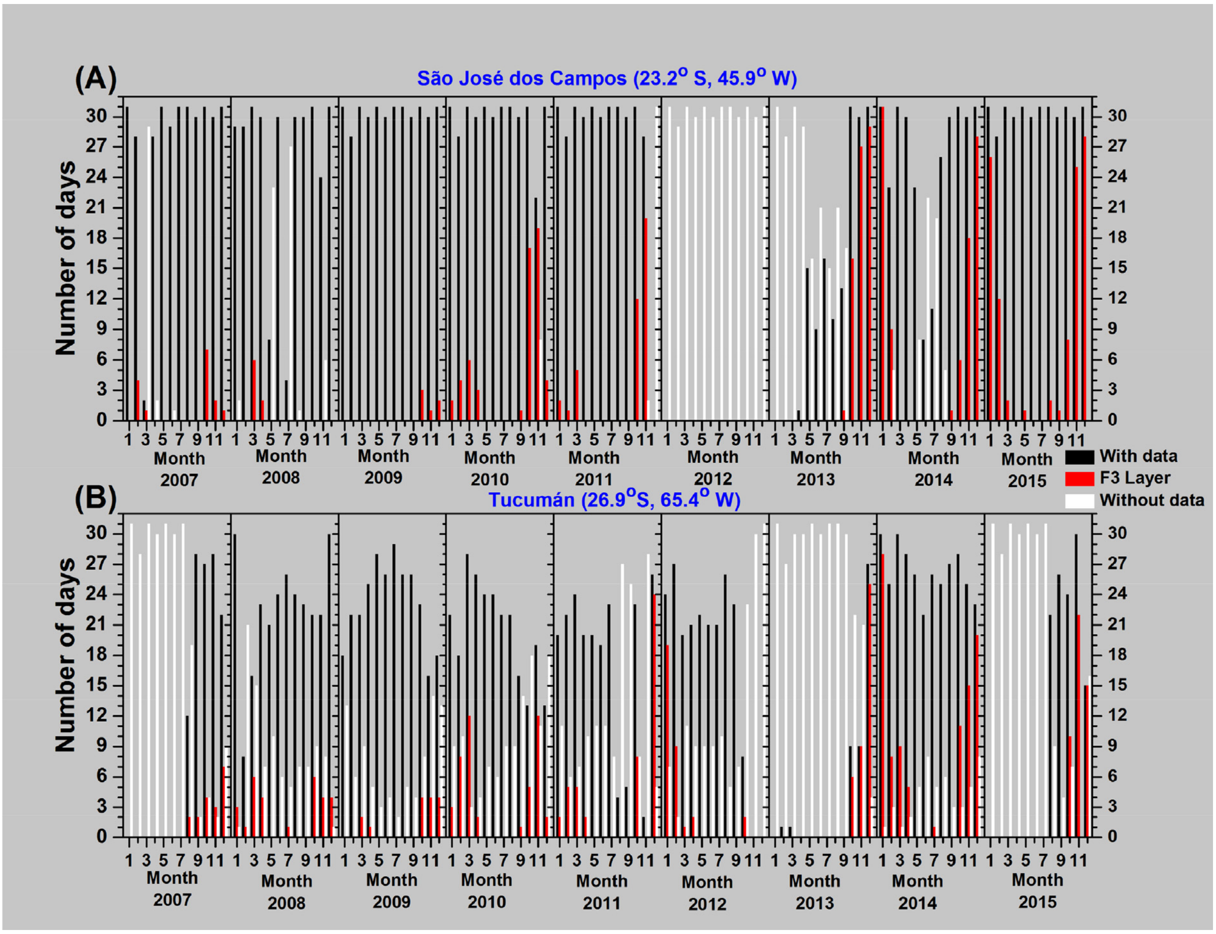

Fig. 3. (A) Monthly number of days showing an F3 layer (red bars), with available data (black bars), and without data (white bars), from 2007 to 2015 at SJC. (B) The same as (A) but for TUC. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

An important question that has not yet been answered is whether there is any similarity or difference characterizing the seasonal or day-to-day variation of the occurrence of F3 and F4 layers as a function of the solar cycle, when comparing locations at different longitudes near the EIA crest region. To try to answer this question, ionograms recorded in South America, specifically in the eastern sector at São José dos Campos (SJC, 23.2° S, 45.9° W; hereafter SJC), Brazil, and in the western sector at Tucumán (26.9° S, 65.4° W; hereafter TUC), Argentine, will be used to study the day-to-day and seasonal variations in the frequency of occurrence of F3 and F4 layers as a function of the solar cycle.

2. Data and methodology

This investigation was carried out using data recorded by a Canadian Advanced Digital Ionosonde (CADI) operating at SJC (Brazilian sector) and an Advanced Ionospheric Sounder-Istituto Nazionale di Geofisica e Vulcanologia (AIS-INGV) ionosonde operating at TUC (Argentine sector).

The CADI ionosonde operates transmitting radio wave pulses at a vertical incidence from 1 to 20 MHz with a power of 600 W and covers heights from 90 to 1000 km. The pulse has a length of 40 µs, which provides a height resolution of ± 6 km (Grant et al., 1995; MacDougall et al., 1997). Furthermore, the CADI ionosonde works in two different sounding modes: in the first mode, it operates every 300 s (5 min) giving a high spectral resolution; in the second mode, it operates every 100 s at six fixed frequencies (3, 4, 5, 6, 7, and 8 MHz) making available a high time resolution (Fagundes et al., 2007). The AIS-INGV ionosonde operates transmitting radio wave pulses from 1 to 20 MHz with a peak power of 250 W. Pulses have a length of 30 µs, which gives a height resolution of about ± 5 km (Arokiasamy et al., 2002; Zuccheretti et al., 2003; Pezzopane et al., 2007).

The main objective of this investigation is to study in the South American sector the F3- and F4-layer frequency of occurrence in two different longitudinal sectors of the EIA crest as a function of the solar cycle. The data periods studied for both SJC and TUC are: from January 2007 to January 2011 (low solar activity – LSA: the corresponding

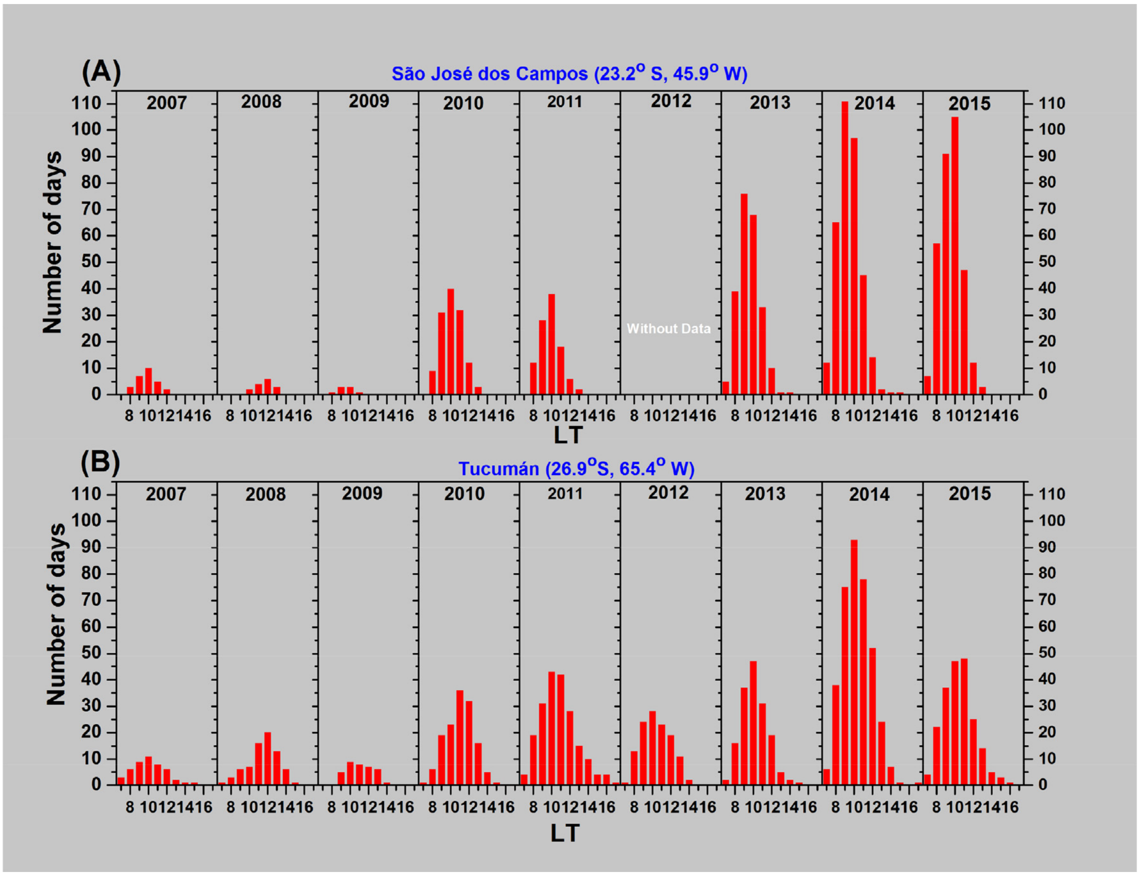

Fig. 4. (A) Yearly number of days showing an F3 layer (red bars) as a function of Local Time (between 7:00 and 17:00 LT) from 2007 to 2015 at SJC. (B) The same as (A) but for TUC. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

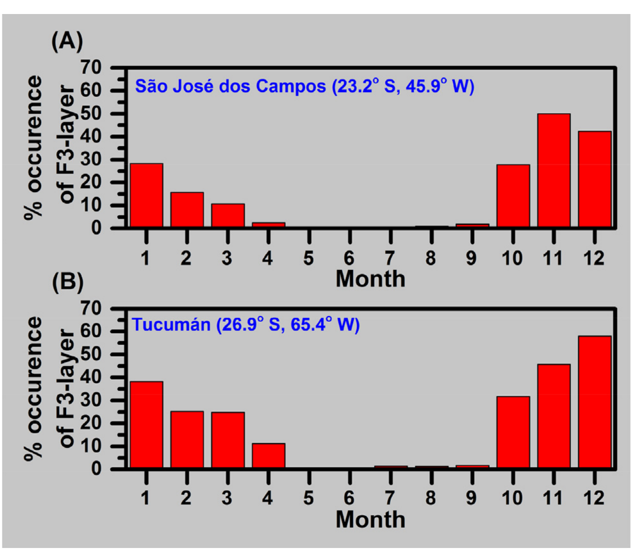

Fig. 5. (A) F3-layer seasonal variations at SJC, joining data from 2007 to 2015. (B) the same as (A) but for TUC.

value of the solar index F10.7 is $\mu\pm\sigma = 75 \pm 34$, where μ is the average and σ the standard deviation); from February 2011 to November 2013 (medium solar activity – MSA: F10.7 $\mu\pm\sigma = 118 \pm 19$); from December 2013 to December 2015 (*moderately high solar activity* – HSA: F10.7 $\mu\pm\sigma = 133 \pm 27$). *It is worth highlighting that solar cycle 24 has a maximum value of F10.7 which is by far lower than those of previous solar cycles.*

Since the occurrence of F-layer stratifications is a typical daytime phenomenon, only ionograms recorded between 07:00 LT and 17:00 LT were used in this investigation. (Balan et al., 1998; Batista et al., 2002; Tardelli and Fagundes, 2015; Tardelli et al., 2016, 2018). During the considered periods, the CADI ionograms at SJC were obtained with a sounding repetition rate of 5 min, while the AIS-INGV ionograms at TUC were obtained with different sounding repetition rates: 5, 10, or 15 min.

Fig. 1A shows the map of South America where the SJC and TUC sites are highlighted by a circle and a square, respectively. Since the dip-latitude changes over time in both sites, during the solar cycle, its average annual values for SJC and TUC and the corresponding annual difference (Δ dip) are shown on the right side of Fig. 1A.

It is worth noting that the geomagnetic equator is moving northward in the American sector and the dip-latitude of both stations has changed along the time with different speed, which makes our study more interesting and complex. This means that the position of the stations has changed within the EIA crest over the years, with both stations

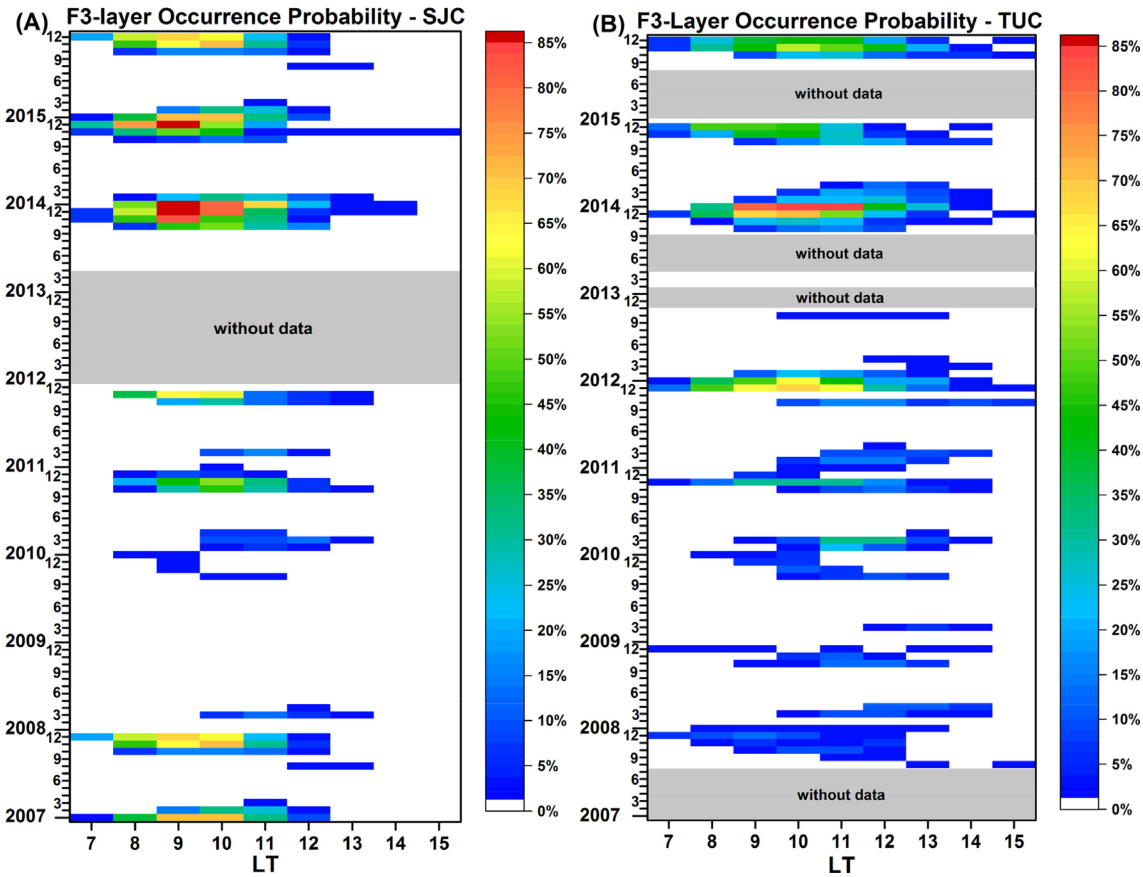

Fig. 6. (A) Monthly F3-layer occurrence probability as a function of LT (7:00 to 15:00 LT) from 2007 to 2015 observed at SJC. (B) The same as (A) but for TUC.

moving to the edge of the EIA crest. Fig. 1B shows the F10.7 solar flux variation from 2005 to 2017. The present study covers the period from 2007 (LSA) to 2015 (HSA).

Fig. 2(A) and (B) show the formation of multiple stratifications of the F region recorded at SJC and TUC. Fig. 2 (A) shows an example of the formation of layers F1, F2 and F3 occurred simultaneously at SJC and TUC on 10 January 2014 at 13:50 UT. Fig. 2(B) instead shows an example of the F-layer quadruple stratification (F1, F2, F3, and F4), for both SJC and TUC. In this case the ionograms are not simultaneous.

3. Results and discussion

The number of available days from 2007 to 2015 with ionosonde data, to investigate the presence of F3 and F4 layers, is 2520 and 1812 for SJC and TUC, respectively.

3.1. F3-layer solar cycle and seasonal variations

Fig. 3 shows the monthly number of days for which the F3 layer occurred from 2007 to 2015 (red bars) for both SJC and TUC. The black and white bars indicate the number of days with and without data per month. The analyzed period includes time windows of LSA, MSA and HSA (see Fig. 1B). The F3 layer shows a higher frequency of occurrence for HSA than LSA in both sites.

This result agrees with Fagundes et al. (2011), who showed that in the Brazilian sector, near the EIA crest, the F3-layer occurrence is higher during HSA than during LSA.

Considering the whole dataset of 9 years of observations, the number of days showing an F3 layer at SJC is 396, and taking into account that the total number of available days is 2520, the percentage of appearance is 15,71%. At TUC the number of days showing an F3 layer is 370 and, considering the available number of days (1812), the percentage of appearance is 20,42%. So, the F3-layer frequency of occurrence is higher in the western sector (TUC) than in the eastern sector (SJC). This seems to suggest that, within the EIA crest, the F3 layer in the South American sector has a different frequency of occurrence for different longitude sectors. Tardelli et al. (2018) proposed that the direct proportionality between the F3-layer occurrence and the solar activity at low latitudes is an evidence that GWs are most likely the main triggering factor of the phenomenon in this latitudinal band. This

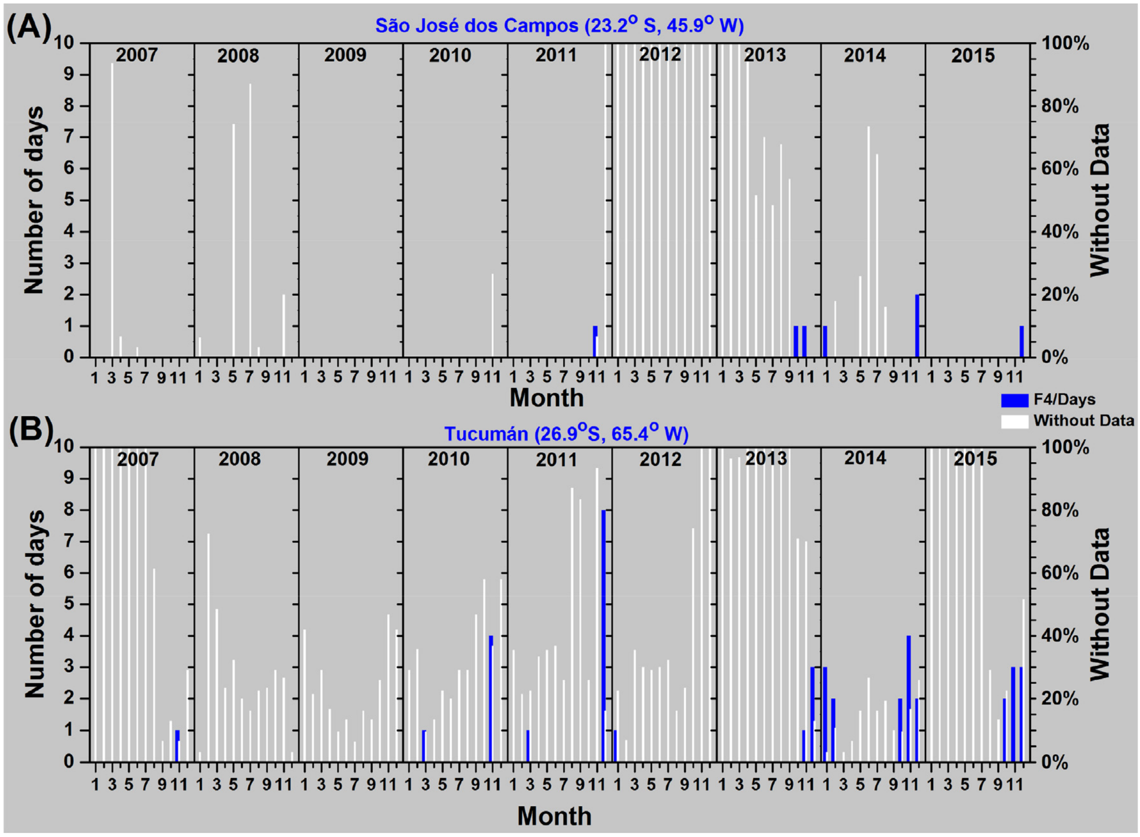

Fig. 7. (A) Monthly number of days showing an F4 layer (blue bars), from 2007 to 2015 at SJC. (B) The same as (A) but for TUC. The thin white bars indicate the percentage of days without data for each month. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

proposal is supported by the fact that Klausner et al. (2009) studied the propagation of GWs at F-layer heights during HSA and LSA periods, using digital ionosonde observations carried out at a low-latitude region in the Brazilian sector, and showed that the occurrence of GWs is higher during HSA than during LSA. The difference between the eastern and the western longitudinal sectors highlighted by this analysis could be attributed to the fact that the GW activity, besides depending on solar activity, it depends also on longitude (Liu et al., 2017).

When an F3-layer phenomenon occurs, it has a lifetime, which is different from one day to another. In addition, the F3-layer lifetime shows a seasonal and solar cycle dependence. Combining the annual data of the F3-layer lifetime, Fig. 4 shows that for the considered years this additional layer occurs between 7:00 LT and 17:00 LT. However, the lifetime of the F3 layer can vary from day-to-day (10–15 min up to hours), and this time duration can occur at different local times.

Fig. 4A shows that at SJC the period of occurrence of the F3 layer can start at 8:00 LT and end at 13:00 LT during LSA and can start at 7:00 LT and end at 15:00 LT during HSA. On the other hand, at TUC (Fig. 4B) the period of occurrence of the F3-layer can start at 07:00–08:00 LT and end at 14:00–15:00 LT during LSA and can start at 7:00 LT and end at 15:00–16:00 LT during HSA. In both sites, the maximum frequency of occurrence is around 10:00–11:00 LT (before the local noon). Fig. 4 shows also that at both sites the formation of the F3 layer increases as the solar activity increases.

Fig. 5 shows the F3-layer seasonal variations for both SJC and TUC. This investigation was made by joining all available data from 2007 to 2015. It is noticed that the F3 layer has an annual variation in both sites, showing a maximum occurrence in spring/summer (October, November, December, January, February, and March) and a minimum occurrence in autumn/winter (April, May, June, July, August, and September). Moreover, Fig. 5 shows also that the occurrence is higher at TUC than at SJC.

The results presented by Tardelli et al. (2016) about the F3-layer occurrence near the magnetic equator (Palmas; 10.3°S, 48.3°W; dip latitude 6.6°S) show a semiannual variation, with the main maximum in summer and a secondary maximum in winter. The present results show that the F3-layer occurrence near the EIA crest is instead characterized by an annual variation with maximum and minimum occurrence in summer and winter, respectively. These results suggest that behind the F3-layer stratification, near the equatorial region and within the EIA crest (SJC and PAL), there are different mechanisms of triggering, as on the other hand proposed by Tardelli et al. (2018). Anyhow, Fig. 5 shows that the spring/summer F3-layer appearance

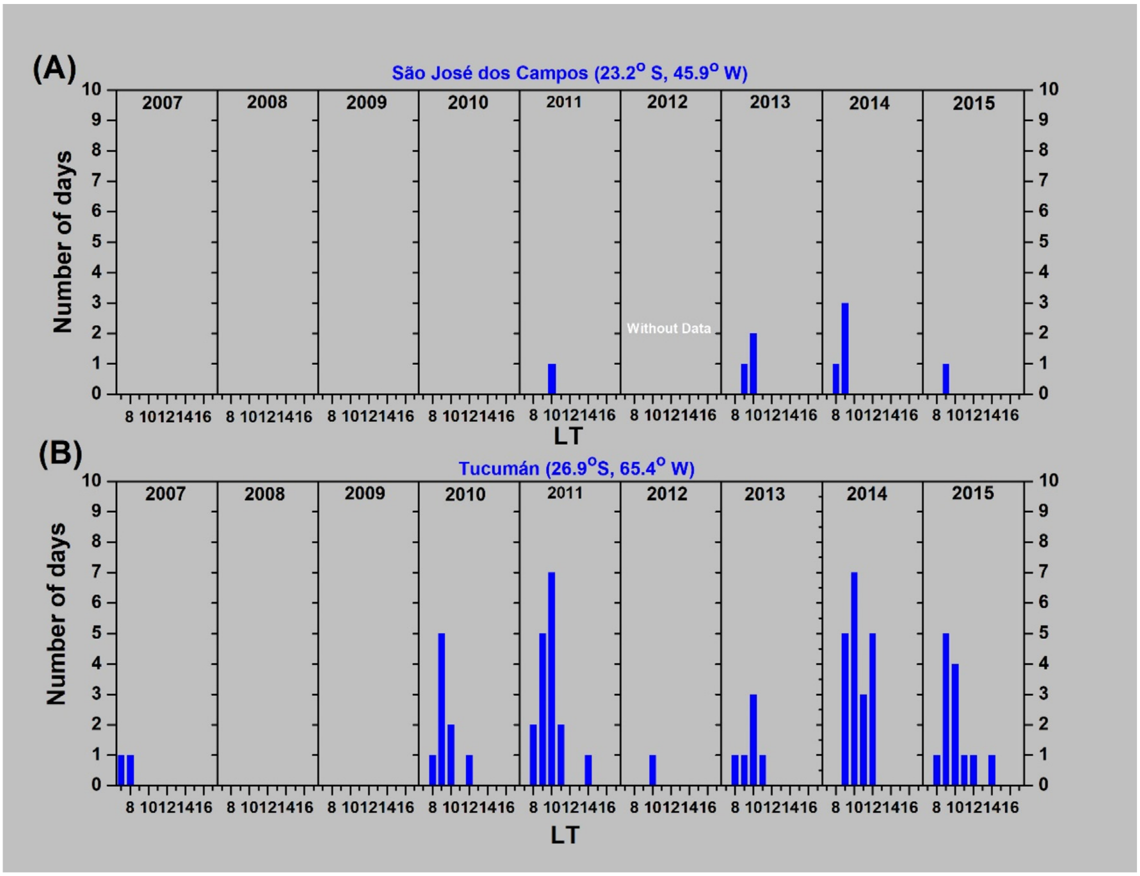

Fig. 8. (A) Yearly number of days showing an F4 layer (blue bars) as a function of Local Time (7:00 and 17:00 LT) from 2007 to 2015 at SJC. (B) The same as (A) but for TUC. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

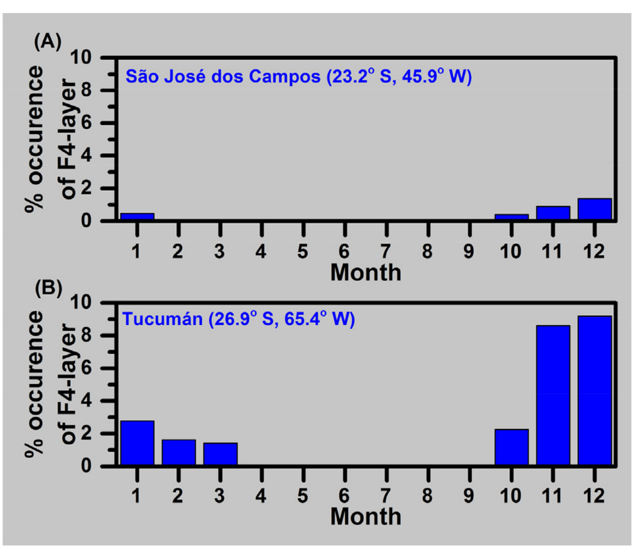

Fig. 9. (A) F4-layer seasonal variations at SJC, joining data from 2007 to 2015. (B) The same as (A) but for TUC.

in the two longitudinal sectors under study is a little bit different, with TUC showing an occurrence percentage that is overall higher than that characterizing SJC. This could be due in part to the fact that thermospheric meridional winds, at the base of the F-layer additional stratifications formation, depend on longitude (Medeiros et al., 1997). *Using a Kalman filter technique*, Lomidze and Scherliess (2015) have recently presented a new method to estimate the climatology of the zonal and meridional components of thermospheric neutral wind at low and middle latitudes. Their results showed that in the December solstice the meridional winds at 250 km of altitude are northward and more intense in the western sector than in the eastern sector of South America. This supports our results, namely that the F3 layer is most likely to appear at TUC than at SJC. On the other hand, their results show also that in June solstice in the South American sector the meridional winds at 250 km of altitude are southward, a condition which is against the F3-layer formation.

Fig. 6A and 6B show the monthly F3-layer occurrence probability from 2007 to 2015 as a function of LT at SJC and TUC, respectively. Each bin in Fig. 6A and 6B is of size 1 LT × month for a specific year. Fig. 6 shows that the F3-layer occurrence probability presents a solar cycle and seasonal variation. The occurrence probability is > 75% during HSA in 11–12/2013, 01/2014, 12/2014, and 01/2015 at SJC and in 12/2013 and 01/2014 at TUC.

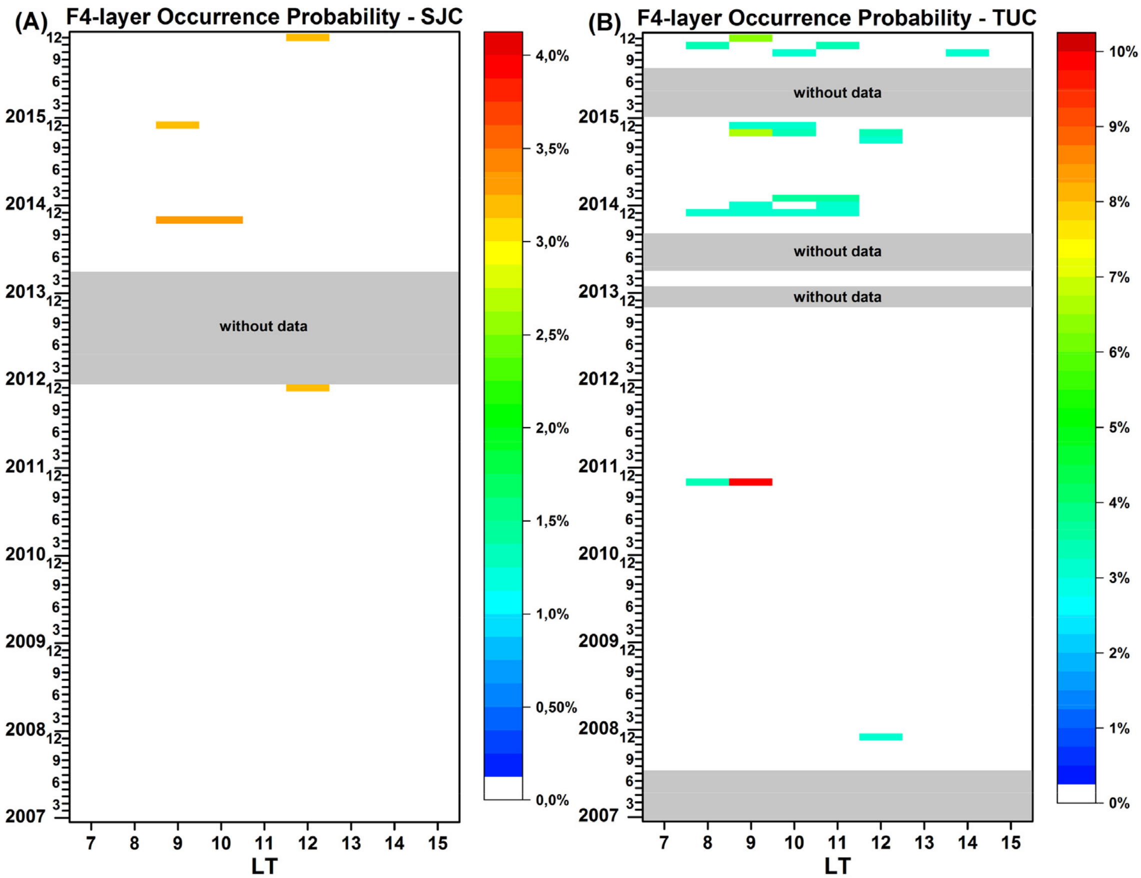

Fig. 10. (A) Monthly occurrence probability of the F4 layer as a function of LT (7:00 to 15:00 LT) from 2007 to 2015 observed at SJC. (B) The same as (A) but for TUC.

3.2. F4-layer solar cycle and seasonal variations

Fig. 7A and B show the monthly number of days that the F4 layer occurred from 2007 to 2015 at SJC and TUC. The total monthly number of days with and without data at SJC and TUC was shown in Fig. 2. However, Fig. 7 shows all the same the period without data for each month studied through the percentage of days without data in relation to the total number of days in each month. The comparison between Figs. 3 and 7 highlights that the frequency of occurrence of the F4 layer is much lower than that of the F3 layer.

At SJC the F4-layer stratification occurs in January and from October to December (summer) during MSA and HSA (2011 and 2013–2015) and is completely absent during LSA (2007–2010). At TUC instead it appears for all solar activities, except during the deep LSA (2008 and 2009) between solar cycles 23 and 24. Moreover, the highest frequency of occurrence is recorded in December 2018 (MSA).

The number of days presenting the F4-layer stratification at SJC (7 days) is lower than that at TUC (41 days). Joining the 9 years of observation, the percentage of occurrence of the F4 layer at SJC is 0,28% and at TUC is 2,26%. Taking into account also the results shown in the previous section, this is the first time that it is shown how in the South America sector the F3 layer and F4 layer present a frequency of occurrence that depends on the longitude.

As previously shown for the F3 layer, also the F4 layer has a different lifetime from one day to another day. When joining the data annually, the occurrence of the F4 layer as a function of LT at SJC and TUC is quite different.

Fig. 8A shows that at SJC the F4 layer appears between 08:00 LT and 10:00 LT during MSA and HSA. Fig. 8B shows instead that at TUC the F4 layer appears at the beginning (2007) and at the end (2010) of the LSA, forming between 7:00 LT and 8:00 LT in 2007 and between 8:00 LT and 13:00 LT in 2010, and between 08:00 LT to 14:00 LT during MSA and HSA.

Fig. 9A and B show the F4-layer seasonal variations for both SJC and TUC, joining all available data from 2007 to 2015, and highlight that the F4 layer has an annual variation both at SJC and at TUC, with a maximum in December. Specifically, at SJC the F4 layer is present from October to January and absent from February to September, while at TUC it is present from October to March and absent from April to September. These results agree with those presented by Tardelli et al. (2018). However, the longitudinal difference of the F4-layer percentage of occurrence, greater at TUC than at SJC, is rather unexpected, because both sites are located near the EIA crest. Anyhow, Tardelli et al. (2018) suggested that also for the F4-layer appearance GWs play a key role both at low and near-equatorial latitudes. So, as already said also for the F3 layer, this longitudinal difference characterizing the eastern and the western sectors of South America might be ascribed to the different intensity of GWs, which is longitude dependent (Liu et al., 2017).

Fig. 10A and B show the monthly occurrence probability of the F4 layer from 2007 to 2015 as a function of LT and month at SJC and TUC, respectively. This figure shows that the occurrence probability of the F4 layer is very low in both sites. At SJC, the occurrence probability is approximately > 3% during MSA and HSA. At TUC, the occurrence probability reaches the value of 10% at the end of the LSA period, while during the HSA the occurrence probability is between 3% and 6.7%.

4. Conclusions

This investigation presents the daytime seasonal and solar cycle variations of the F-layer multiple stratification (F3 and F4 layers), carried out using ionosonde data recorded at SJC, Brazil (eastern South American sector) and at TUC, Argentine (western South American sector). The main results are:

1. The frequency of occurrence of the F3 and F4 layers is higher in the western sector (TUC) than in the eastern sector (SJC). This is the first time that such a result is outlined, that is F3 and F4 layers in the South America sector present a frequency of occurrence depending on the longitude. This difference might be ascribed to a different GW intensity characterizing the two sectors.
2. The F3 and F4 layers occurrence shows an annual variation in both sites (SJC and TUC), with a maximum occurrence in spring/summer and a minimum occurrence in autumn/winter. Overall, the seasonal maximum is higher at TUC than at SJC and a variation of the thermospheric meridional winds intensity in the two sectors could be responsible for such a difference.
3. Regarding the start–end period of the F3-layer appearance, it was observed that at SJC during LSA the F3 layer starts at 08:00 LT and ends at 13:00 LT, while at TUC starts at 07:00–08:00 LT and ends at 14:00–15:00 LT. Instead, during HSA, the start–end period of the F3 layer presents a similar behavior for both locations, starting at about 07:00 LT and ending at about 16:00 LT.
4. Both the F3- and F4-layer occurrences present a direct proportionality with the solar activity, both at TUC and SJC. This strenghten the fact that GWs play a key role in triggering these layers, because at low latitudes the GW occurrence is higher for HSA than for LSA.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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