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Climatology of intermediate descending layers (150 km) over the equatorial and low latitude regions of Brazil during the deep solar minimum of 2009

Ângela M. Santos[1], Inez S. Batista[1], Mangalathayil A. Abdu[1,2], José .H. A. Sobral[1], Jonas. R. Souza[1]

[1]National Institute for Space Research (INPE) S. J. Campos, SP, Brazil
[2] Instituto Tecnológico de Aeronáutica, DCTA, São José dos Campos, Brazil

Correspondence to: Ângela M. Santos (angela.santos@inpe.br, angelasantos_1@yahoo.com.br)

Abstract. In this work, we report for the first time the climatology of intermediate descending layers over Brazilian equatorial and low latitudes regions during the extreme solar minimum period of 2009. The occurrence frequency of this layer is very high, being >60% over São Luís (2 ° S; 44 ° W, I: -5.7°) and >90% in Cachoeira Paulista (22.42 ° S; 45 ° W, I: -34.4°). Our results reveal that in most of the cases the intermediate layers (IL's) appear during the day at altitudes varying from 130 to 180 km and present a descent movement that reaches the lower altitudes (~100 km) in a time interval of a few minutes to hours. Differently from other longitudinal sectors, the diurnal tide (24h) can be considered as the main cause of IL's for the low latitude region, followed by a smaller dominance of semidiurnal (12h), terdiurnal (8h) and quarter-diurnal (6h) tide components. In the equatorial sector, similar behavior was found, with the exception of the semidiurnal tide, which in general does not appear to influence the IL's dynamics (except in summer). The IL's mean descent velocities over São Luís and Cachoeira Paulista show a day-to-day variability that may be associated with gravity waves propagation. Some peculiarities in the IL's dynamics have been noted, such as the presence of the IL's during the night hours, ascending IL's, simultaneous IL's, and descending IL's been formed from some connection with the ionospheric F layer. Quite often, these characteristics are observed in the presence of strong signatures in the ionogram F-layer trace similar to those caused by the gravity wave propagation. We will show further that the descending intermediate layer over Brazil can be formed through a process of F1 layer base detachment. Besides that, we will present an interesting case study in which an ascending IL's, initially detected at ~ 140 km, reached the

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base of F2 layer, probably due to the gravity wave propagation and/or due to the effect of the prompt penetration electric field.

1 Introduction

The first observations on the existence of intermediate layers were reported in 1930s (Schafer and Goodall, 1933; Appleton, 1933; Ratcliffe and White, 1933). It was observed that this ionization layer, which is located between the E and F1 ionospheric layers, occurred regularly at around 130 - 150 km of altitude. Since then, some studies have been carried out on the behavior of IL's over different longitude sectors using radar observations (Kudeki and Fawcett, 1993; Chau and Kudeki, 2006; Kudeki et al., 1998; Tsunoda and Ecklund 2004) and Ionosonde data (Rodger et al., 1981; MacDougall, 1974; MacDougall, 1978; Wilkinson et al., 1992; Szuszczewicz et al., 1995). Balsley (1964) showed that the existence of these layers located at ~150 km of altitude exhibited a downward movement during the daytime and ascending movement at dusk, with the intensity varying on a time scale of 5 to 15 minutes. Shen et al. (1976), observed that the IL's over Arecibo can lasted for several hours. They also mentioned that in the valley region, the peak electronic density ranges from ~$3x10^2$ to $1x10^3$ cm^{-3}.
According to Fujitaka and Tohmatsu (1973), the S2 and S4 propagation mode of atmospheric tide can be the dominant cause of the intermediate layers at night over middle latitude. In the equatorial region, the IL's can possibly be caused by gravity waves (Kudeki and Fawcett, 1993) however, some characteristics observed also suggest that the phase velocity along the line-of-sight must be controlled firstly by the large-scale electrodynamics effect (driven by tides) and secondarily by the gravity waves of short period.

Some particularities of the IL's such as seasonality and cause-effect relationships have been observed and studied over many years. Mathews and Bekeny (1979), for example, investigated the role of tidal winds in their diurnal and semidurnal components in the formation of IL's and concluded that the winds could play a key role in the generation of this phenomenon. Using Ionosonde data, MacDougall (1978) observed that the periodicity of the intermediate layers in the ionograms appeared to be related to semidiurnal oscillations. Mathews (1998) reported the important role of diurnal and semidiurnal tides in

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the generation and height descent of the intermediate layers over Arecibo. Tsunoda (1994) suggested that a gravity wave wind driven interchange instability could be a possible generation mechanism of the field-aligned plasma irregularities responsible for the echoes.

Regarding the study of IL's made with radar data, also known as the "150-km echoes", the first observations over Brazilian sector were made by de Paula and Hyssel (2004). The 150-km echoes were identified by the radar around 09 LT at ~ 165 km altitude, and at 12 LT the echoes were already located at ~ 145 km. A gradual upward movement of the IL's reaching 160 km of altitude was also observed in the following hours. At 17 UT the IL disappeared, presenting in this way a "collar" shape as observed in other longitudinal sectors. From the analysis of the RTI maps, Rodrigues et al. (2011) showed that the lowest rate of occurrence of the 150-km echoes in Brazil was during the March equinox, whereas the strongest and longest duration echoes were observed between June and September. Another important finding by Rodrigues et al. (2011) was that there was an apparent variability of the Doppler displacement with height, indicating that the IL's over Brazil might have a different formation mechanisms from those operative in other longitudinal sectors. The IL's observed with the 30 MHz radar at São Luís presented a thickness of 3 to 5 km and were located between 140 and 170 km of altitude.

In this paper, we present for the first time, the climatology of intermediate layers over the equatorial and low latitude Brazilian station during a period of extremely low solar activity. The important points to be discussed in this paper will include the influence of atmospheric tides and gravity waves in the IL's dynamics and the possible contribution of disturbed electric fields in some specific cases. Some peculiarities found in the IL's over Brazil will also be discussed.

2 Methodology and data presentation

The observational data analyzed in this work were obtained from the Digisondes operating in São Luís – SL (2 ° S; 44 ° W, I: -5.7°) and Cachoeira Paulista - CP (22.42 ° S; 45 ° W, I: -34.4°) during the period of extreme solar minimum activity of 2009. For SL it was analyzed data from March to December and for CP data from January to December. The following criteria were established in order to ubiquitously classify a certain layer as intermediate layer:

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(a) When the critical frequency of the lower layer (extraordinary trace) exceeds the minimum frequency of the ordinary trace of layer F, the layer in question was considered as IL. Otherwise, the layer was classified as a regular E2 layer. Depending on the height of this layer, we carefully evaluated the identification of the IL case by case;

(b) In the cases in which the characteristics described in item (a) were not clear, a sequence of ionograms was used to classify the type of the layer;

(c) When a new layer appeared to be formed from a detachment of F1 layer, the IL was only considered when such detachment was total;

(d) For a descending layer to be classified as IL it should first occur at or above 130 km;

(e) When the studied layer was initially detected below 130 km, but in the sequence of the ionograms an ascending movement reaching $h \geq 130$ km was observed, the layer was classified as an IL;

(f) The IL's height and frequency parameters were extracted from the extraordinary trace. Besides that, they were processed during their downward movement until they merged into the sporadic-E (Es) layers.

It is important to note that, according to the criteria mentioned above, the layers considered here as "intermediate" may have evolved into a normal c-type sporadic-E layer, for example. Figure 1 shows an example of an intermediate layer located at ~ 150 km (h'IL) with a top frequency (ftIL) of 4.51 MHz. We can see that the minimum frequency of the F layer (~ 4.1 MHz) was lower than the top frequency of IL, thus satisfying the criteria described in item (a).

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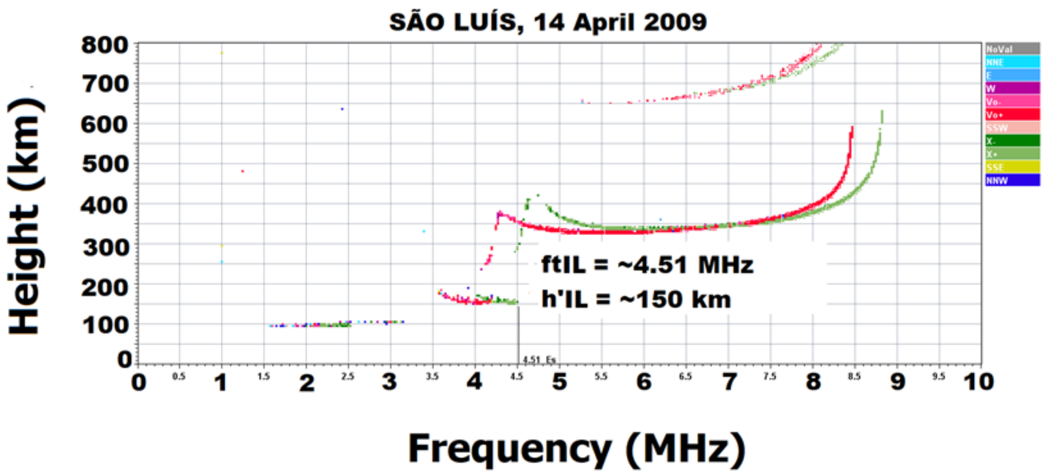

FIGURE 1: Ionogram over São Luis during 12 April 2009. The height (h'IL) and the top frequency (ftIL) of intermediate layer are indicated in this Figure.

3 Results

Figure 2 presents the month-to-month variation of the percentage occurrence of the intermediate layers over SL and CP. This analysis was performed based on the available data and the days with either ascending or descent intermediate layers, regardless if they were observed more than once during a day or not. The upper panel of Fig. 2 shows the results for SL. It is interesting to observe the high occurrence rate (above 60%) during 2009 for this sector. In July and August, the occurrence reached 100%. Over Cachoeira Paulista, the high occurrence was even more pronounced throughout the period analyzed, reaching 100% in the months of April, June, July and December.

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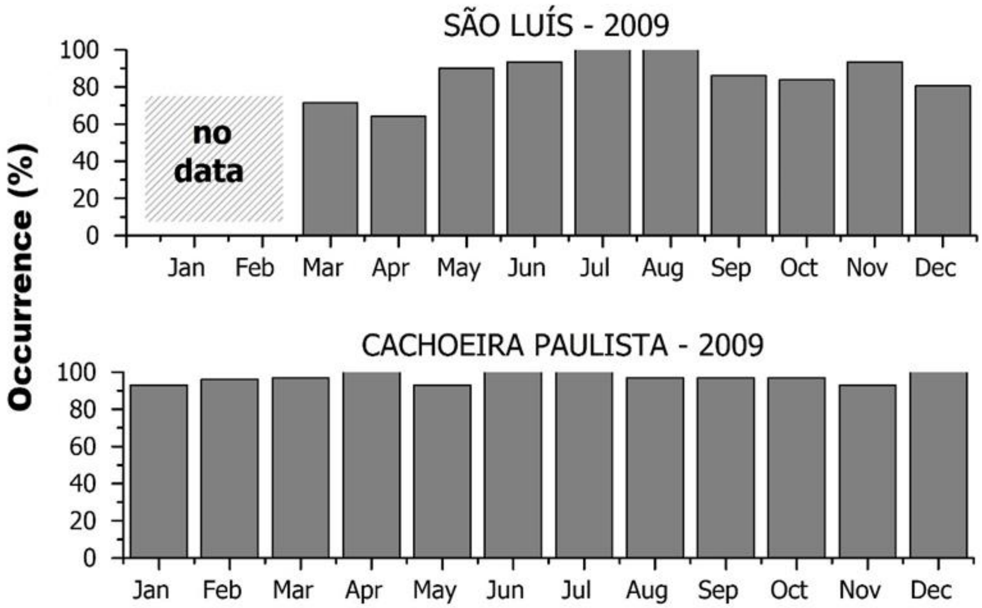

FIGURE 2: Monthly mean percentage occurrence of descending intermediate layers for solar minimum period of 2009 at São Luís (upper panel) and Cachoeira Paulista (bottom panel). The shaded area in upper panel indicate the lack of data during January and February.

3.1 Seasonal and diurnal variations

In Figure 3 we show the mass plots of the height (h'IL) and top frequency (ftIL) of the intermediate layers as function of the time. The data set were grouped into equinox (March-April; September-October), winter (May to August) and summer solstice (November to February) seasons. The data availability and occurrence of the IL's for these periods are summarized in Table 1. The main results of this analysis for SL and CP can be summarized as follows: **(a)** the IL is a phenomenon that occurs predominantly during the day; **(b)** in general the higher top frequencies are observed for the intermediate layers that descend in height (h ≤ 130 km); **(c)** Over São Luís, nocturnal intermediate layers were observed between 01 and 08 UT (22 and 05 LT) in the equinox and summer solstice, but not in the winter during the same interval. A

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few cases were observed also after 21 UT. Over CP, the nocturnal IL's were observed between ~ 22 and 09 UT during the three seasons; **(d)** At dawn (~ 06 LT), the lowest average top frequency of the intermediate layers over SL was ~ 2.5 MHz during equinox and in summer, and ~ 2.1 MHz in winter solstice. In CP, these values were ~ 2.5 MHz in equinox, 2.1 MHz in summer and 1.9 MHz in winter; **(e)** Ascending and descending layers were observed at altitudes above 200 km during the equinox and winter over SL, but it is important to mention that the summer months are underrepresented due to the absence of data for January, February and some days in March. Over CP, it was possible to identify layers at altitudes slightly higher than 200 km during the three seasons. In all the cases, during the interval between 05 and 07 LT (08-10 UT), the classification of the layers as IL's was complicated because this is the time in which the ionospheric E layer begins to be registered in the ionograms.

Table 1: Number of days used in our study

SEASON	NUMBER OF DAYS WITH AVAILABLE DATA		NUMBER OF DAYS WITH THE IL'S	
	SL	**CP**	**SL**	**CP**
Equinox	110	118	85	113
Winter Solstice	122	123	117	121
Summer Solstice	61	119	53	114

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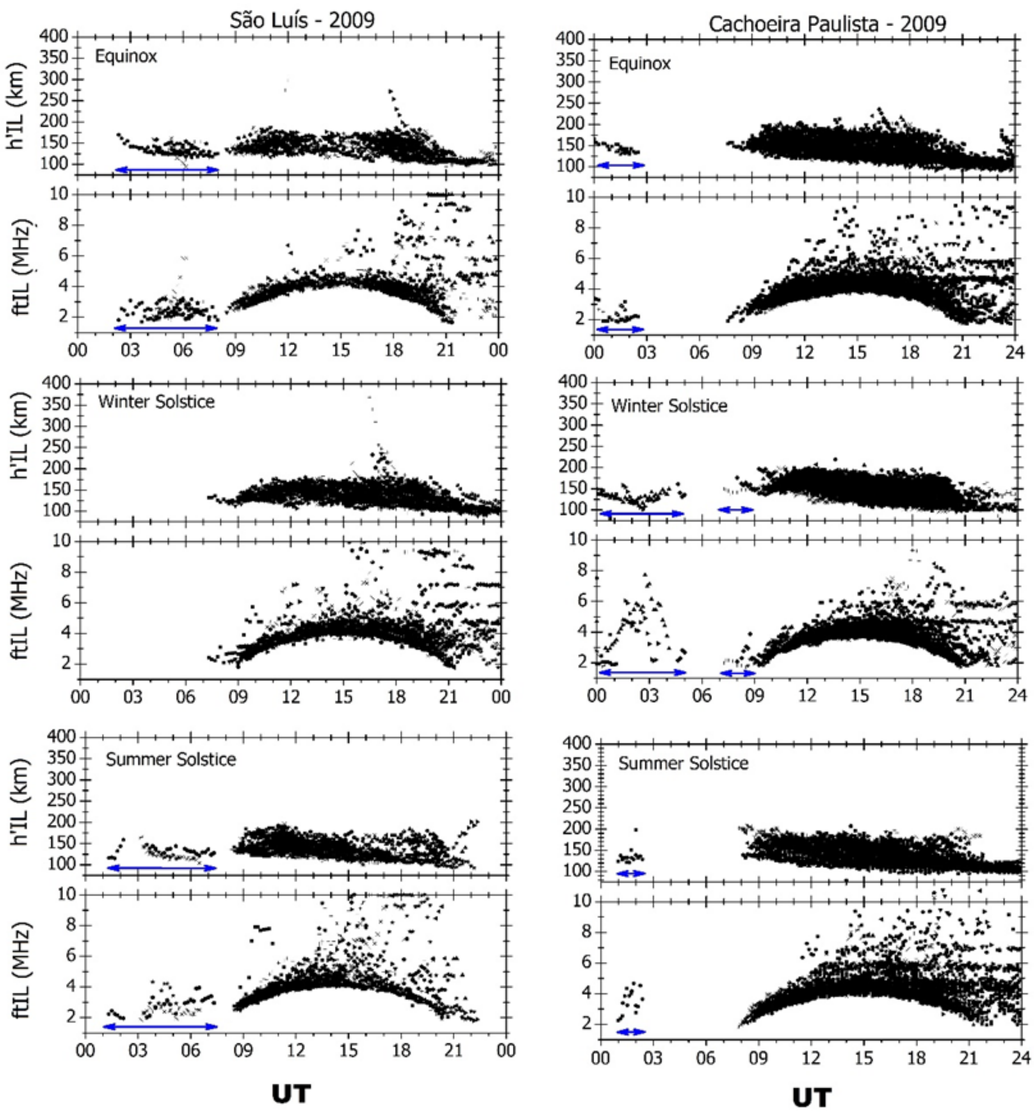

FIGURE 3: Time variation of intermediate layer parameters over São Luís and Cachoeira Paulista for different seasons. The horizontal blue arrow indicates the presence of nocturnal layers between 00 and 09 UT.

Figure 4 shows the daily variation of the IL's parameters over SL and CP for each month. In Fig. 4a, we may note that in March, for example, of the 21 days analyzed, the presence and the absence of the intermediate layers was noted on 15 and 6 days, respectively. Besides that, it is interesting to observe that in many cases, the descent of the layer reached heights less than 130 km after 15 UT or 18 UT. Only in October, November and December, the layer descent started earlier, that is, soon after ~09 UT and 13

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UT. The IL's were not observed in March and April between 12 and 15 UT. Over Cachoeria Paulista (Fig. 4b), it is possible to note the IL's tendency to reach altitudes below 130 km some hours earlier when compared with that over SL, except in Nov. and Dec.. The maximum limit of the vertical axes of Figures 4a and 4b was fixed at 200 km, but it is possible to see that on some days, the IL's were registered at altitudes much above this limit. In addition, in almost all the cases, they were formed from 09 UT, both at SL as well as at CP.

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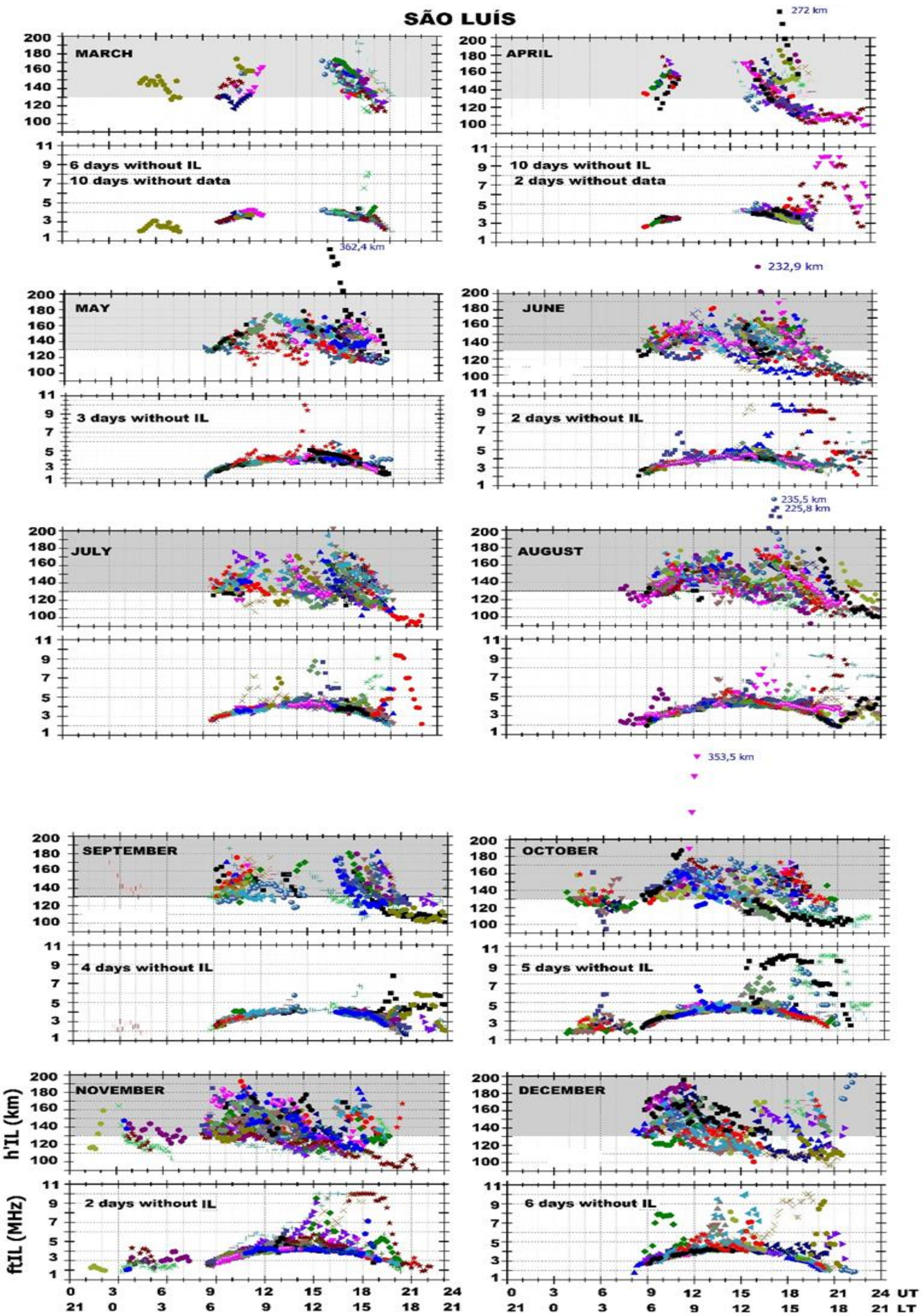

FIGURE 4a: Time variation of the virtual height (h'IL) and top frequency (ftIL) of intermediate layers over São Luís from March to December 2009. The information's about the absence of IL´s in each month is included in the plot.

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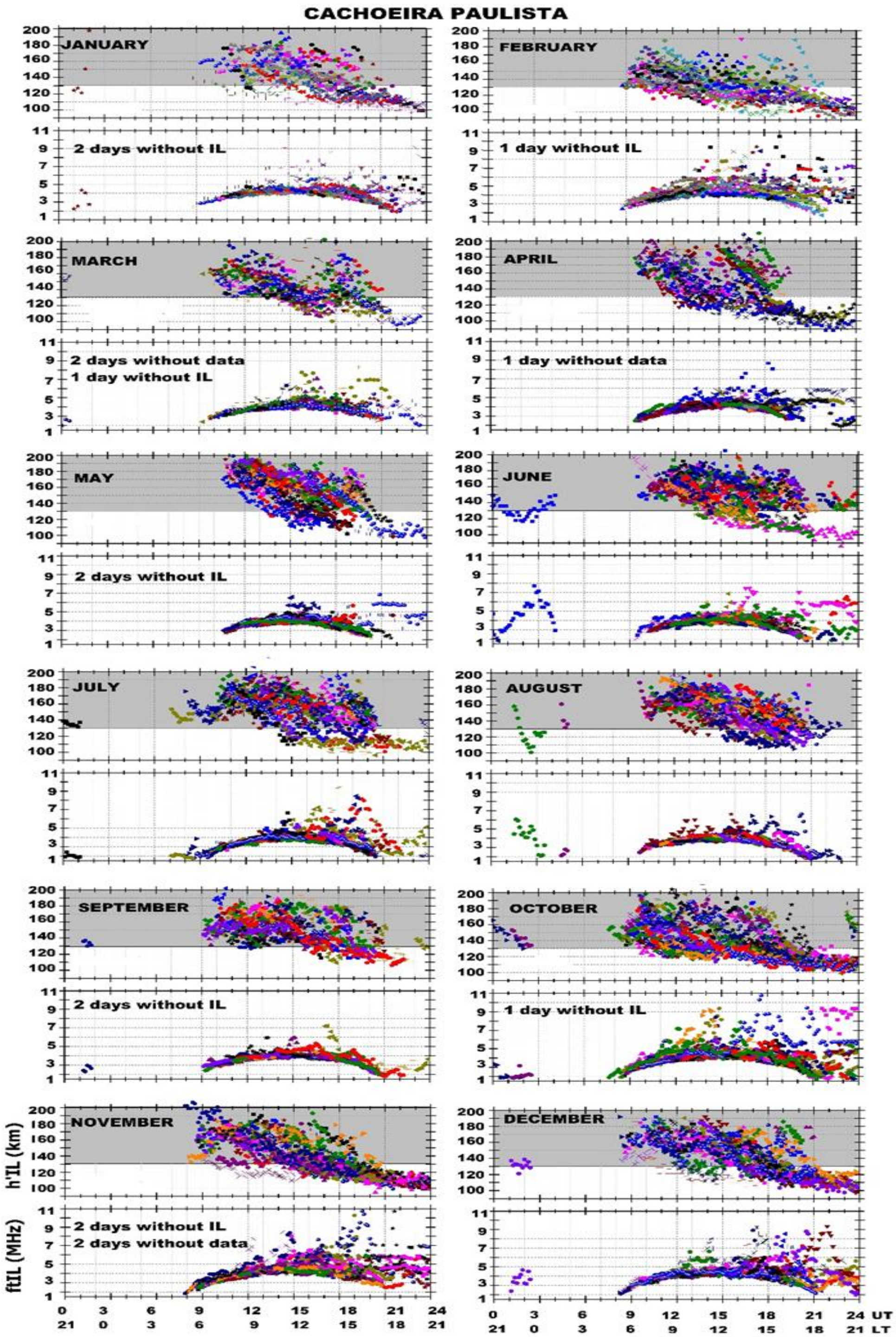

FIGURE 4b: Same as Figure 4a, but for Cachoeira Paulista from January to December 2009.

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In general, the results presented in Figure 4 make clear that the height at which the IL's are detected is quite variable and the behavior of the layer top frequency is very similar to that of the E-layer with a maximum at noon. In most of the cases, the IL´s present descending movements, but, in some days, an ascending movement was also identified. Besides that, in our database, we verify two types of IL's occurring at the same time; the IL's that may or may not evolve to altitudes less than or equal to 130 km; the IL's that appear and disappear several times a day and the IL's that may be connected in some way with the F layer (that is, at h ≥150 km).

3.2 Nocturnal intermediate layers

The occurrence of nocturnal intermediate layers was one of the peculiarities found in our studies. Over São Luís, the highest number of cases was detected between October and November. Figure 5a shows some examples of nocturnal IL's occurring between 0120 UT (2220 LT) and 0830 UT (0530 LT) over SL. The times in the ionograms do not necessarily indicate the exact moment in which the intermediate layer was formed, but they indicate the times at which they could be better visualized. It is interesting to note that in these examples, the nocturnal layers exhibited a similar shape in almost all cases, with a straight and "spreading" base appearance. The height/top frequency of these layers varied between ~ 130 and 170 km / 2.2 and 3.5 MHz. Similar to the diurnal intermediate layers, the nocturnal layers also had descending and ascending characteristics.

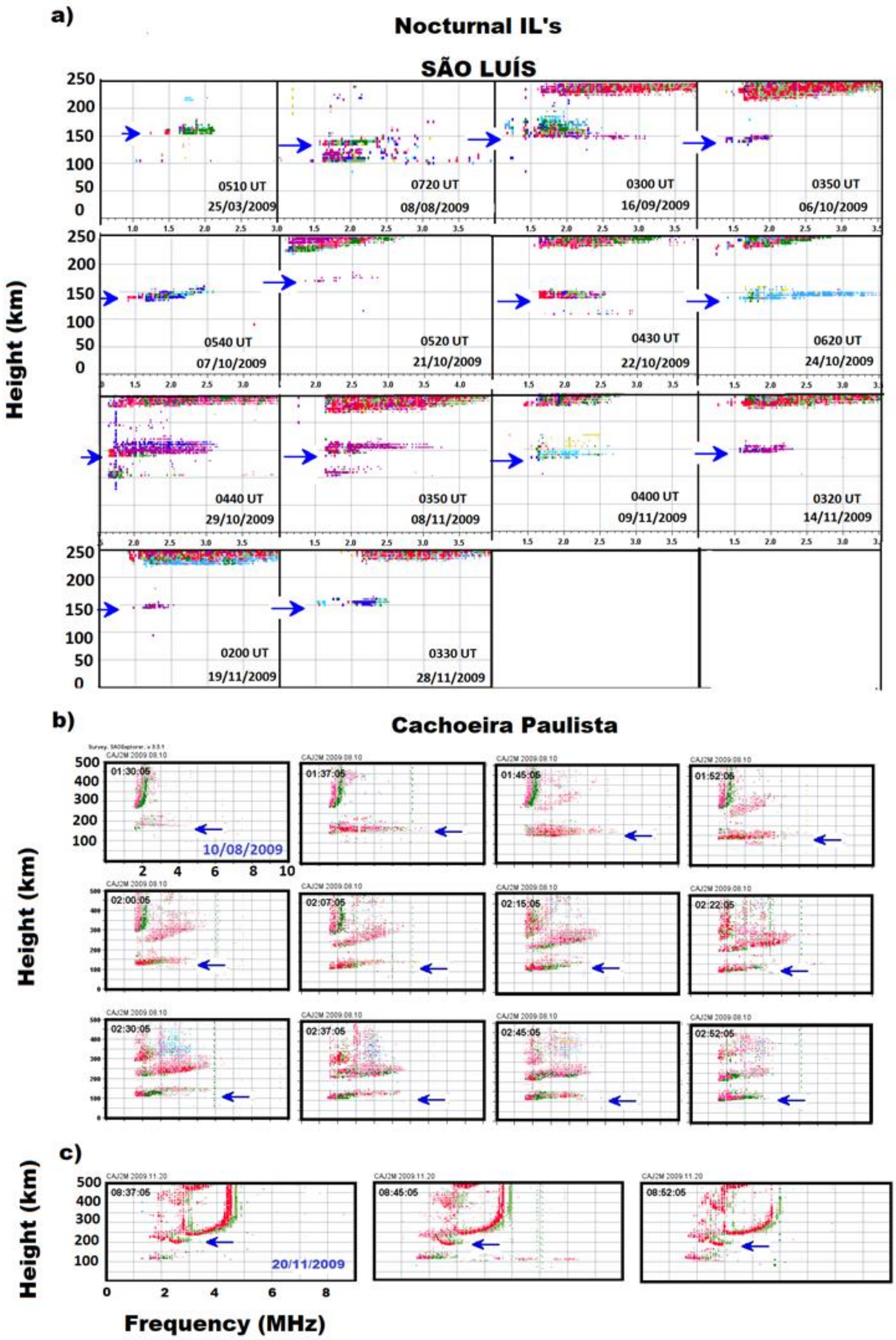

FIGURE 5: a) Ionograms from São Luís showing some examples of nocturnal intermediate layers on different days. b) Nocturnal intermediate layer over Cachoeira Paulista during August, 10. c) Nocturnal intermediate layer over CP starting with a retardation in height similar to that of the h-type sporadic layer.

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Over Cachoeira Paulista, also the nocturnal intermediate layers were registered. The highest occurrence was in June and October (5 days in both months). Figure 5b shows an example of this type of layer on 10 August. At around 0130 UT we can observe the starting of an IL at ~150 km. The subsequent sequence of ionograms shows that the IL rapidly descended to ~ 110 km of height. The range spreading characteristic of the IL was observed also in the nocturnal IL's, which in this case presented a range of ~ 50 km. On the other hand, a different shape was found in the IL of 20 November, starting at 0837 UT, as shown in Fig. 5c. We can observe at 200 km a curved format like that of the 'h' type Es-layer. The sequence (not presented completely here) shows that this layer descent only a few kilometers and at 1037 UT it was already connected to the F1 layer.

3.3 Simultaneous IL's and those that are connected to the F region

Besides the occurrence of simultaneous IL's, we identify some cases in which the formation of IL's was connected to the F region. They are: a) intermediate layers formed at the high frequency end of the F1 layer (IL'F1t), b) IL's formed from a detachment of the F1 layer base (IL'F1b), c) IL's formed from a perturbation in the F2 layer base (IL'F2b), and d) ascending IL's that reached the base of F2 layer. Between the above cited, the most common case observed at both São Luís and Cachoeira Paulista was that in which the layers formed from a detachment of the F1 layer base.

Figure 6 shows an example of ascending intermediate layer over SL that was located initially at ~ 130 km. At 11 UT, this layer presented a weakening followed by an intensification after 10 minutes. Between 1020 and 1120 UT, we can observe an ascending movement of the IL (from 132.9 to 153.5 km)

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and the subsequent merge with the F1 layer at 1130 UT. From this time on, an extra ionization at the high frequency end of the F1 layer with an ascending structure was observed and attained the F2 layer base at 1230 UT (370 km). It is also interesting to note the changes that occurred in the F2 layer trace during this period.

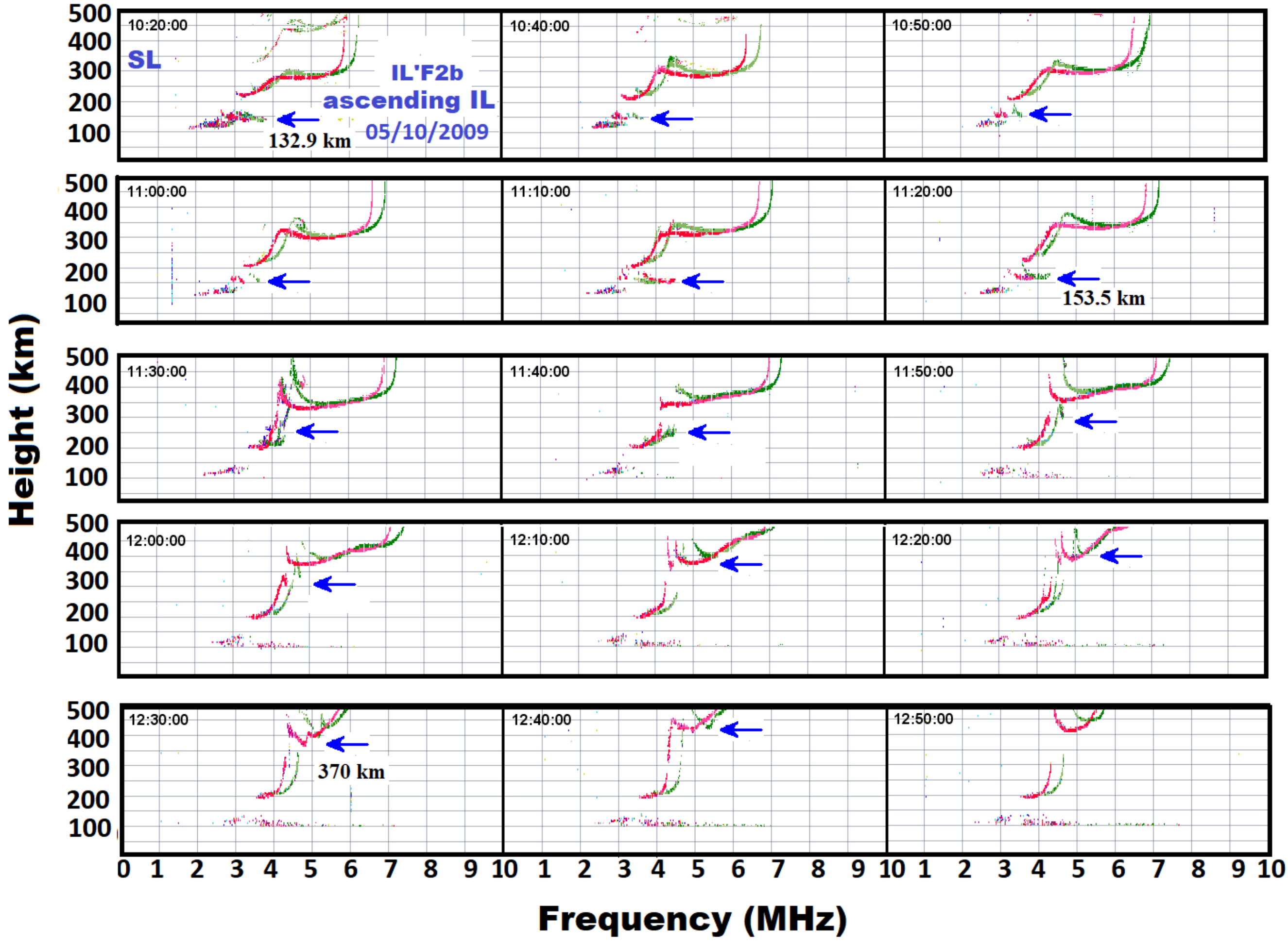

FIGURE 6: Sequence of ionograms taken during 1020 – 1250 UT on 05 October 2009 showing the presence of ascending intermediate layers over São Luís. The blue arrow indicates more clearly the raise of IL.

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A reverse situation appears to be present in the ionograms in Figure 7. As indicated by the blue arrows, an initial perturbation in the F2 layer base was observed at 1540 UT, around 400 km. At 1630 UT, this disturbance had already reached the F1 layer (~ 350 km). The ionograms show clearly a downward movement of this stratification. At 1810 UT, the IL's was already located at ~ 170 km. It is also interesting to note the presence of a second intermediate layer (as indicated by purple arrow) that was in progress when a disturbance in the F2 layer was identified. This second layer also presented a downward movement and oscillated between moments of intensification and weakening, thus denoting the high complexity involved in the behavior of these layers.

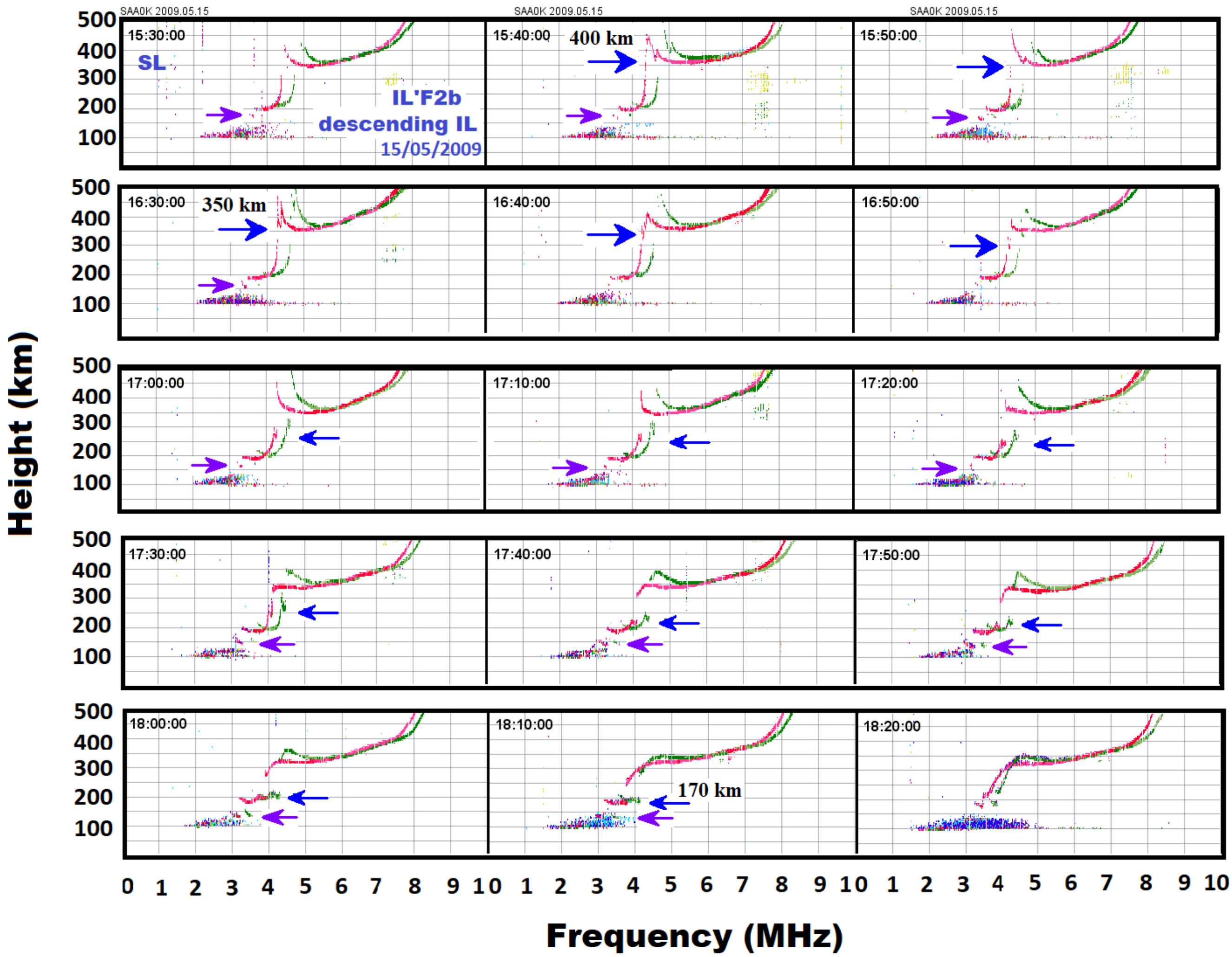

Figure 7: Sequence of ionograms taken during 1530 – 1820 UT on 15 May 2009 showing the perturbation in the F2 layer trace that reached low altitudes and evolved to a descending intermediate layer over São Luís. The blue arrow indicates the downward movement of perturbation in F layer and the purple arrow indicates the presence of another IL occurring simultaneously.

Figure 8 shows an example of simultaneous intermediate layers over CP. We may note that at 1407 UT there is an IL at ~ 170 km (indicated by the blue arrow) and another at 150 km (indicated by the purple arrow). In both cases, there is a very slow descent movement or nearly a stagnation of the layer at a specific height. The presence of these two layers was verified until 1722 UT (not shown here). At 1730 UT the two layers merged at ~130 km. After that, only a single layer was observed till 21 UT.

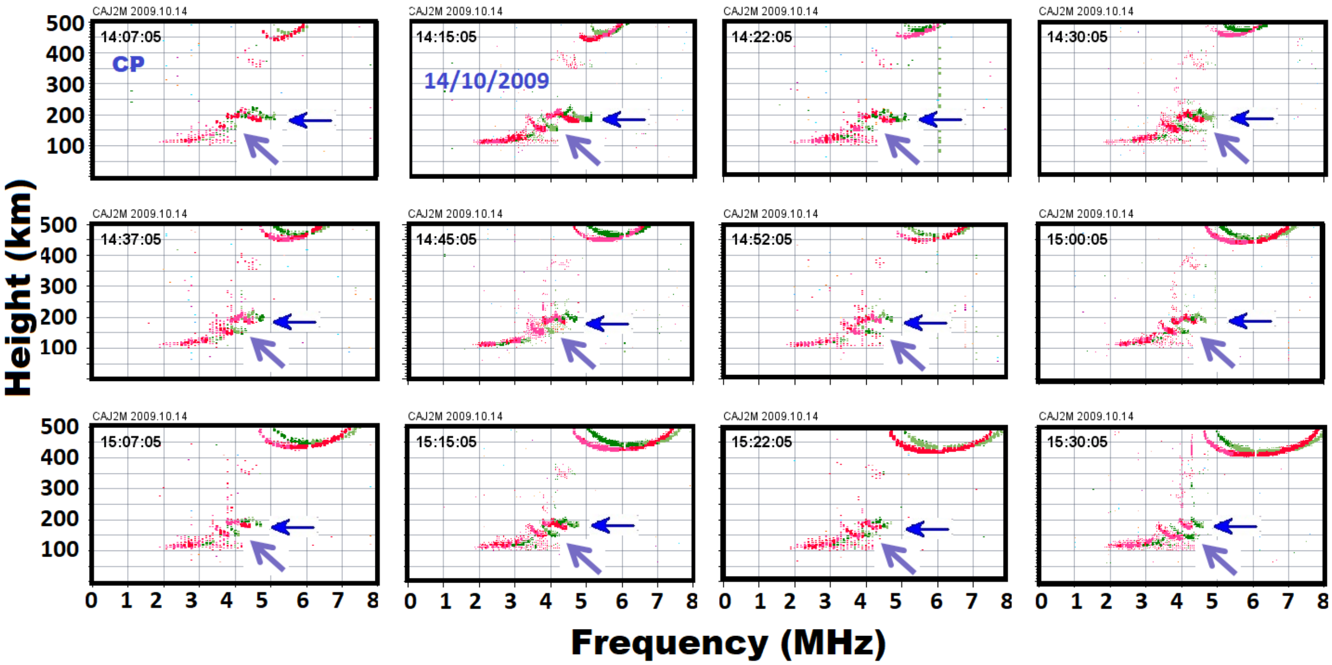

Figure 8: Sequence ionograms over CP showing the presence of simultaneous intermediate layer, one being initially detected in 180 km height and other in 150 km.

The occurrence of intermediate layer from a detachment of the F1 layer was the most common case found in our study. The ionograms in Figure 9 show that at 1715 UT on 18 March, the F1 layer base exhibited a deformation (stratification), which extended to the following times. This deformation showed a clear detachment from the F1 layer at 1730 UT, reaching the height of ~ 150 km at 19 UT. It is important to mention that in many other cases, a deformation in the F1 layer base was registered, however the total detachment did not occur or occurred only later. Besides that, there were some cases in which the detachment was verified, but after some time the detached part joined to the F1 layer again.

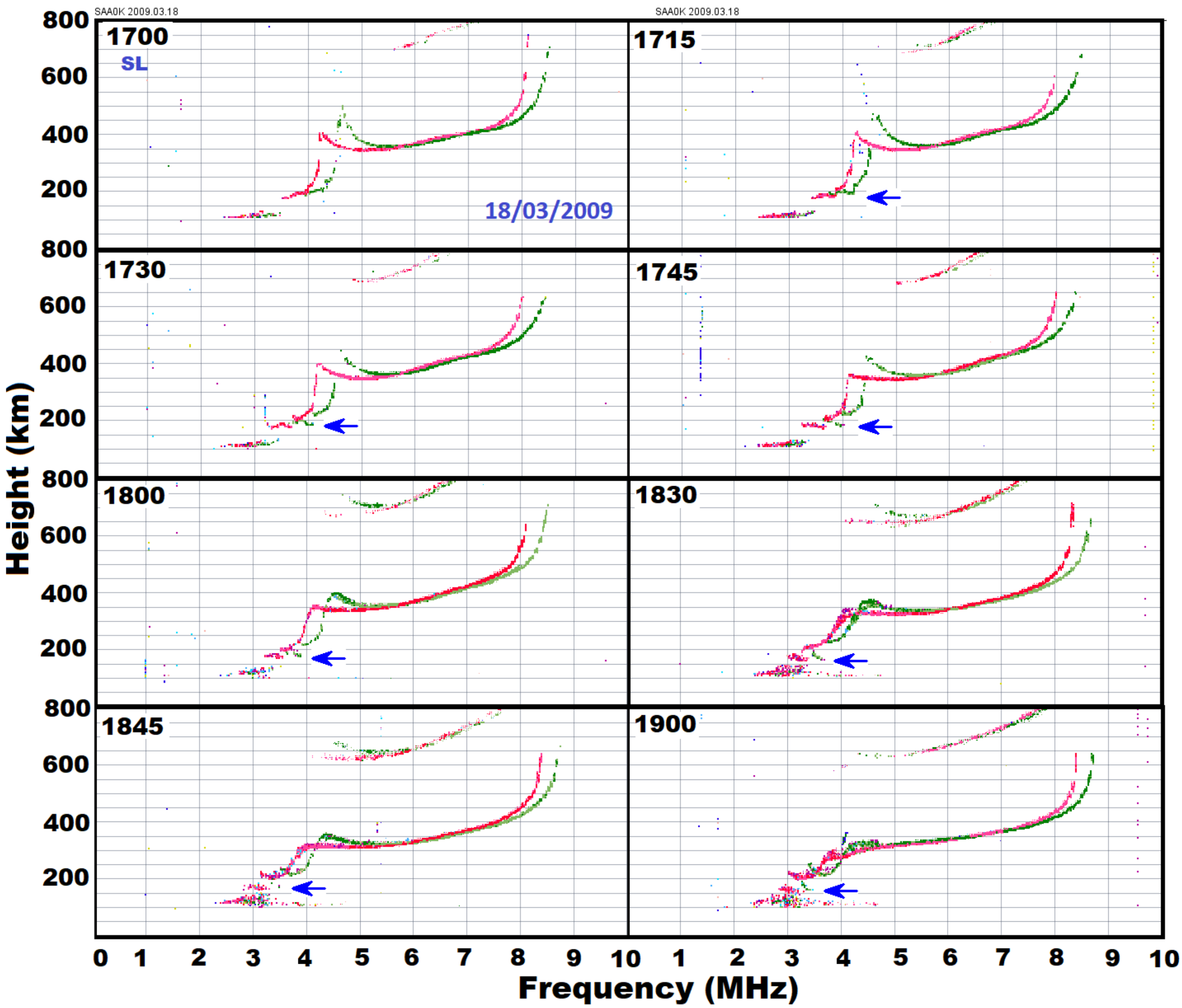

Figure 9: Sequence of ionograms from SL during 18 March 2009 showing the formation of an intermediate layer from a detachment of F1 layer base.

3.4 Intermediate layers descent velocities

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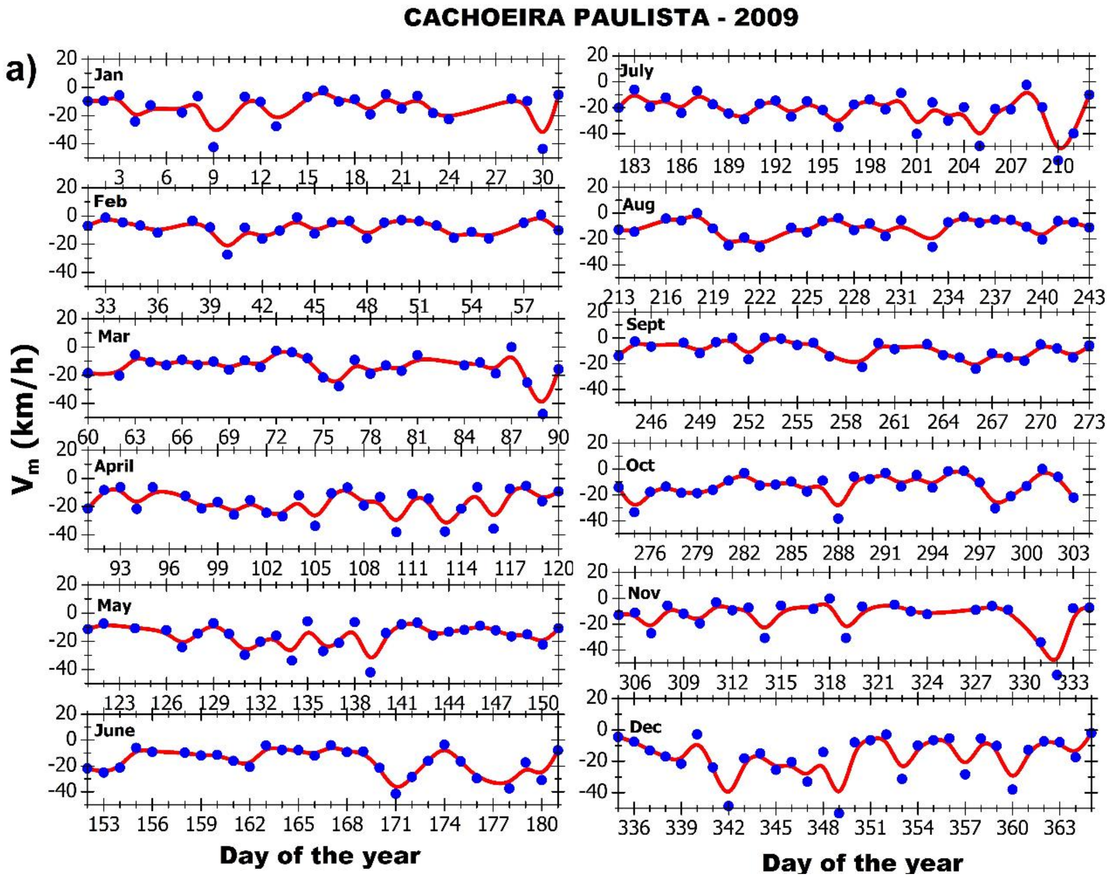
The calculated mean descent velocities of the IL's for each day is presented in Figure 10. We may note a day-to-day variability in a shape of wave (in the B-spline analysis represented by the red curve) possible indicating the influence of gravity waves in the formation process of the intermediate layers. The drift values found here is in agreement with Ninranjan et al. (2010). The authors showed a case in which the IL was observed in two different moments at the same day. In the first interval, the initial descending velocity was around 20 km/h and towards the end it was 6 km/h. In the second interval, the velocity was quite high 40 km/h in the first 15 min and it slowly came down to 8 km/h before it merged with the normal E layer. The daily velocities plotted in Figure 10 were used to calculate the mean velocity for each month, which is shown in Fig. 11. We can observe that over CP, the velocities oscillated between ~ - 13 and -23 km/h, whilst over SL the velocity varied from -18 to -30 km/h. It is interesting to note that a similar behavior in the velocities is present in March, April and May. From May to June, a decrease/increase in the drift over SL/CP was observed. During June and July months, the velocities over both sites were very similar, but later clear anti correlation between the velocities may be noted.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a)
Jan
Feb
Mar
April
May
June
July
Aug
Sept
Oct
Nov
Dec
V_m (km/h)
Day of the year
Day of the year

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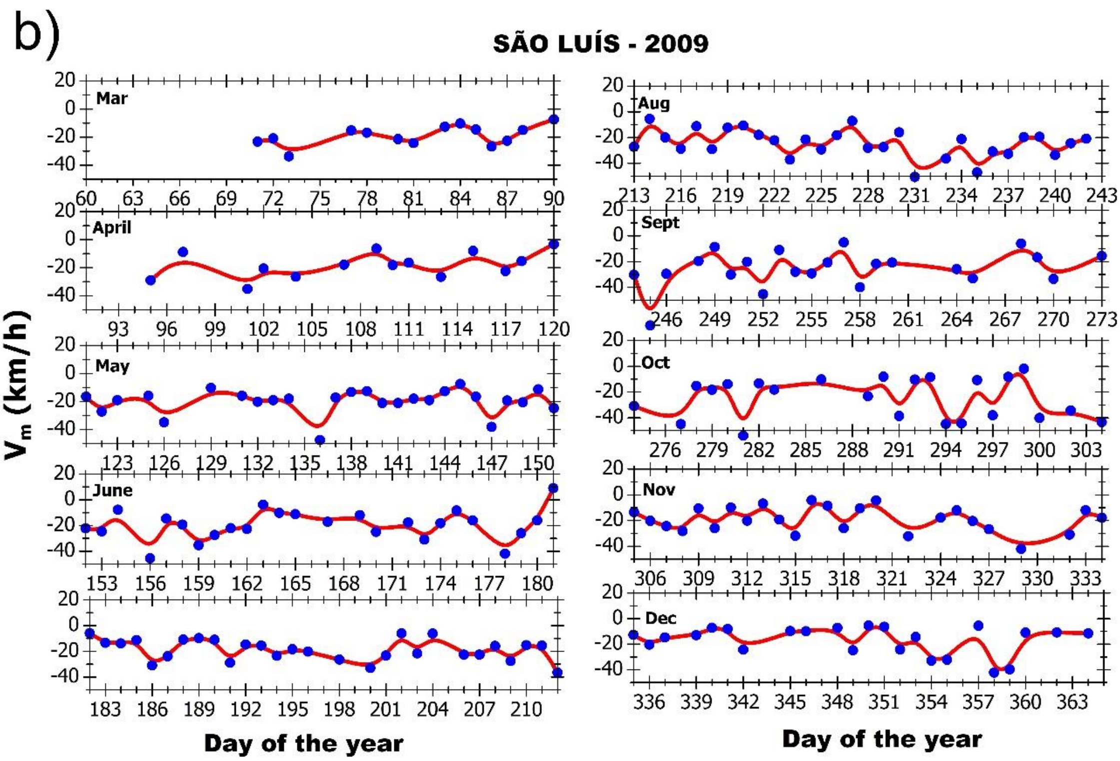

Figure 10: a) The average descending velocity of intermediate layers for CP and b) for SL.

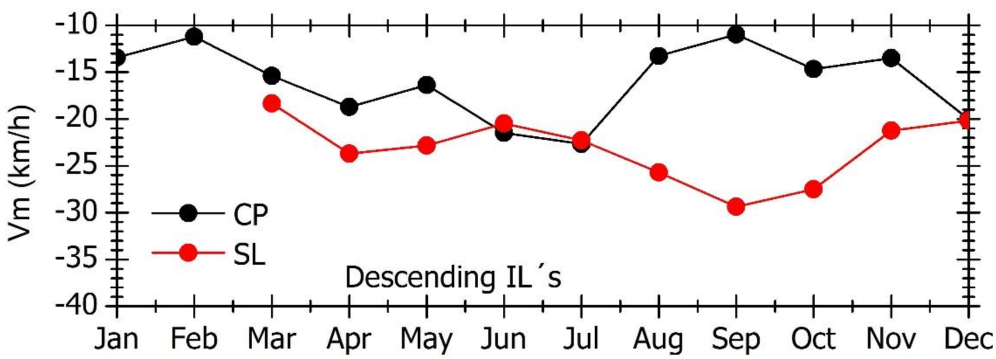

Figure 11: The monthly average descending velocity of intermediate layers for CP and SL.

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4. Discussion

The analysis of Digisonde data collected over an equatorial and low latitudes at the Brazilian sectors shows, for the first time, a high frequency of occurrence rate of the IL's during the solar minimum period with some distinct features. Previous studies have emphasized that the IL's could result primarily from the wind shear process driven by different tidal modes (Fijitaka and Tohmatsu, 1973; Mathews and Bekeny, 1979; Tong et al., 1988). Using the MIRE model, Resende et al. (2017a, 2017b) verified that the diurnal component of the zonal wind is very important in the formation of the Es-layers (at 90-140 km) over Brazil; however, the descending movement is simulated only when the meridional wind is included in the model. Lee et al. (2003) found for an equatorial anomaly region in Japan that the semidiurnal tide mode is dominant in the spring and winter, while the quarterdiurnal prevails in summer/autumn. For an Indian station, Niranjan et al. (2010) observed a high occurrence probability in winter, moderate occurrence rate during equinox and low occurrence during summer solstice.

Our results show that the occurrence of this kind of layer over the equatorial and low latitudes regions does not present any seasonal preference, but the daily occurrence probability of descending IL's shows an interesting perspective. In Figure 12 we may note that during the equinox, the occurrence of IL's above 130 km over SL shows two maxima, one at 11 UT and other at 18 UT, with the probability of ~ 25-30%. Very small occurrence was observed during the night (~ 5%). Similar behavior is observed in the winter solstice (~ 35% in both peaks). In this case, the nocturnal IL's were not observed. In the summer, only one dominant peak was observed at 12 UT with an occurrence probability of 60%. During the night, the occurrence was below 5%. Unlike São Luís, the maximum probability over Cachoeira

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Paulista was characterized by a broad maximum with a peak at times between 12 and 15 UT for all periods analyzed and frequency of occurrence varied between 50 and 70%.

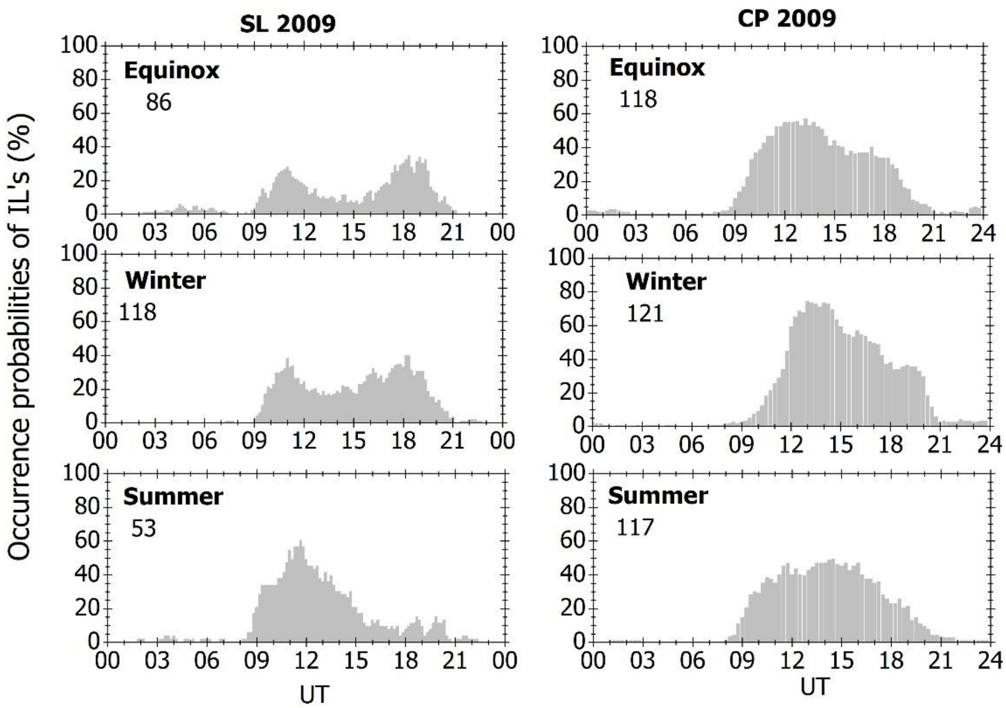

Figure 12: Occurrence probability of the intermediate layers (h≥130 km) over SL and CP during 2009. In this plot, all the simultaneous IL's observed were considered. The number of occurrence of IL's is indicated in each panel.

It has been known from previous studies that the intermediate layers are influenced by the atmospheric tides, mainly by the semidiurnal mode. In order to investigate how these waves can affect the IL's dynamic over Brazil, we applied the fast Fourier transform analysis in the height parameter and found that the semidiurnal mode could influence the IL's mainly over Cachoeira Paulista, but the dominance in all the cases, for both SL and CP, comes from the diurnal tide. In this analysis, the data

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gaps, which indicates the non-occurrence of the IL (with exception in January and February for SL) were replaced by the number "zero". Figure 13 (top panel) shows that in equatorial region, the descending IL's presents a well-defined diurnal periodicity in all seasons, followed by the terdiurnal and quarterdiurnal modes. There is an exception in summer, when the contribution of semidiurnal mode is also evident. However, as mentioned previously the lack of data during January and February can affect this result. Similar to SL, the role of the diurnal tide is dominant over CP (see bottom panel of Fig. 13), but the influence of semidiurnal mode was evident, mainly in the equinox and summer. A little influence from the terdiurnal and quarterdiurnal also can be identified during the equinox and winter.

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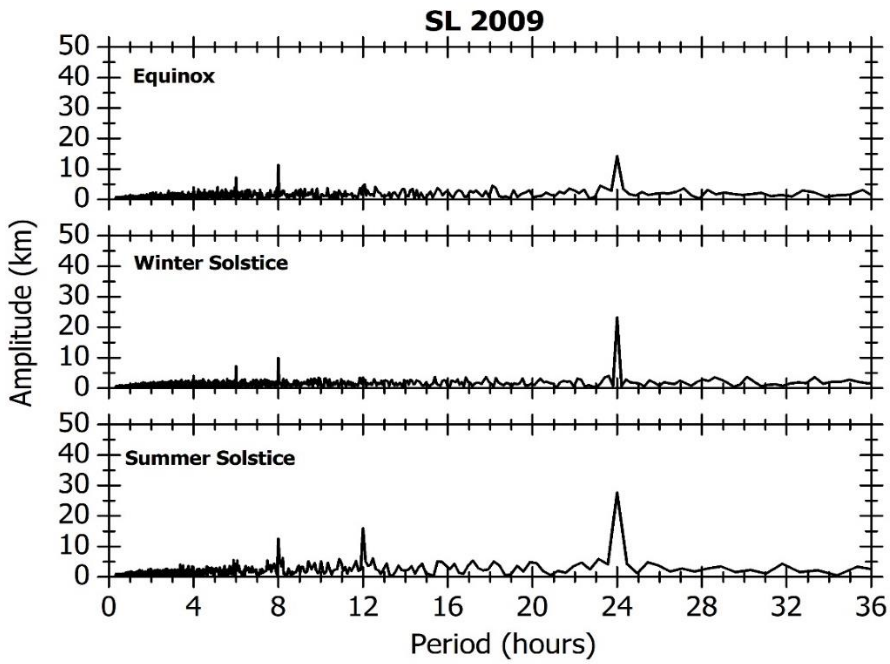

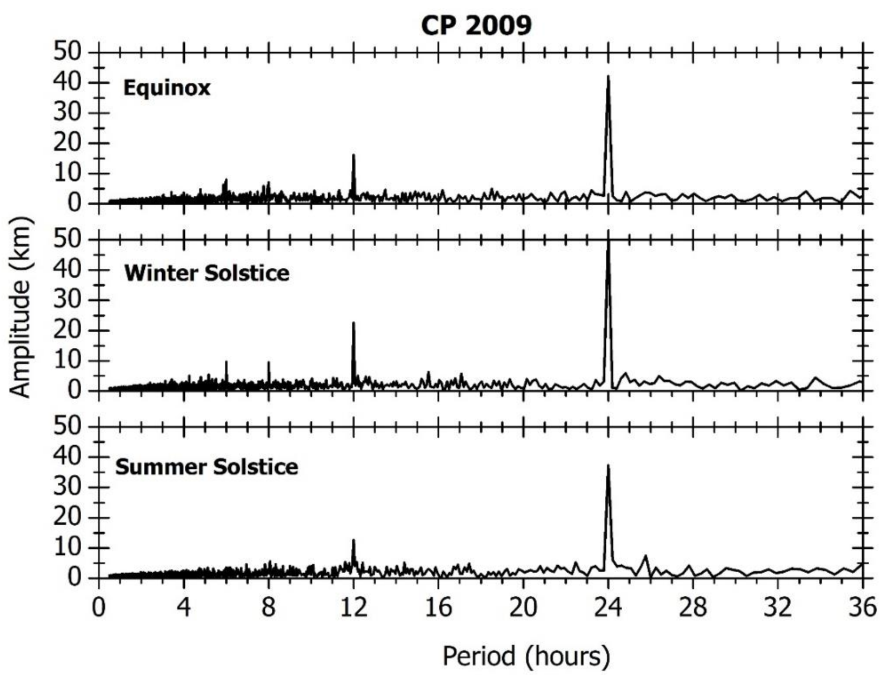

FIGURE 13: The FFT analysis of the intermediate layers height recorded at SL (top) and CP (bottom) during 2009.

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The presence of some nocturnal IL's over CP and SL during almost all season (except during the June solstice in SL) was another differential factor observed in our study. As mentioned by Lee et al. (2003), this result may be influenced by a limitation in the Digisonde, when the plasma frequency is lower than the lowest sounding frequency (1MHz), or by a blanketing caused by an underlying Es layer (l/f type). Over Arecibo, a middle latitude region, for example, the nocturnal IL is a very common phenomenon (Shen et al. 1976; Osterman et al. 1994). Rodger et al. (1981) also reported the presence of nocturnal IL's over South Georgia. The authors mentioned that the behavior of the F-layer some time before the occurrence of the IL suggested that the ionization increase observed in the valley region resulted from a downward transport of the F layer probably due to the solar semidiurnal tide. According to them, the probability of occurrence of the IL's is very low when the F layer height is higher than 220 km, but increases rapidly as they falls towards lower altitudes. As shown in the examples of Fig. 5, in almost all the cases for SL, for example, we noted that the F layer was located at ~ 225 km, but there are some exceptions, like on 25 March; 8 Aug. and 7 Oct. In those cases, the F region was slightly above 250 km. Over CP, the nocturnal layers had similar characteristics. On 10 Aug., we can see clearly that the descent of the intermediate layer was accompanied by an ascending of the F layer until 02 UT. It is also interesting to note the similarity of the IL during this day with the sporadic-E layer formed due to particle precipitation (a-type Es layer), with high range spreading.

One of the most interesting aspect about the climatology of intermediate layers over Brazil is the remarkable presence of ascending intermediate layers, especially, the case that happened in the equatorial region during 5 Oct. Some studies have mentioned about this peculiar feature, but hardly any discussion about them has been made until now. Figure 14 shows some parameters of the F layer and intermediate

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layers during this day. In the first panel are presented the F-layer virtual height (h'F), the F1 and F2 layer peak heights (hmF1, hmF2), and the minimum virtual height of the IL trace (h'IL). The second panel shows the band-pass filtered oscillations in F layer true height at specific plasma frequencies (4.1, 4.2, 4.3 and 4.4 MHz), as observed by the Digisonde. They are plotted with their base values displaced by 5 km (cumulatively) at each frequency. The last two panels present the distribution of the tropospheric convective zones as obtained from the GOES satellite above Brazil at 07 and 08 UT. We may note that at ~1115 UT, the IL height starts to increase going from 130 to 350 km in an interval of one hour. At the same time, the hmF2 parameter is also intensified. A gravity wave manifestation in the form of oscillations in F layer true heights can be in part responsible for the raising of the IL. The lower two panels show pictures of the convective zones (with the temperatures below -60º C) around São Luis (~700 and 1000 km of distance) taken some hours before the increase in the height of IL (07 - 08 UT), which give some support to the idea about the role of gravity waves. According to Vadas and Fritts (2004), the gravity waves excited by convective systems can have strong impacts in the atmosphere in high altitudes due to the fact that they have long vertical wavelengths and propagate in all directions from the convective source. However, the increase in the AE index from 25 to 175 nT at 1130 UT, appears to have produced some effect through the action of a prompt penetration electric field with eastward polarity in the behavior of the F layer height at this time.

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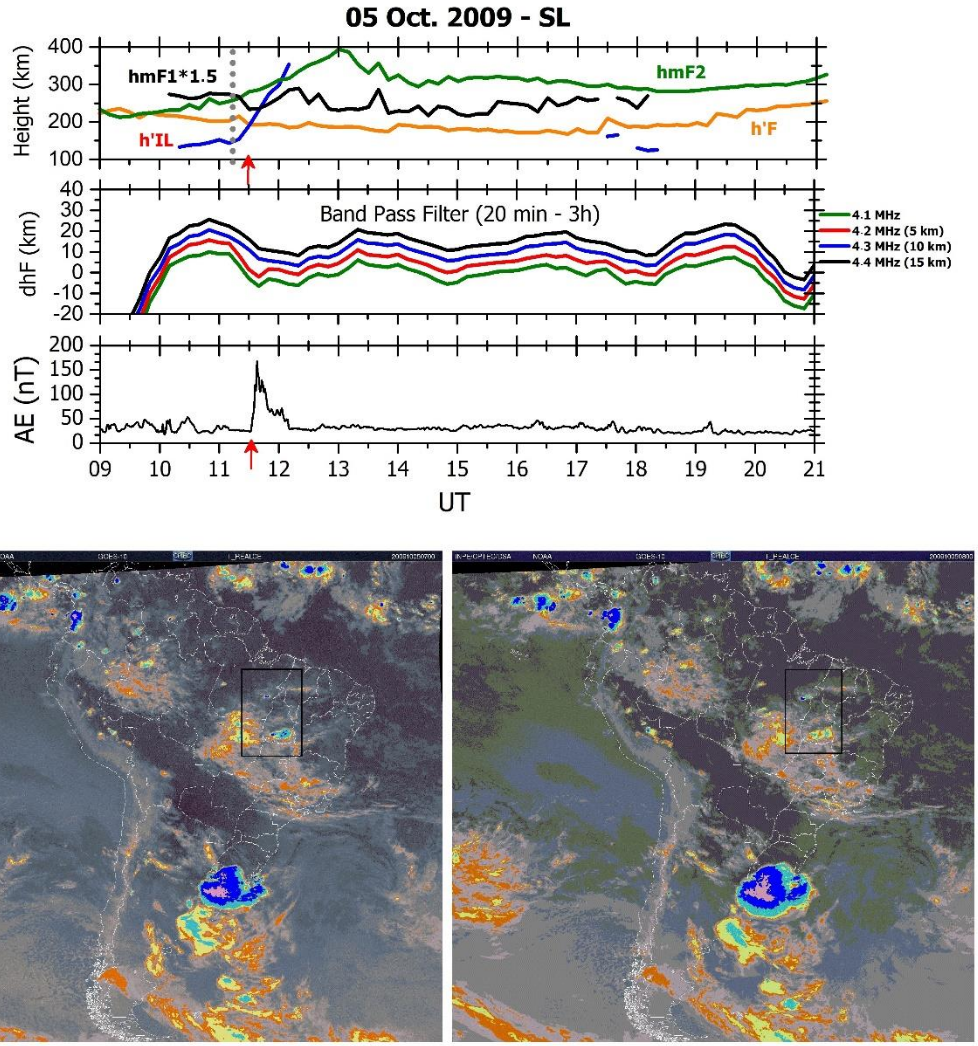

FIGURE 14 – Ascending intermediate layer over SL during 5 Oct. The first panel (from top to bottom) shows the virtual height of the F layer (h'F, gray line), the F1 and F2 layer peak (hmF1 and hmF2, black and green lines) and the virtual height of IL's (h'IL, red line). The hmF1 parameter was multiplied by a factor of 1.5. The middle panel shows the Band-pass filtered (for 20 min. to 3h periods) height oscillations at frequencies 4.1 to 4.4 MHz. The third panel shows the auroral activity index AE indicating the possible influences of prompt penetration electric field. Images from GOES satellite for 07 and 08 UT showing the convective zones near to São Luis (as indicated by the black rectangle) is shown in the last panel.

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The sequence of ionograms in Figure 6 showed that during this day, the IL initially detected at ~130 km attained first the F1 layer until progress to the F2 layer base. In this interval, considerable modifications, like a bifurcation (see for example the ionogram from 1210 UT) was seen mainly in the F2 layer. As mentioned by Abdu et al. (1982), distortions like this in the F layer trace can be a result of ionospheric disturbances induced by the atmospheric gravity waves. Besides that, our study was made during a period in which the ionosphere was considerably contracted due the extremely low level of solar fluxes (UV, EUV and X-rays) (Heelis et al., 2009 and Liu et al., 2011). As mentioned by Balan et al. (2012), under these conditions, and considering the absence of severe magnetic disturbances, the tides and waves originating in the lower atmosphere can be expected to register their effects in the thermosphere and ionosphere more easily. In agreement with Essien et al. (2018), the occurrence of small (SSGW) and median (MSGW) scale gravity waves over São João do Cariri from 2000 to 2010, was higher in 2009 followed by 2008. During 2009, 289 events of SSGW and 66 events of MSGW were identified in 199 nights of observations (175 with a clear-sky and 24 with clouds). These results are very interesting in that they reveal the special conditions of the coupling between the atmospheric layers during this period of the deep solar minimum activity.

The distortion in the F-layer trace was a frequent feature seen in our data. Figure 15 shows some examples over equatorial and low latitude stations in Brazil. Large modifications in the F1 and F2 layers were noted, not only throughout the bifurcations as previously mentioned, but also in the form of forking trace in both F1 and F2 layer, besides other modifications that were not very well defined. The ionograms from 13 Oct. (SL), 08 Dec. (CP) and 5 Oct. (SL) show some examples of the presence of forking trace. Note that the last ionogram example corresponds to the same day discussed in the case study presented in Figure 14. The Digisonde registered this feature over Cachoeria Paulista for more than 2 hours. On 23 July, some interesting aspects also may be noted. At 1707 UT, well-defined F1 and F2 layers can be noticed. Eight minutes later, the F2 layer structure was considerably modified. The critical frequency reduced from ~ 7 to 5.5 MHz, however the more interesting modifications were verified at 1730 UT, when the F2 layer detached from the F1 layer and rose by ~ 120 km. The sequence of ionograms (not shown here) shows that the F1 layer was transformed into an intermediate layer with descending movement, as expected. The strong uplift of the layer in a short time scale is generally caused by a prompt penetration electric field (Abdu et al. 2009; Santos et al. 2012; Santos et al. 2016) but, in this case, the interplanetary magnetic field was weakly to south (~ -2 nT) and in its recovering phase. The AE and Dst indices were 150 nT (recovery phase) and -23 nT, respectively. In this scenario, we do not believe that this distortion and uplifting of the layer were caused by a penetration of electric field, because the over-shielding electric field (based in AE recovery), which is westward in this case should make the layer go down and not rise as observed. Therefore, it is highly probable that this modification in the F2 layer and the subsequent formation of the IL was caused by a gravity waves propagation. Some oscillations were also observed over SL (not showed here), with a forking trace observed at 21 UT. Figure 15 shows other common examples of distortions occurring in the F1 layer. Oscillations like those presented on 18 Aug. generally evolve into an intermediate layer from a detachment of the F1 layer base. In another example, on 13 April, a different aspect was noted at the high frequency end of the F1 layer. In the course of time, this characteristic that appeared to be an extra ionization evolved to a descending intermediate layer that attaining heights below 130 km for example. The oscillatory pattern of velocities also shown in Figure 10

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also suggested a possible influence of gravity waves propagation in the dynamics of the intermediate layers.

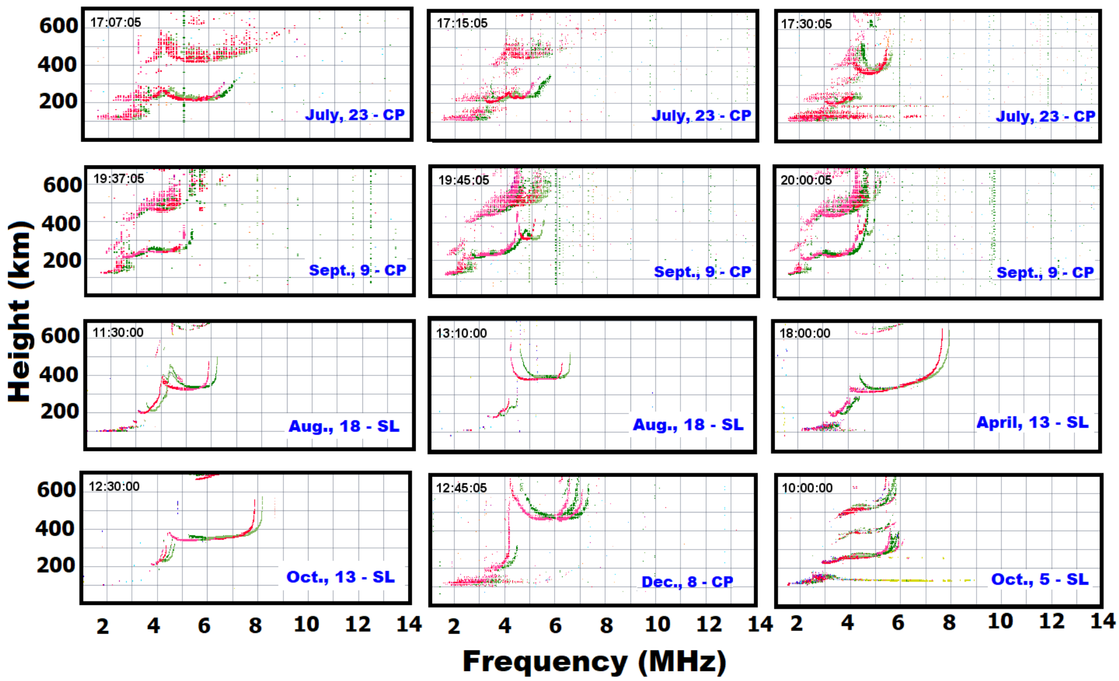

FIGURE 15: Ionograms showing the possible manifestation of gravity waves in the intermediate layer at equatorial (SL) and low latitude (CP) regions.

5. Conclusions

In this work, we have presented for the first time the climatology of the descending intermediate layers over equatorial and low latitudes regions in Brazil during the extended solar minimum of 2009. The results show that this layer has a high probability of occurrence in such latitude ranges, occurring predominantly during the day with well defined descent movement. The ftIL parameter presents a behavior similar to that of the normal E layer critical frequency, with a maximum intensity at ~12 LT. The study realized here revealed that the high occurrence rate of the IL was not related with seasonality.

Some peculiarities were found, such as the presence of nocturnal layers, simultaneous IL's, ascending IL's and also the intermediate layers formed from a detachment of the F1 layer base. It was showed from the Fourier analysis that the dynamics of the IL's over Brazilian region is dominated by the diurnal tide, followed by the semidiurnal, terdiurnal and quarterdiurnal tides. Besides that, the gravity waves propagation and the prompt penetration electric fields may also influence the dynamics of IL's.

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