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# Some Differences in the Dynamics of the Intermediate Descending Layers Observed During Periods of Maximum and Minimum Solar Flux

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**Abstract** In this paper, ionograms from São Luís (SL, 2°S; 44°W, I: −3.8°) and Cachoeira Paulista (CP, 22.42°S; 45°W, I: −34.4°) are analyzed to examine the characteristics of the intermediate descending layers (ILs) over the Brazilian equatorial and low-latitude regions under different solar flux conditions. The solar flux effects on the ILs are investigated in terms of the rate of occurrence of the IL; the seasonal behavior of some parameters such as the height, frequency, and velocity; and the duration and the number of ILs events observed per day. One of the main results of this work is that unlike over CP, the ILs over SL presented some peculiarities, such as a lower rate of occurrence during a period of solar maximum activity (2003) when compared with a period of solar minimum activity (2009). This apparent variation was likely caused by the magnetic equator moving away from SL during this period. The duration of the ILs was also investigated, and it was found that in 2009, the ILs presented higher life time than in 2003. The descending velocity of the ILs is compatible with the semidiurnal and quarter-diurnal tides. Over SL, the larger descending rate in some cases (>10 km/hr) may reveal the additional influence of the gravity waves in the IL's dynamics.

## 1. Introduction

Intermediate descending layers (ILs) are regions of enhanced electron density located in the ionospheric valley region that extends from the upper $E$ region to the $F$ layer bottomside. Among the important characteristics of the IL is its downward motion that may last from several minutes to hours, reaching the heights of the ionospheric $E$ region and merging with the sporadic-$E$ (Es) layers. Shen et al. (1976) reported that the maximum density of the ILs over Arecibo varied from ~$3 \times 10^2$ to $1 \times 10^3$ cm$^{-3}$ in the altitude region near 130–160 km.

Earlier studies have shown that in the midlatitude regions, the ILs result from an ionization convergence driven by the neutral wind systems (Constantinides & Bedinger, 1971; Smith, 1970). They are very frequent after midnight, being dominated by the S2 and S4 propagation modes of the atmospheric tides (Fujitaka & Tohmatsu, 1973). Tong et al. (1988) mentioned that the ILs occurrence over Arecibo also could be influenced by the quarter-diurnal tide component. Using a numerical simulation of the ion trajectories, they showed that a combined 12- and 6-hr periods wind system is required to explain the upper $E$ region observations. Using very high frequency (VHF) radar data from the low-latitude region of Gadanki (79.2°E, 13.5°N), Patra et al. (2002) observed descending structures of the upper $E$ region field-aligned irregularities that resemble the intermediate layers observed over the midlatitude sector. They observed the presence of ionization at about 140–160 km of altitude at ~21:00 LT that presented a downward movement with time merging eventually with the continuous band of normal $E$ region echoes below 120 km.

Recently, Dos Santos et al. (2019) presented a climatological study of the ILs over the equatorial and low-latitude regions in Brazil during a period of extreme solar minimum activity. They found an ILs' rate of occurrence higher than 90% over the low-latitude sector and higher than 60% over the equator. The day-to-day variability observed in the ILs parameters such as the height, frequency of occurrence, and descent velocity may result from variations of tides, the electric fields, the metallic ion, or due to the influences of gravity waves (Nygrén et al., 1990; Wilkinson et al., 1992). In addition, Dos Santos et al. (2019) also mentioned
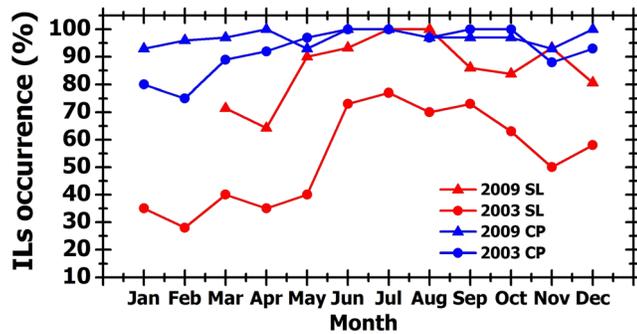
**Figure 1.** Intermediate descending layers' occurrence over SL (red lines) and CP (blue lines) during 2003 (circles) and 2009 (triangles).

that the IL formation from a detachment of the F1 layer base was one of the most commonly observed characteristics.

Although the ionospheric valley region has often been investigated, it continues to be one of the least understood regions of the atmosphere-ionosphere system. The lower electron density of the intermediary (valley) region between the $E$ and $F$ layers makes it difficult to study this region by the conventional ground-based ionospheric instruments. As mentioned by Chen et al. (1991), the regions of decreased ionization between the ionospheric layers do not reflect the radio wave, and the resulting discontinuity leads to uncertainty in the true height calculation in the valley region. The ionosonde measurements, for example, can be used to determine the occurrence and location of the ionospheric $E$-$F$ valley, but they cannot be used to infer the detailed parameters such as the depth and the height of the valley (Denisenko & Sotsky, 1978; Mahajan et al., 1994), differently from the measurements by an Incoherent Scatter Radar (ISR) that provides electron density with spatial and temporal resolutions at $E$-$F$ altitudes, such as the measurements made at the Arecibo Observatory (Raizada et al., 2015, 2018; Trost, 1979).

In this context, this work explores the essential features of the ILs observed by two Digisondes operated in Brazil during periods of maximum and minimum solar activity. Specifically, we will investigate the probability of occurrence of the ILs, as well as the seasonal behavior of the height, frequency, velocity, and the duration and the number of the ILs events observed per day.

## 2. Experimental Data

We will examine the observational data of the virtual height (h'IL) and the top frequency (ftIL) of the ILs as observed by the Digisondes operated at São Luís (SL, 2°S; 44°W, I: −3.8°) and Cachoeira Paulista (CP, 22.42°S; 45°W, I: −34.4°) during 2003 and 2009, representatives of maximum and minimum solar activity, respectively. The Digisonde is a sweeping frequency radar, which is very sensitive to detect the ILs over the Brazilian region. Although this instrument does not provide the electron density profile in the valley region where the ILs usually occur, some interesting characteristics of the general behavior of the ILs can be explored. Essentially, the ionospheric survey made by this instrument is based on the reflection of the electromagnetic signal transmitted vertically to the ionosphere at frequencies ranging from 0.5 to 30 MHz. The ionospheric information is recorded in the form of ionograms that display the virtual height of the returned echoes versus their frequency, registered at 15-min intervals. For more details on the Digisonde, see Reinisch (1986). The criteria used for processing the h'IL and ftIL data from the ionograms using the SAO-explorer software were the same as those described by Dos Santos et al. (2019).

For the seasonal analysis to be presented in the next section, the data were grouped into three different groups classified as equinoxes (March, April, September, and October), winter or June solstice (May, June, July, and August) and summer or December solstice (January, February, November, and December).

## 3. Results and Discussion

Figure 1 shows the monthly occurrence rate of the IL during the years 2003 (descending part of Solar Cycle 23, represented by the circles) and 2009 (solar minimum, represented by the triangles) over SL (red lines) and CP (blue lines). For evaluating the percentage occurrence, we have considered the days on which the layer appeared at least once in a day. The number of days used in the ILs occurrence analysis for 2003 is shown in Table 1. Regarding the 2009 data, see Dos Santos et al. (2019). It is interesting to observe that over the low-latitude station of CP, the occurrence rate of the ILs is high in all the months evaluated, for both periods of maximum and minimum solar activity. Over the equatorial region (SL), the occurrence rate is lower in 2003 when compared with that of 2009. There is an increase in the occurrence rate as winter approaches in both 2003 and 2009 and a tendency of decrease in the equinoxes and summer months mainly in 2003.

In general, the results for SL during 2009 are very similar to those found by Rodrigues et al. (2011). Analyzing radar data, they showed that the occurrence of the 150 km echoes over SL during 2008 was higher between

**Table 1**
*Number of Days Used in This Study—2003*

| 2003 | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| São Luís | | | | | | | | | | | | |
| Number of days with data | 31 | 28 | 30 | 28 | 30 | 30 | 31 | 31 | 30 | 27 | 30 | 31 |
| Number of days with ILs | 11 | 8 | 12 | 10 | 12 | 22 | 24 | 22 | 22 | 17 | 15 | 18 |
| Cachoeira Paulista | | | | | | | | | | | | |
| Number of days with data | 21 | 28 | 26 | 27 | 31 | 30 | 31 | 31 | 30 | 30 | 25 | 31 |
| Number of days with ILs | 17 | 21 | 23 | 25 | 30 | 30 | 31 | 30 | 30 | 30 | 22 | 29 |

June and September, with a percentage occurrence of 100%. During these months, the echoes were also more intense and long lasting. Similar to the present results, they found a reduced occurrence rate around the March equinox (February–April).

Considering that in 2009 the solar flux values were much lower than in 2003 and that the occurrence of ILs over CP in these two periods was significant, we may state that apparently, the solar activity does not affect the IL's occurrence over this region, except in summer when an increase of about 10% was noted from the high to low solar activity. However, distinct characteristics were observed over the equator. As in some months (especially in winter) the occurrence of the IL over SL was very similar to that over CP during the solar minimum, and as significant difference was observed in the IL occurrence between solar maximum and minimum over SL, we believe that the increase in the percentage occurrence in 2009 over SL has had a considerable contribution arising from the magnetic equator displacement from SL during this period. According to the IGRF model, the magnetic inclination angle over SL varied from $-1.6°$ in 2003 to $-3.8°$ in 2009. In an attempt to quantify the possible effect of the dip angle variation over SL in the vertical ion velocity we have used Equation (4) from Mathews (1998) that describes the ion vertical velocity in absence of electric field ($E = 0$). We found that the factor that modifies the meridional wind U was ~2.5 times higher in 2009 when compared to 2003. On the other hand, almost no difference was observed in the factor that modify the zonal wind $U$. Therefore, we can say that the influence of the wind in generating the IL can increase rapidly at a given latitude from which the Equatorial Electrojet (EEJ) is receding, allowing the increased role of the tidal wind. Dagar et al. (1977) and Oyinloye (1971) showed that for dip angle higher than 2°, the ion convergence is predominantly caused by the neutral wind shear.

The high IL' occurrence over CP during both the solar maximum and minimum years emphasizes the efficiency of the winds in the IL formation over this region. Using ionosonde data from the low-latitude station of Townsville, Australia, Wilkinson et al. (1992) tracked the birth of the layers above 150 km of altitude and their systematic downward motion to the 110 km region. The observations were compared with the National Center for Atmospheric Research (NCAR) TIGCM (Thermosphere-Ionosphere General Circulation Model), and the results showed that the transitional layers located between 100 and 200 km were formed due to meridional wind shear-node convergence with an insignificant control by zonal winds. They also showed that the electric fields could play an important role in the effectiveness of the ion convergence and the downward transport processes at altitudes above 125 km. The authors suggested that ILs may not be considered as single-layer phenomena, but they could be a result of multiple processes at varying heights, intensities, and thicknesses, extending from regions close to the magnetic equator up to high latitudes to midlatitudes. The dominance of the meridional wind shear forces also was verified by Szuszczewicz et al. (1995). Using the ILs data collected by 12 ionosondes stations during September 1989 (ascending phase of Solar Cycle 22), they also found that the mechanisms for layer formation and transport are primarily driven by meridional and zonal wind shear forces. Their results also suggested that the TIE-GCM (NCAR Thermosphere-Ionosphere -Electrodynamics General Circulation Model) electric fields are too large to allow dominance of kinetic wind shear forces in the IL process. As mentioned by them, much weaker electric fields are sufficient to produce a good correlation between the observational data and the simulation.

Over SL, the importance of the winds seems to become evident only when the weakening of the equatorial electrojet occurred, allowing in this way an additional contribution of the winds in the formation of the ILs over this region. The impact of the magnetic equator displacement on the development of Es layers over Brazil has been discussed in the literature. Abdu et al. (1996), for example, showed that the secular drift
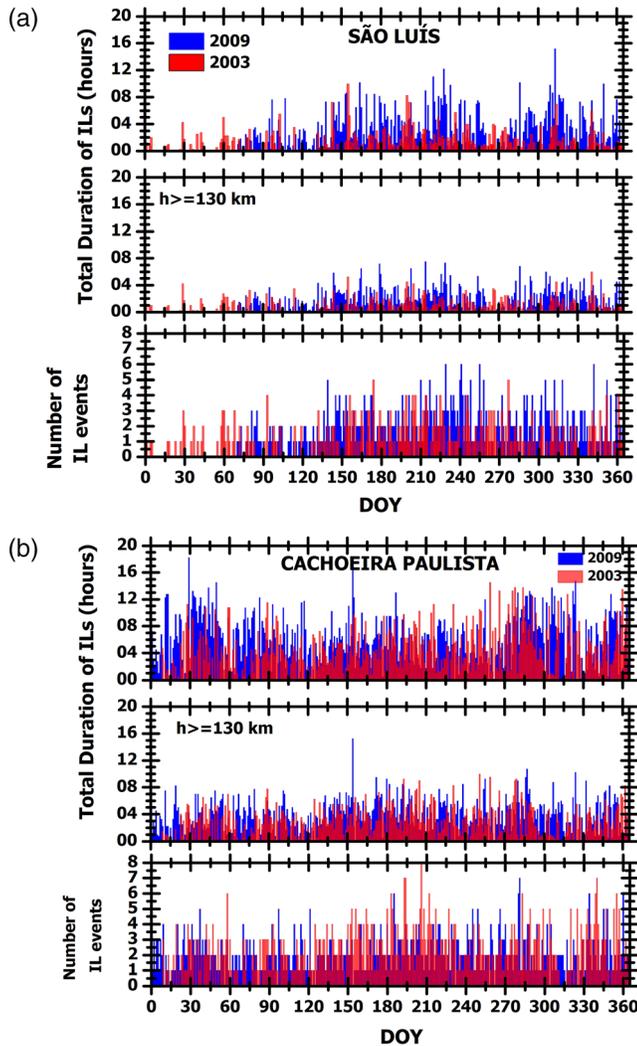
**Figure 2.** (a) Intermediate descending layers duration for different ranges of altitude (from top to bottom, first and second panel) and number of events over SL (third panel) during 2003 (red color) and 2009 (blue color). (b) Same as Part (a), but for CP.

of the magnetic equator to northward of Fortaleza was responsible for a systematic decrease in the q-type Es layer (arising from electrojet instability processes) over Fortaleza from 1975 to 1990, during which the magnetic equator drifted to north of Fortaleza by ~400 km. During the same period, an increase was observed in the types of Es layers that are very common over low-latitude regions that are known to be produced mainly by wind shear mechanism. These results reveal the competing roles of the equatorial electric field and the wind systems in the generation of the different types of Es layers as a function of the distance from the electrojet center. Resende et al. (2013) also reported the occurrence of different types of Es layers over SL during magnetic storm periods. An interesting study about the role of the winds in sporadic layer formation over SL during the same period of solar minimum studied here, that is, 2009, was made by Resende et al. (2018). Using observational data and the theoretical model for the $E$ region (MIRE), they found that the Es layers over SL did not present a well-defined pattern due to the competition between different mechanisms that involves the weakening of the electrojet electric field and the influence of the winds. Similar to Abdu et al. (1996), Resende et al. (2018) also found a reduced number of the Es type that are related to the irregularity strength from the equatorial electrojet (q-type Es layer) and the presence of other Es layers formed due to the wind shear influence. It is important to mention that the model used by Resende et al. (2018) covered the height range between 86 and 140 km only; therefore, the model did not cover the entire altitude range in which the ILs are observed.

As mentioned by Dos Santos et al. (2019), as the intermediate layers descend in height they may evolve into a normal Es layer, in the form of the c-type Es layer, for example. We do not count specifically the number of cases in which the ILs transformed into a normal Es layer attaining altitudes lower than ~130 km, but the analysis of the ILs total duration revealed that over the equatorial region the duration of ILs in 2003 was considerably shorter than in 2009. Figure 2 shows the durations of the ILs separately through the years 2003 and 2009 over SL and CP (Figures 2a and 2b, respectively) as well as the number of the detected ILs per day. The ILs' duration was measured from the moment in which they were initially detected until they attained altitudes higher than or equal to 130 km (middle panel of Figures 2a and 2b) and the duration since the time they were initially detected until they descend to heights

lower than 130 km and merge with the Es layer in development (upper panel of Figures 2a and 2b). In general, the ILs duration was higher during solar minimum than during solar maximum period, for both CP and SL. As the ILs are mainly a diurnal phenomenon with a behavioral pattern very similar to that of the $E$ layer (Dos Santos et al., 2019), the longest lifetime in 2009 can be partially attributed to the weakening of the $E$ region dynamo in this period (Santos et al., 2017). On the other hand, over the equatorial station, the duration of the ILs was lower when compared with the low-latitude region. This may probably mean that the mechanisms responsible for the maintenance of the ILs over SL may be different in some aspects when compared to that over CP. Besides that, the fact of the IL duration to be higher in 2009 mainly for heights below 130 km means that a higher number of ILs evolved to normal Es layers during this period in which the magnetic equator was displaced from SL. This result is in general agreement with those presented by Abdu et al. (1996) and Resende et al. (2013, 2018).

Figure 3 shows the percentage occurrence of the number of IL events per day calculated considering the number of days with $x$IL events (where $x$ denotes the number of ILs per day) divided by the total number of days analyzed (with or without IL) for each season during 2003 and 2009. Missing values for high number of events means probability of occurrence equal to 0. The average solar flux and the respective standard
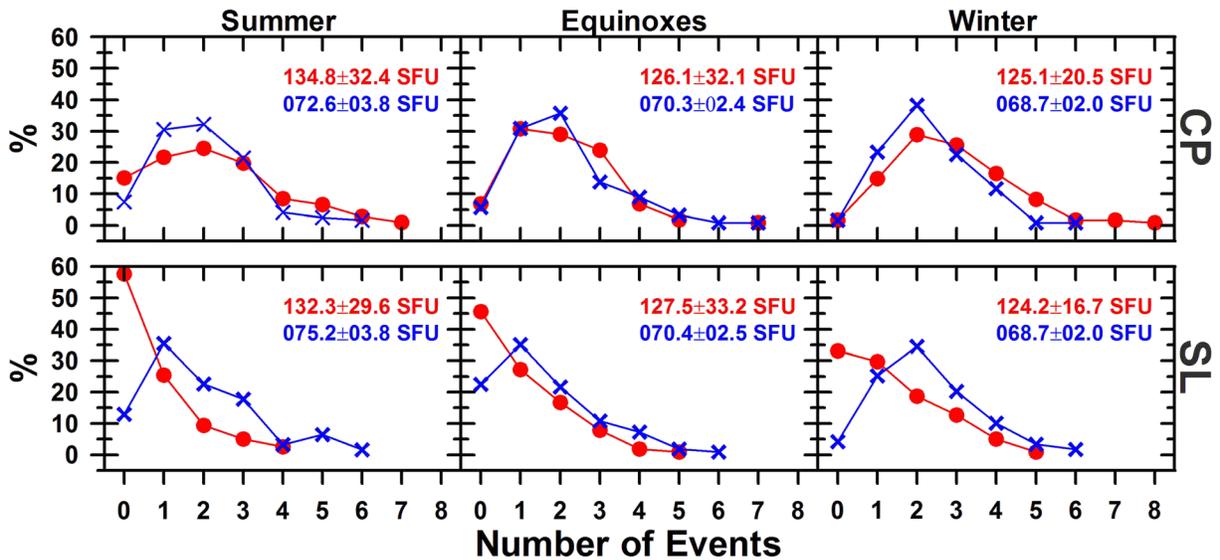
**Figure 3.** Percentage of occurrence of the number of events per day for December solstice, equinoxes, and June solstice (panels from left to right, respectively) over Cachoeira Paulista and São Luís (upper and bottom blocks, respectively). The red profiles represent the year 2003, while the blue ones the year 2009. Following the same color representation, each panel displays the average of solar flux as well as its standard deviation for each period in solar flux unit (1 SFU = $10^{-22}$ Wm$^{-2}$ Hz$^{-1}$).

deviation are also indicated inside each panel. Over CP, a small difference in the occurrence of the number of events per day during the equinoxes of 2003 and 2009 can be observed. December (summer) and June (winter) solstices exhibited similar behavior, with more occurrences of fewer events per day for low solar activity and more occurrences of days with higher events for more intense solar activity. In most of the cases, the intermediate layer appeared twice a day with a percentage occurrence of ~30% to 40% in 2009 and ~20% to 30% in 2003 in a given season. Over SL, a decrease in the number of days with more events in all seasons for the maximum solar activity can be seen, mainly during the June (winter) and December (summer) solstices. Besides that, the number of days without events over SL shows a drastic increase for periods of more intense solar activity, reaching up to 60% of no IL occurrence. Unlike CP, in 2009 the highest occurrence in SL was for the cases in which the IL appeared only once a day, except during June solstice (winter).

The local time and seasonal variations of the h'IL and ftIL for low and high solar conditions are presented in Figure 4. The left and right panels show the results for SL and CP, respectively. The number of points used in the average calculation is displayed at the bottom panel of each block of seasonal panels. It may be noted that the differences between high (red line) and low (blue line) solar activity are small, with the exception of some periods over SL, mainly in the equinoxes and summer. While over CP the average behavior of the height and frequency parameters during the daytime (06:00 LT to 18:00 LT) is rather smooth, over SL an oscillatory pattern is observed for all seasons. In general, for both maximum and minimum solar periods, the ILs are a daytime phenomenon, with a few cases being observed during nighttime as well (see the bottom panel for each location and season). This result can be influenced in part by a limitation of the Digisonde to detect the low ionization density that exists during these times. It is important to point out that experimental observations involving the variation of the virtual height of the intermediate layer may differ somewhat from its true height, particularly close to the critical frequency of the layer. However, in the absence of the true height values, the h'IL can provide us an insight of the behavior of the IL as per any study so far of the ionospheric layer dynamics using the virtual height as reference parameter. The same comment applies to the vertical drift derived from the h'IL, which will be discussed later.

A comparison between the ILs registered by the VHF radar at SL and the collocated Digisonde revealed interesting characteristics on 19 June 2009 (not shown here). While the radar registered ILs occurring simultaneously at different heights in the time intervals of ~13:00–14:00 LT, and ~16:30–17:00 LT, the Digisonde showed only one single layer in the time intervals of 15:35 LT to 16:35 LT and 17:20 LT to 18:10 LT. We can
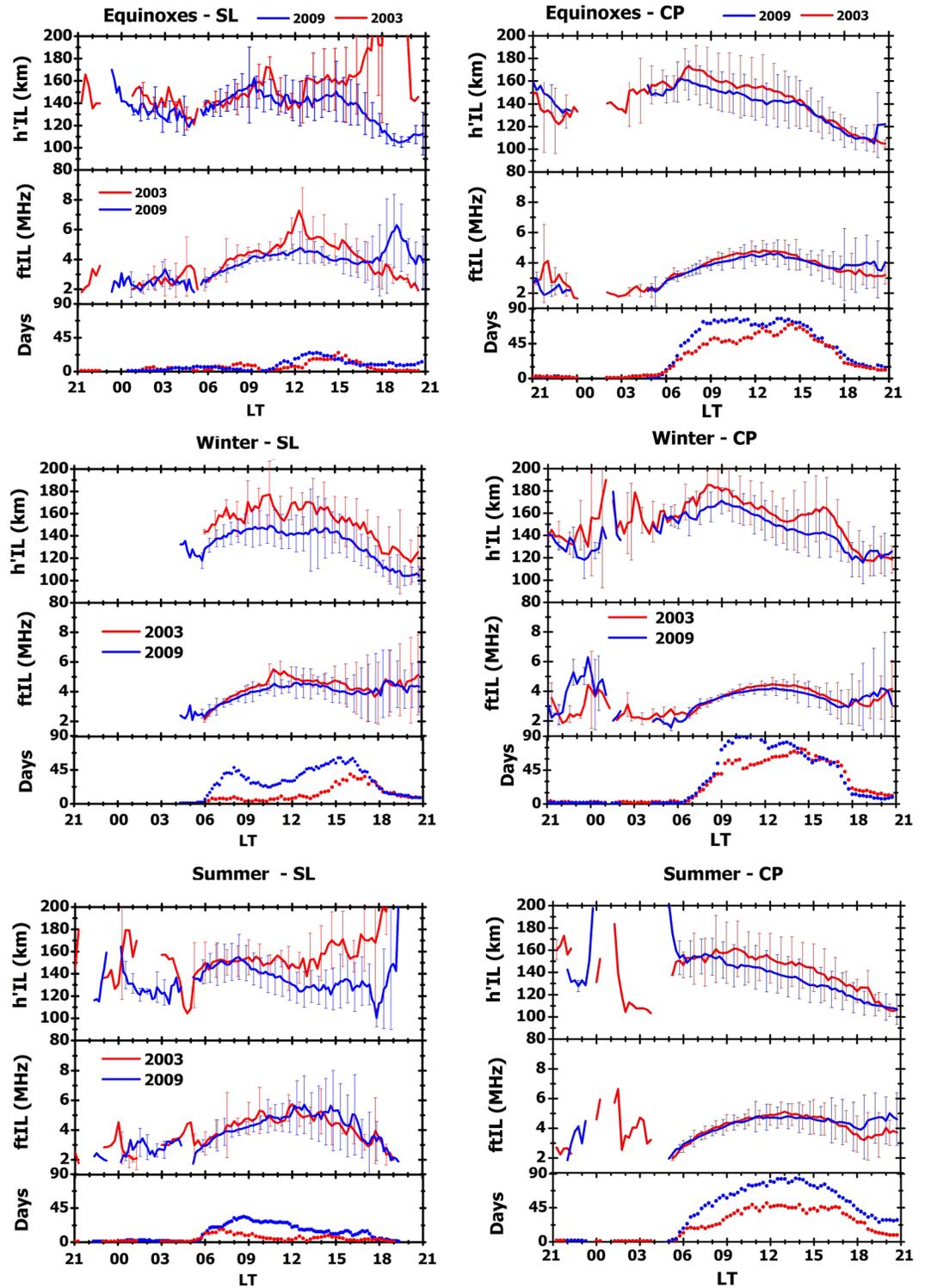
**Figure 4.** Local time variation of h'IL and ftIL from SL (left panels) and CP (right panels) for low and high solar activity periods (blue and red, respectively) for different seasons. The vertical bars represent the standard deviation. The bottom smaller panel of each plot shows the number of occurrences per local time.

observe that the time intervals in which the ILs were observed in the radar were not coincident with the register from the Digisonde. As mentioned by Dos Santos et al. (2019), simultaneous ILs were a common feature observed over SL, but during this specific day, they were not observed by the Digisonde as by the radar. Another point is that both the ILs from the Digisonde were formed from the detachment of the F1 layer. In the first case, the ILs presented a high descent velocity (~40 km/hr = 11 m/s) reaching the $E$ layer altitudes in 1.2 hr. On the other hand, the second layer was detached from the F1 layer at higher altitudes when compared with the first case and presented a lower descent velocity (1 km/hr = 0.3 m/s). In none of the cases, the ILs registered by the radar reached the $E$ region heights as observed by the Digisonde. This simple analysis shows that more investigation is needed in order to understand better the basic characteristics of this ionization located in the ionospheric valley. It is important to emphasize that these two sounding techniques detect different features of the ILs. While the ILs detection by the Digisonde is based on the partial or total reflection of the electromagnetic signal transmitted vertically to the ionosphere, the detection by the VHF radar occurs when the IL became unstable, generating field-aligned irregularities that provide coherent backscatter. This means that if the ILs do not become unstable, the radar may not see them, but the Digisonde will. The opposite also is true. When the IL becomes unstable, small-scale irregularities can be generated in a cascade effect and the Digisonde cannot be able to detect the ILs. This can explain the differences observed in the ILs detection in the example given above.

The mean h'IL values presented in Figure 4 can help us to find an explanation for the lower duration of the ILs in 2003 (of higher solar activity) as compared to 2009 (of relatively lower activity), mainly over SL (as discussed previously in Figure 2). As mentioned by Wilkinson et al. (1992), the issue goes beyond the forcing terms and may include questions on ion composition. However, as shown in Figure 4, over both SL and CP, the ILs remained at higher altitudes in 2003 as compared to 2009. This means that in 2003, the ILs were located in a region of higher background density wherein the layering process operates less efficiently than in a background of relatively smaller electron density. On the other hand, in 2009, the ILs descent range was higher attaining the altitudes with the dominance of the metallic ions, which, in turn, have a longer lifetime. This characteristic added to the weakening of the $E$ layer dynamo possibly explains the higher durability of the ILs in 2009 than in 2003. However, a detailed study based on numerical simulations need to be carried out to validate this hypothesis.

Oscillatory patterns were observed in the mean values of h'IL and ftIL over SL (mainly for 2003) as presented with more details in Figure 5. Over SL located very close to the dip equator, the vertical displacement of the IL (like that of the $F$ layer) cannot be caused by meridional wind. Therefore, the height oscillations observed over SL are clear indications of the role of zonal electric field oscillations that can be induced by gravity waves. In the first two panels (Figure 5a) are plotted the monthly mean values of h'IL (upper) and ftIL (bottom) for 2009 and in the middle two panels (Figure 5b) similar results are presented for 2003. Color-coding was used to identify the different months of the year. During 2009, the mean values of h'IL presented small variation among the months analyzed and attained heights lower than 130 km after 01:00 LT, 10:00 LT and also mainly after 17:00 LT. Only in December, an increase was observed in the mean h'IL after 18:00 LT. Regarding the ftIL parameter, in some months a considerable increase was observed after 17:00 LT, mainly in April and July months. After 22:00 LT only small values of ftIL (< ~3 MHz) were observed. The scenario for 2003 was different in some aspects. In most of the cases, the ILs attained heights lower than 130 km only after 18:00 LT. In contrast to 2009, higher values of ftIL were observed during the day and the night. As indicated by the horizontal black lines in the h'IL parameter of Figure 5b, the ILs in 2003 showed larger variation in the range of height (from ~130 to 190 km) when compared to 2009 (when the range varied from 130 to 160 km). As shown in Figure 5c, the F10.7 cm index was considerably higher in 2003 (red lines) than in 2009 (blue lines) with a large degree of day-to-day variability, as indicated by the standard deviation bars. It is known that with the increase in the solar flux, the ionospheric electric fields, mainly during evening time, will also increase in the form of prereversal enhancement (Abdu & Brum, 2009; Fejer, 2011). As the ILs were located at higher altitudes during 2003 than in 2009, the oscillatory pattern observed in the h'IL parameter may have been caused in part by the more intense zonal electric fields during 2003. It is possible to verify that in 2003 the ILs present a rise in the afternoon during the months of January, April, October, and November. In 2009, only in December, the same characteristics was observed. This characteristic seems to be related to the influence of the prereversal enhancement of the zonal electric field (PRE) that is observed around the time in which the IL's rise is observed. Santos et al. (2013) and Abdu et al. (2010) studied the
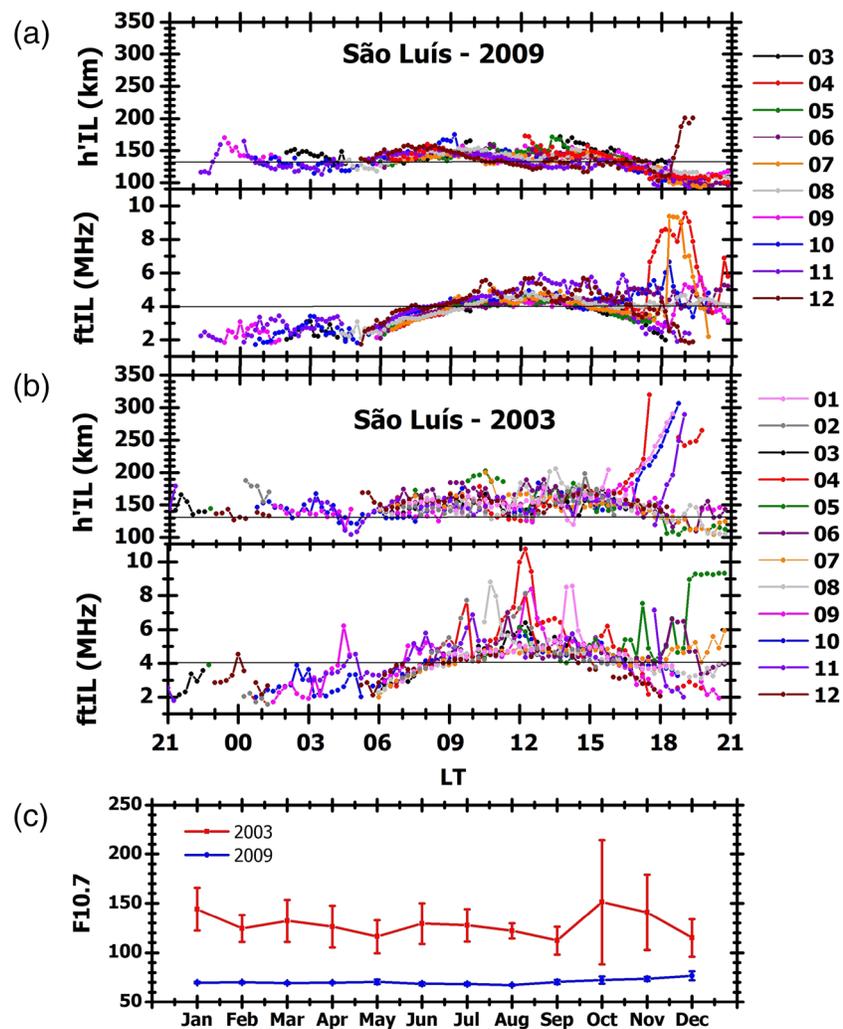
**Figure 5.** Monthly mean values of h'IL and ftIL over SL during (a) 2009 and (b) 2003. (c) The monthly mean F10.7 cm index (SFU) for 2009 (blue) and 2003 (red).

impacts of solar flux on the evening prereversal vertical drift over SL and Fortaleza and showed that the vertical plasma drift peak/zonal electric field is strongly dependent on solar emission fluxes. The solar flux has an important influence on the ambient ionosphere conductivity gradient at sunset as well as on the thermospheric winds responsible for the dynamo of the *F* region. Goel et al. (1990), for example, observed that the *E* region conductivity gradient during the solar maximum is higher by a factor of 2 when compared to the solar minimum period. In this context, we believe that the rise of the ILs at sunset can also be caused by the PRE. As verified in our data, if on the one hand the PRE can be probably responsible for the ascending movement of the IL, on the other hand, the probability of an intermediate layer to occur at about 18:00 LT (the time of PRE's occurrence) is drastically reduced. This seems to be a very interesting feature that deserves a more profound investigation in a separate study.

Figure 6 shows a comparison of the seasonally averaged local time variation in the occurrence of ILs events (in percentage) over SL and CP during 2003 and 2009. Only the layers above 130 km were considered in this analysis. Differently from the results in Figure 1, which considered the IL occurrence during a day, independent of whether they were observed more than one time per day or not, the IL's percentage occurrence presented in Figure 6 considered all the IL events observed on a given day including those that occurred simultaneously. The number of days with IL events used in this statistic is shown inside each panel of Figure 6 (when simultaneous IL occur in a given time interval, the respective day was computed twice).
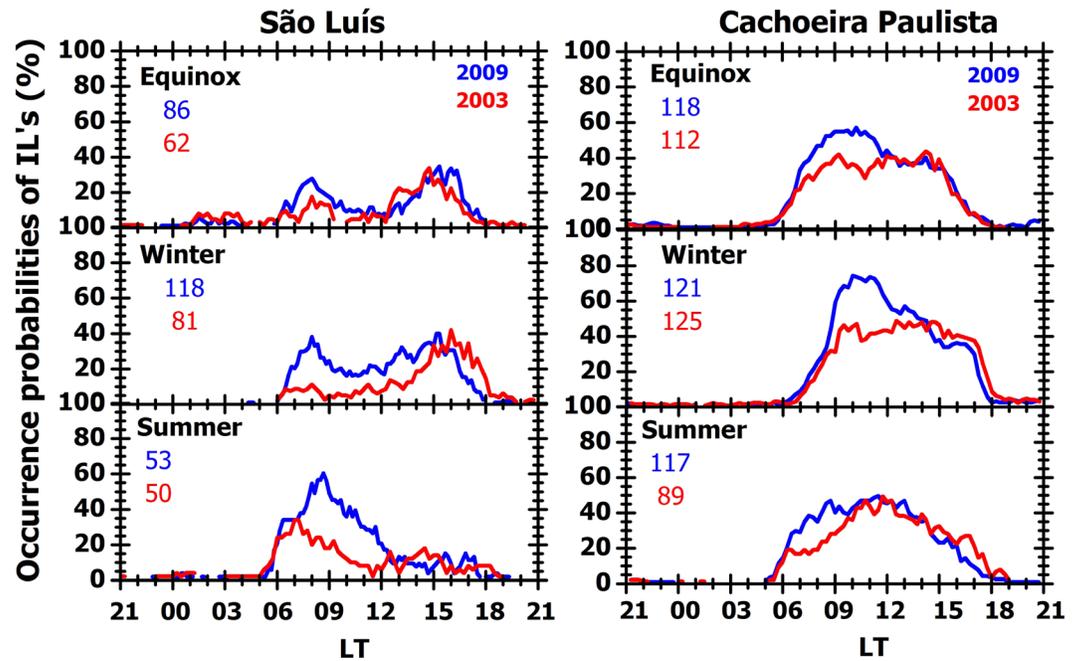
**Figure 6.** Occurrence probability of the intermediate layer events over SL (left) and CP (right) during 2009 (blue lines) and 2003 (red lines). Only the layers above 130 km were considered in this statistical analysis. The number of days with IL events used in the occurrence percentage calculation is indicated in each panel.

Independent of the season, the ILs occurrence over SL is higher in 2009. Besides that, two peaks are observed, one at about 08:00 LT and the other at 15:00 LT in both the periods analyzed. Before midday, the ILs occurrence decreased with the increase of the solar activity. However, during the local afternoon, the occurrence in 2009 and 2003 seems to be numerically similar. Over CP, the higher occurrence also was observed during the low solar activity. Similar to SL, in 2003 the ILs occurrence was lower before midday and in the second part of the day, the ILs occurrence in 2009 and 2003 was very similar. Additionally, it is possible to clearly observe variability in ILs occurrence during the low solar activity, mainly during the winter and equinoxes. The same is observed during 2003; however, the variability is less pronounced.

Figure 7 shows the mean vertical velocities of the ILs over SL (Figure 7a, from 06:00 to 15:00 LT) and CP (Figure 7b, from 09:00 to 18:00 LT) for the different seasons during the periods of 2003 (red line) and 2009 (blue line). The respective standard deviation is also presented in these Figures. Both descending and ascending ILs have been considered in this analysis. The large standard deviation, which in this case was divided by a factor of 3 for better visualization, reveals the large day-to-day variability in the vertical velocity. This probably occurred due the fact that velocity had been calculated from the virtual height of layer, which can be significantly modified when the underlying ionization undergoes fast changes or when the sounding signal frequency is close to the critical frequency of the ionospheric layer. In general, the descent velocity over CP during the interval between 09:00 and 18:00 LT reached a value between ~5 and 10 km/hr, with a few exceptions. The Vz over SL varied from ~5 and −5 km/hr in the first hours of the day and between 06:00 and 15:00 LT presented an oscillatory pattern as compared to that over CP, attaining a maximum negative value of ~15 km/hr. Considering that the actual descent rates (taking into account the real height instead of virtual height) must be ~30% lower (Szuszczewicz et al., 1995), the velocity values found here are compatible with the semidiurnal (12 hr) and quarter-diurnal (6 hr) tides (see, e.g., Lee et al., 2003; Macdougall, 1978; Niranjan et al., 2010; Szuszczewicz et al., 1995). However, a detailed study based on more observational data is needed to verify the influence of the atmospheric tides in the ILs. The large velocity found in some cases over SL may indicate that the descending movement of the ILs is not modulated only by the tidal waves, but also by the gravity waves (Chu & Wang, 1997). As mentioned previously, the velocity values can also be affected by the steep rise of the h'IL as the Digisonde frequency approaches the critical
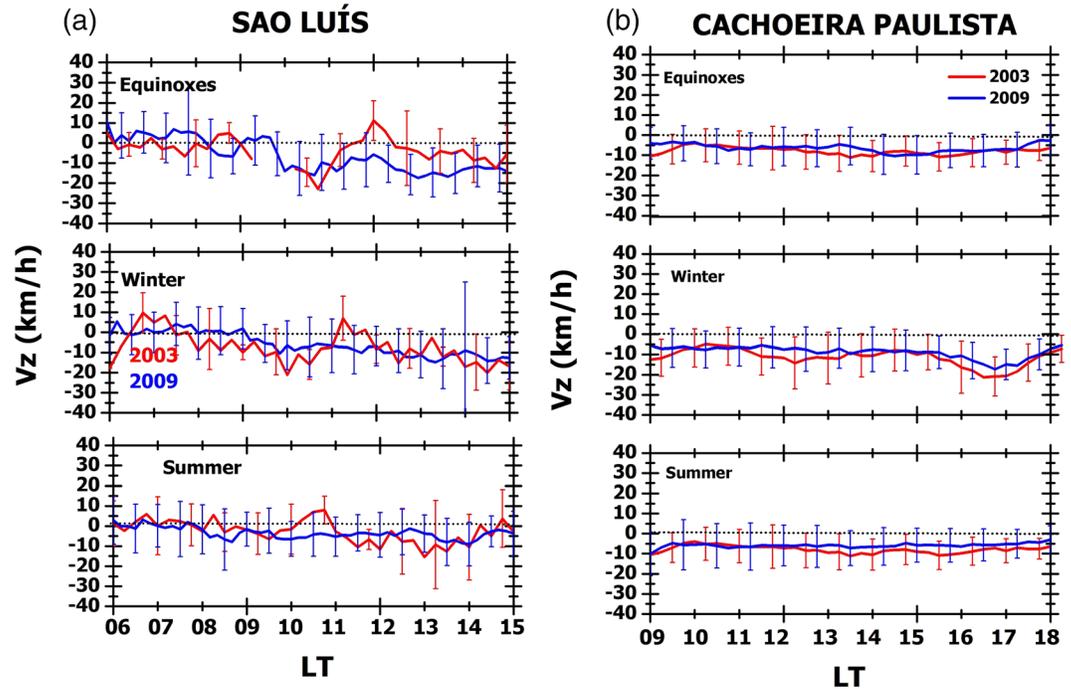
**Figure 7.** (a) Mean IL's vertical velocity (Vz) over SL for equinoxes, winter, and summer during 2003 (red line) and 2009 (blue line). (b) The same, but for CP. For a better visualization, the standard deviation shown in each panel was divided by a factor of 3.

frequency of the IL. Dos Santos et al. (2019) reported the possible influence of the atmospheric gravity waves in the ILs during the period of 2009. The average velocity magnitudes presented in Figure 7 are in agreement with those observed from the VHF radar of SL. In a specific case during 19 June 2009 (not shown here), for example, the descent velocity was found to be $\sim -14.5$ km/hr.

## 4. Conclusions

This work investigated the behavior of the ILs over Brazilian regions during solar maximum (2003) and minimum (2009) periods. This was the first study on the morphology of the ILs during different solar activity epochs using exclusively Digisonde data that showed the peculiarities of the ILs including the effects of the magnetic equator displacement. The results presented in this work have potentiality to help the development of a theory to further explain the climatology of this phenomenon in the future.

Our results showed that the occurrence rates of the ILs over the low-latitude sector (CP) do not show significant dependence on the solar flux variations. On the other hand, over the equator, some differences in the occurrence rates were observed between maximum and minimum solar activity. In our study we showed that these differences were most probably caused by the displacement of the magnetic equator away from SL, showing in this way the important role of the winds in the formation of the intermediate layers over this region at the same time in which the weakening of the equatorial electroject is occurring. Regarding the ILs' duration, we noted that the ILs over SL and CP lasted longer during the solar minimum. Further, the duration of the ILs was shorter over the equator than at the low-latitude region.

The seasonal variability of the frequency and height parameters of the ILs over SL and CP was similar during both solar maximum and minimum periods. The specific analysis of the mean monthly behavior of height and frequency over SL showed an oscillatory pattern in 2003 when compared to 2009. The day-to-day variability observed in the F10.7 cm index, which directly affects the ionospheric electric fields, can be one of the reasons for the IL's variability over SL.

The local time variation in the ILs' occurrence was higher both over SL and CP during solar minimum. Over the equator, two ILs peaks occurrence were observed in both the periods analyzed. Over the low-latitude sector, a variability in the ILs' occurrence in 2009 was found, mainly during the winter and equinoxes. The same was observed in 2003; however, the variability was less pronounced. Both over SL and CP, the ILs rate of occurrence during solar maximum was lower before midday. However, during the local afternoon, the occurrence in 2009 and 2003 seems to be numerically similar.

The number of IL events observed over CP presented a small difference during 2003 and 2009. On the other hand, during the December and June solstices, a similar behavior was observed, in which higher occurrence of fewer events per day was observed during low solar activity and higher occurrences of days with higher events for more intense solar activity. Over SL, a decrease in the number of days with more events in all seasons for the maximum solar activity was seen, mainly during the June and December solstices. Besides that, the number of days without events showed a drastic increase for periods of more intense solar activity, reaching up to 60% occurrence.

The influence of the PRE in the dynamics of the ILs over SL is an interesting feature observed in this paper. While in 2009 only one case of the ILs rise near to sunset was registered in December, in 2003 the same characteristic was observed in January, April, October, and November showing, in this way, the increasing role of the zonal electric field in the ILs during the maximum solar activity period.

Finally, the IL's vertical drift velocities over CP for both maximum and minimum solar activity conditions were similar to each other and presented values between 5 and 10 km/hr that are compatible to the semidiurnal and quarter-diurnal tide. Over SL, the velocities were more intense in some intervals indicating possible contribution of gravity waves in the downward movement of the ILs.

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