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F Region Electric Field Effects on the Intermediate Layer Dynamics During the Evening Prereversal Enhancement at Equatorial Region Over Brazil

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Key Points:

- The PRE can cause an upward movement of the intermediate layers (ILs) located in altitudes higher than ~170 km
- The prompt penetration electric field also can contribute to the uplift of the ILs and Es layers
- The uplift of the ILs at sunset seems to be more common over the equatorial sector during maximum solar activity

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Abstract Using ionograms from the Brazilian equatorial site of São Luís (SL, 2° S; 44° W, I = −3.8°), the relationship between the uplift of the intermediate layers (ILs) at sunset and the prereversal enhancement of the zonal electric field (PRE) is investigated. The ILs were studied during the solar maximum (2003) and minimum activity (2009) periods. The presence of the ILs during the PRE occurrence time was very low during both years. In 2003, six ILs' events were observed, being four of them in the summer solstice and one in the March equinox. In 2009, only a single event was registered and occurred during the December month. The results show that depending on the height at which the ILs are located, their upward movement at sunset can be in some way related to the normal F layer rise at sunset due to the PRE. The initial altitude at which such ascending ILs were observed was higher than their normal height near sunset. Additionally, the eastward prompt penetration electric fields (PPEFs) during weak magnetic storms can also contribute to the IL's rise. An interesting case of uplift of a sporadic-E layer from ~120 to 290 km probably due to the PPEF is also investigated.

1. Introduction

It is well known that the electric field that controls the ionospheric plasma drifts is generated by the dynamo process in the E and F regions. During the day, the zonal electric field is directed to the east and produces the upward vertical drift, however, before its reversal to the west in the evening, a significant and fairly sharp increase in the eastward electric field is observed. This intensification in the vertical drift that is known as prereversal enhancement of the zonal electric field (PRE) is caused by the F region dynamo driven by the thermospheric zonal wind in the presence of a rapid decrease in the E layer conductivity across the terminator (I. S. Batista et al., 1986; Farley et al., 1986; Heelis et al., 1974; Rishbeth, 1971). The magnitude of the PRE is dependent on various factors, such as the upward propagating planetary waves (M. A. Abdu et al., 2006), the disturbance electric fields (M. A. Abdu, 1997; M. A. Abdu et al., 2009; B. G. Fejer and Scherliess, 1997; Richmond et al., 2003; A. M. Santos et al., 2016; Sastri et al., 1997), the disturbance winds during magnetic storms (M. A. Abdu et al., 1995) and the variability in the solar flux (M. A. Abdu et al., 2010; I. S. Batista et al., 1996; Fejer et al., 1991, 1979; A. M. Santos et al., 2013).

The PRE vertical drift controls some major phenomena of the equatorial ionosphere, such as the post-sunset resurgence of the equatorial ionization anomaly and the plasma instability processes responsible for the development of the plasma bubble irregularities/spread F (see e.g., Huang, 2018 and Balan et al., 2018). However, the direct or indirect effect of the PRE on the layers located in the lower and upper E region hasn't received much attention. Using observational data over Fortaleza (4°S, 38°W), M. A. Abdu et al. (1996) showed, for the first time, that the often observed disappearance of the post sunset sporadic-E (Es) layers could be related to the evening F layer vertical uplift. As explained by M. A. Abdu et al. (2003), the association between the PRE vertical drift and Es layer disruption/formation arises from the Hall conduction upward/downward electric field originating from the E and F region electrodynamic coupling processes. Depending on the PRE intensity, such an upward electric field, that is associated with the eastward zonal wind, can cause the partial or complete disruption of an ongoing Es layer. It was observed that higher values of the PRE could disrupt the Es layers whereas for smaller PRE amplitudes such disruption may not occur. Using numerical simulation, Carrasco et al. (2007) also reported that depending upon the direction of the vertical electric field associated with the PRE, the Es layer over Fortaleza and São Luis could be disrupted or enhanced. M. A. Abdu et al. (2013) showed that during magnetic storms, the formation and disruption of the Es layers over the low-latitude sector could be strongly controlled also by the magnetospheric electric fields that penetrate to the equatorial ionosphere.

Besides the Es layers that are located near 100 km of altitude and are formed by the wind shear mechanism, there are those layers that are located in the upper E region or in the ionospheric valley region which formation mechanism is not very well understood yet (Appleton, 1933; Ratcliffe & White, 1933; Schafer & Goodall, 1933; Shen et al., 1976). Fujitaka and Tohmatsu (1973) have reported that over the middle latitudes, the atmospheric tidal winds could be the dominant cause of these layers that are known as intermediate layers (ILs). Over the equator, Kudeki and Fawcett (1993) suggested that the gravity waves could play a key role in the generation of these phenomena. As will be shown in the present work, the ILs can be influenced by the evening enhancement in the zonal electric field. Dos Santos et al. (2019) and A. M. Santos et al. (2020) studied the behavior of the ILs over the Brazilian equatorial and low latitude regions of São Luís (SL) and Cachoeira Paulista (CP), respectively, during periods of maximum (2003) and minimum (2009) solar activity. In summary, it was found that: (1) the IL's occurrence rate over both regions is high; the occurrence in SL was higher in 2009 ($I = -3.8°$) than in 2003 ($I = -1.6°$), indicating a possible dependence with the magnetic inclination angle (I); (2) the ILs' occurrence rate appears to be independent (or weakly dependent) on the solar activity condition; (3) the dynamic of the ILs can be influenced by atmospheric tides, gravity waves and electric fields; (4) the ILs occur predominantly during daytime and present a well-defined downward movement; however nocturnal and ascending ILs also can be observed over the Brazilian region; (5) depending upon the height of its formation, the ILs can descend and merge with the normal Es layers; (6) the IL's lifetime is longer in solar minimum period (both over SL and CP), with shorter life time over the equator (SL) independently of the solar activity ; and (7) the descending rate of the ILs over SL and CP seems to be compatible with that of the semidiurnal and quarter-diurnal tides. However, a larger descending rate over SL in some cases (>10 km/h) may reveal the additional influence of the gravity waves in the IL's dynamics.

In this study, we will address for the first time the impacts of the PRE in the unusual movement of the ILs located, in most of the cases, at altitudes higher than 170 km, during both quiet and disturbed periods. Besides that, we will discuss an interesting case of a regular Es layer that presented a strong uplift near the PRE time, become displaced from ∼ 120 to 290 km of height in ∼1 h, possibly due to the additional effect of an eastward prompt penetration electric field (PPEF).

2. Observational Data

To investigate the connection between the PRE and the uplift of the ILs, we examined the digisonde data from the equatorial station São Luis (SL, 2° S; 44° W; dip angle in 2003: −3.8°). The data used here were taken at 10 and 15 min cadence. The presence of ascending ILs over the equator at sunset times can be considered abnormal since only 7 cases were detected from a total of 357 days analyzed in 2003 and 293 days in 2009, being 6 of them during high solar activity and 1 during low solar activity. Over the low latitude station Cachoeira Paulista (22.42°S; 45°W, I: −34.4°), no event was observed during the same periods (341 days in 2003 and 361 days in 2009).

Figure 1 shows a typical example of IL occurrence over SL on March 27, 2009. It is possible to observe that just before the PRE occurrence time (∼18:20 LT, indicated by the dashed blue line), the IL that was in progress at a height of ∼150 km (see blue arrow) presented a weakening and completely disappeared at 18:20 LT. The IL, in this case, was formed initially at 15:50 LT at ∼194 km from a detachment of the F1 layer (not shown here). On the other hand, the Es layer that was in progress (see red arrow) presented moments of intensification and weakening during the same interval being interrupted only at 19:20 LT (not shown here).

A. M. Santos et al. (2020) reported that the probability of an IL to occur near or after ∼18:00 LT is quite small. Around this time, they showed that the average values of virtual height of the ILs over SL during 2003 are located at altitudes close to 160 km or below. As can be seen in Figures 4a and 4b from Dos Santos

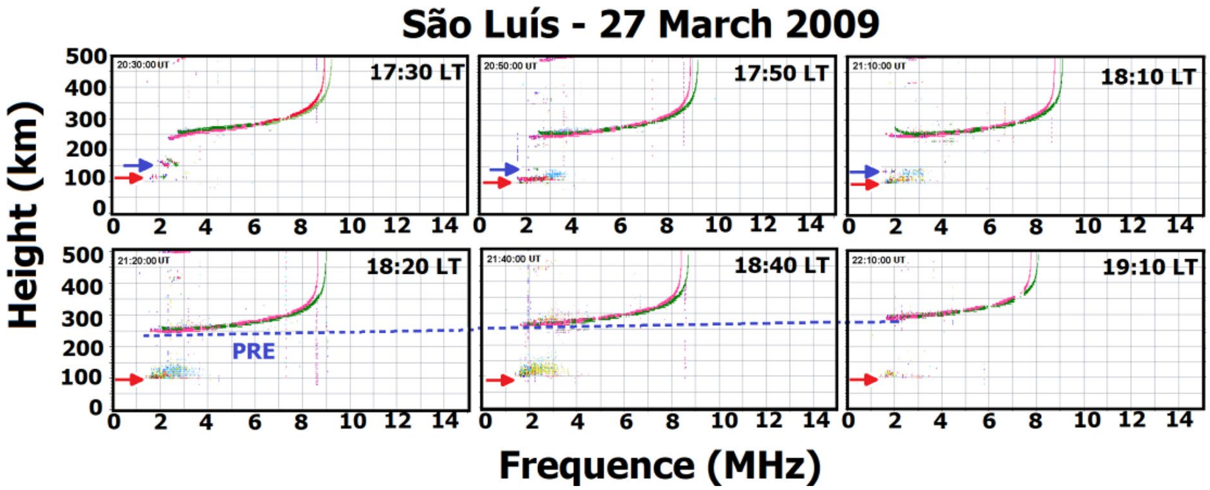

Figure 1. Ionograms over SL on March 27, 2009, showing an example of interruption of IL at the PRE occurrence time. IL, intermediate layer; PRE, prereversal enhancement of the zonal electric field; SL, Sao Luis.

et al. (2019), at ~18:00 LT (21:00 UT) the ILs may either weaken and disappear (similar to what is shown in Figure 1 of the present work) or continue their downward movement to altitudes lower than 130 km. Differently from the example in Figure 1, some cases of ILs over the equatorial site São Luis ascended simultaneously with the F layer elevation due to the enhancement of the zonal electric field instead of disappearing or continuing their downward movement. In 2003, this feature was observed in January (1 day), April (2 days), October (1 day), and November (2 days). In 2009, only in December, a similar characteristic was detected. Some of these events will be discussed in detail below.

2.1. Event 1: October 12, 2003

From top to bottom, Figure 2 shows the one-minute resolution magnetic index Sym-H, the interplanetary magnetic field Bz (positive to the north), the zonal interplanetary electric field Ey (positive westward), and the auroral electrojet activity index AE from 09:00 LT on October 12 to 09:00 LT on October 13, 2003. The F10.7 index during this period was 87.8 SFU (Solar Flux Units; 1 SFU = 10^{-22} W/(m^2Hz)). The minimum virtual heights of the F layer (h'F, blue curve) and of the ILs (h'IL, red curve), as well as the F2 layer peak height (hmF2, purple curve), are presented in the last panel. The period of spread-F occurrence is also indicated by the block of vertical gray bars in the bottom part of the same panel. A single event of ascending IL observed on October 12, 2003, was detected at 16:45 LT at ~188 km. In this case, the IL's rise occurred in the absence of any magnetic storm. The very calm behavior of the Bz, Ey, Sym-H, and AE indices exclude any possibility of interference of disturbance electric fields during the interval in which the IL was observed. Shortly after its formation, the IL presented a rise almost simultaneously with the rise of the F layer due to the PRE. The spread-F started immediately after the disappearance of the IL at ~18:30 LT. In the time interval between 16:45 LT and 18:30 LT, the ftIL decreased by ~0.6 MHz. On this day, the peak of the average vertical drift velocity (V_{zp}), calculated from the F layer true height (hF) variations at 5 and 6 MHz plasma frequencies as dhF/dt, occurred at 18:30 LT and attained a value of ~40 m/s, which corresponded to a zonal electric field of ~1 mV/m.

The ionograms in Figure 3 shows how the digisonde registered the IL and the F layer during some specific times on October 12. It is interesting to note that the freshly-formed IL (close to 17:00 LT) does not appear to be connected with the F layer. However, during its development (see the ionogram at 17:45 LT), the IL became intensified and with a strong tendency to merge with the F layer base. The signature of the IL on this day was very peculiar when compared to that of the normal IL signatures in ionograms. Generally, the ILs present a flat format or at most show a retardation at the lower frequency end. On October 12, specifically, the retardation in the form of a trace curvature was observed in the IL high-frequency end (as

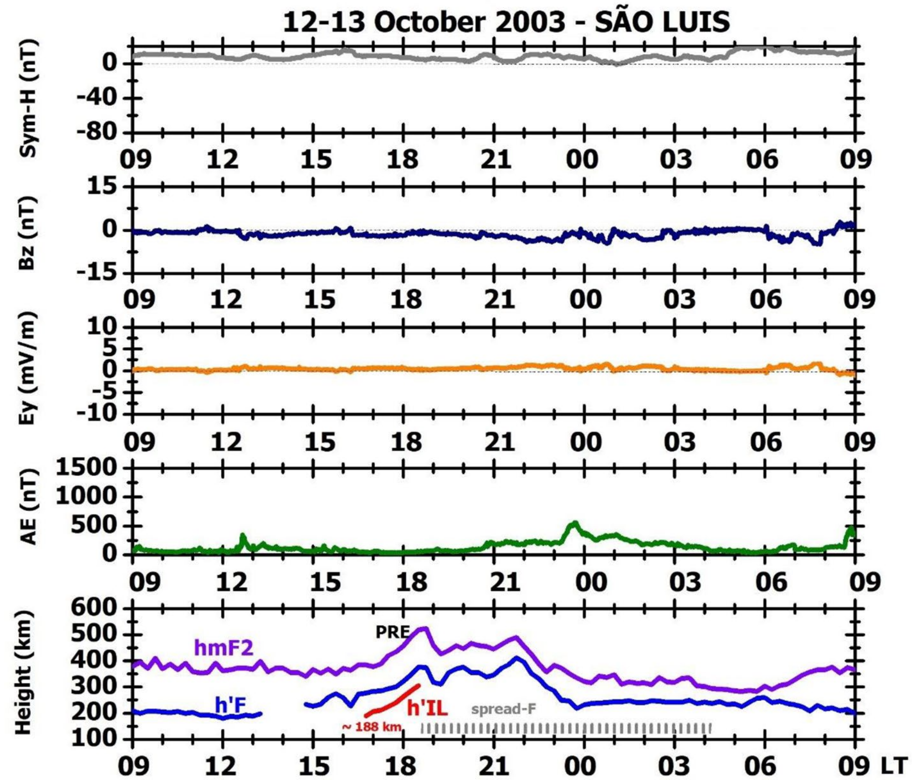

Figure 2. Ascending intermediate layer over São Luis on October 12, 2003, and the geophysical conditions for the period. From the top to the bottom panels: 1 min values of the Sym-H index (first panel), the interplanetary magnetic field Bz (second panel), the interplanetary zonal electric field Ey (third panel), and the auroral index (fourth panel). The virtual height of the F layer h'F (blue curve), the F2 layer peak height hmF2 (purple curve), the virtual height of the intermediate layer h'IL (red curve), and the spread-F occurrence (block of vertical gray bars) are shown in the last panel. The initial height of the IL (~188 km) is also indicated in the last panel. IL, intermediate layer.

indicated by the red arrow), which is very similar to that of the F1 layer trace. However, the ionogram at 17:00 LT (and at other times not shown here) allows us to exclude the possibility of this trace to be referred to as the F1 layer.

2.2. Event 2: December 14, 2009

The single case in which the upward movement of the IL was observed around the sunset during the solar minimum period occurred on December 14, 2009. The average F10.7 cm solar flux for this period was ~78.6 SFU. As can be noted in Figure 4, the interplanetary magnetic field Bz, the Sym-H, and the AE reveal the absence of any magnetic storm during this day. The uplift of the F layer on this day was less intense than the previous event. In this case, the IL height was ~175 km at 18:30 LT. As the IL rose slowly in response to the PRE, its intensity was decreasing until its interruption at ~19:20 LT.

Differently from the previous event, in which the development of the spread-F occurred immediately after the disappearance of the IL, the IL on December 14 continued being registered during the occurrence of spread-F as can be clearly seen in the ionograms in Figure 5 in which the ILs are marked with black arrows. It can be noted that as the spread-F range increases, the intensity of the IL decreases until is interrupted at 19:20 LT. The V_{zp} on December 14 reached ~21 m/s (~0.5 mV/m) at ~18:10 LT. In this case, the F layer height at the fixed frequencies of 5 and 6 MHz was below 300 km. Then the methodology we have used previously to derive the vertical drift does not represent the true velocity of the F layer, and corrections are needed. The correction was done using the same methodology explained by Nogueira et al. (2011) (see also Somayajulu et al., 1991; Subbarao & Krishnamurthy, 1983).

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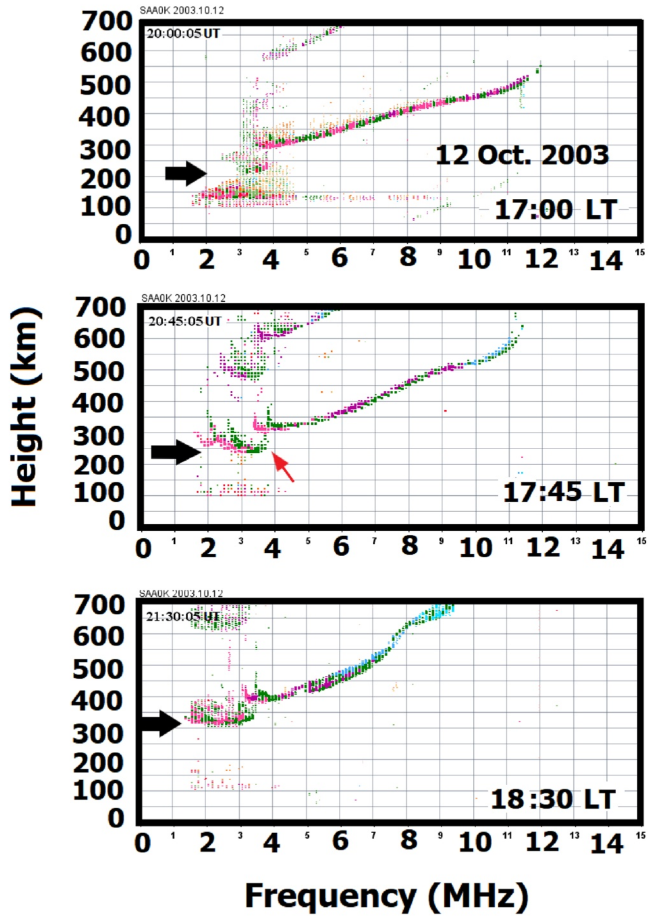

Figure 3. Ionograms for October 12, 2003. The black arrows indicate the ascending intermediate layer. The red arrow shows the incurved trace of the IL at the IL high frequency end. IL, intermediate layer.

2.3. Event 3: April 03, 2003

Figure 6 shows the same parameters described in Figure 2 but for April 03, 2003. The Sym-H index indicates that the ascent of the IL occurred during the main phase of a weak magnetic storm. Sym-H reached its minimum of ∼−40 nT at 23:00 LT. The F10.7 index attained a value of 155.7 SFU. The red curve in the last panel, representing h'IL, shows that IL occurred during three different time intervals, being the last one close to sunset time. When this third event was detected, at ∼17:30 LT, the IL was very close to the F layer base (∼230 km) and remained practically static for the next 35 min. After this, at about 18:10 LT, the IL started an upward movement that was simultaneous with an increase in the h'F parameter (see the gray dashed vertical line). At the same time, Bz presented a rapid reversal to the south as indicated by the pink arrow, which could have generated an eastward PPEF. It is probable that in this case, the uplift of the IL has been caused by the PRE with the additional contribution of the eastward PPEF. The peak value of the vertical drift on this day was 47 m/s (∼1.17 mV/m) at 18:45 LT. During its ascent, the IL' top frequency (ftIL) decreased from 3.1 to 2.1 MHz.

Figure 7 shows a sequence of ionograms during the period in which the IL was observed on April 03. We may note the emergence of the IL at 17:30 LT at the same time that a spread Es layer is ongoing. As indicated by the red arrow in the 18:00 LT ionogram, the IL presented retardation at the lower frequency end as denoted by a well-defined curved trace. It is interesting to note that during the IL development the retardation was less pronounced until it became almost imperceptible at 18:45 LT. In this event, the IL remained very close to the F layer base and apparently disappeared or mixed up with the spread-F from 19:00 LT onwards.

2.4. Event 4: November 10, 2003

The November 10 event occurred during a weak magnetic storm (Sym-$H_{\min}$ = −60 nT at ∼ 21:50 LT) and it was very interesting since it showed the uplift of a dense sporadic-E layer (Es) above ∼ 120 km, where it was first detected. This day was particularly active in terms of sporadic-E occurrence, which started in the morning as a c-type Es layer and persisted until 11:15 LT, sometimes becoming strong enough to partially blanket the F-layer reflection. From 09:15 LT onwards a q-type Es (Es_q) layer was observed simultaneously with the c-type. The Es_q persisted until 16:15 LT with a few interruptions. At 16:30 LT it is possible to see a clear indication of a dense Es layer simultaneously with the Es_q as indicated by the red arrow in the ionogram of Figure 8a. Figure 8b shows that at 18:00 LT, Bz turned northward (reaching ∼ 10 nT), the AE index showed a recovery, and Ey presented a variation of ∼10 mV/m westward. At this time, the polarity of the associated electric field can be either eastward or westward, since it refers to the day-to-night transition period. In this condition, the local conductivities of the ionosphere may decide the direction of the PPEF, whether east or west. In the present case the polarity was initially westward, and soon (within ∼25 min) turned eastward (as can be noted by the upward arrow marked in the figure). This seems to have produced an eastward PPEF that was responsible for the first abrupt increase of the Es height from 120 to 180 km as can be seen between the ionograms at 18:00 LT and 18:30 LT in Figure 9. In these ionograms, it is possible to observe the presence of the mixed Es and multiple F reflection known as M-reflection (identified by the blue arrows). Note that at 18:30 LT the Es was already located in the ionospheric valley region; so from this time on, this layer will be classified as an IL. At around 18:30 LT, the Bz turned to the south, and a second abrupt increase in the IL, probably due to an eastward PPEF, again was detected. In this case, the IL moved from ∼180 to 290 km in ∼30 min. This second IL rise was coincident with an intensification in the auroral index from ∼250 to 650 nT. During this event, the V_{zp} reached ∼18 m/s at 18:15 LT, which corresponds to a zonal electric field

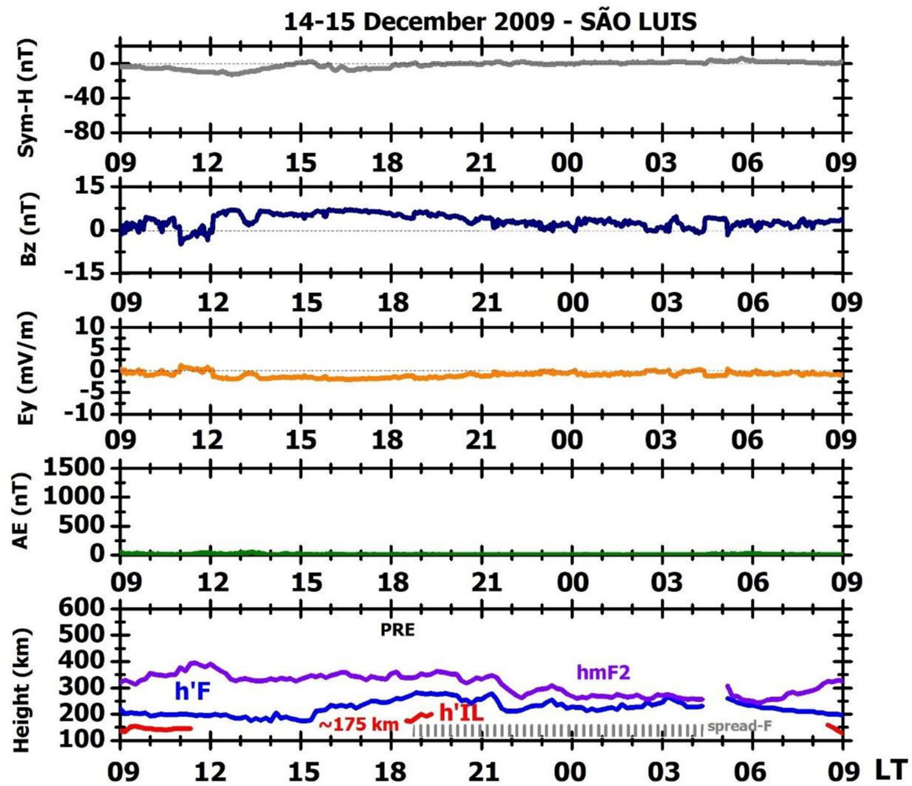

Figure 4. Similar to Figure 2, but for December 14, 2009.

of 0.45 mV/m and the F10.7 was 92.7 SFU. It is interesting note in this case that the upward movement of the IL suffered the contribution of a possible eastward PPEF occurring close to sunset associated both to reversal of Bz to north as to south. This is possible because near sunset occurs the transition of the PPEF signal (from positive to negative for an undershielding event and from negative to positive during an overshielding). As we do not know the exact transition time, it is possible to have an unexpected eastward PPEF during an overshielding if the transit time has been crossed. In other words, for such a situation, normal eastward PPEF can occur during an undershielding if it starts before the transition, but it also may occur during an over-shield if it starts after. Additionally, in this event, it was observed that only the Es layer (and later on the IL) was responsive to the disturbance electric fields during all the intervals discussed. As can be noted, the parameters h'F and hmF2 (blue and purple curves, respectively) in Figure 8b did not show any abrupt change compatible with the variation in the Es/IL that could be associated with the PPEF. Some oscillations can be seen in hmF2 around the time of the PRE, that are due to the switching of the sounding mode resolution from 5 to 10 km from one ionogram to the other during this observation period.

The upward movement of the IL observed over the equatorial site of São Luís during the PRE occurrence time was detected in the other 3 similar events, however, to avoid the text getting tiring for the reader, we decide to include only the basic information about them in Table 1. The letters t_o (t_f), h_o (h_f), f_o (f_f) are used to describe the occurrence time (in local time), virtual height (km), and top frequency (MHz) in which the ILs were formed (interrupted). The vertical drift peak (V_{zp}, m/s), the time of occurrence of V_{zp} (LT), the IL's duration (hours), and the F10.7 index values are also shown in this Table. Note that Table 1 also includes the information about the events discussed previously.

From Table 1, it is possible to observe that in most of the cases, the ILs were formed before the vertical drift attained its maximum value. The formation of one of the ILs on April 08, 2003 (event 5b) occurred at the same time that the peak in the vertical drift was observed. Only in event 2, the ILs rise presented a delay of ~20 min with respect to the V_{zp} occurrence time. The ILs duration varied from 0.5 to 1.75 h. Additionally,

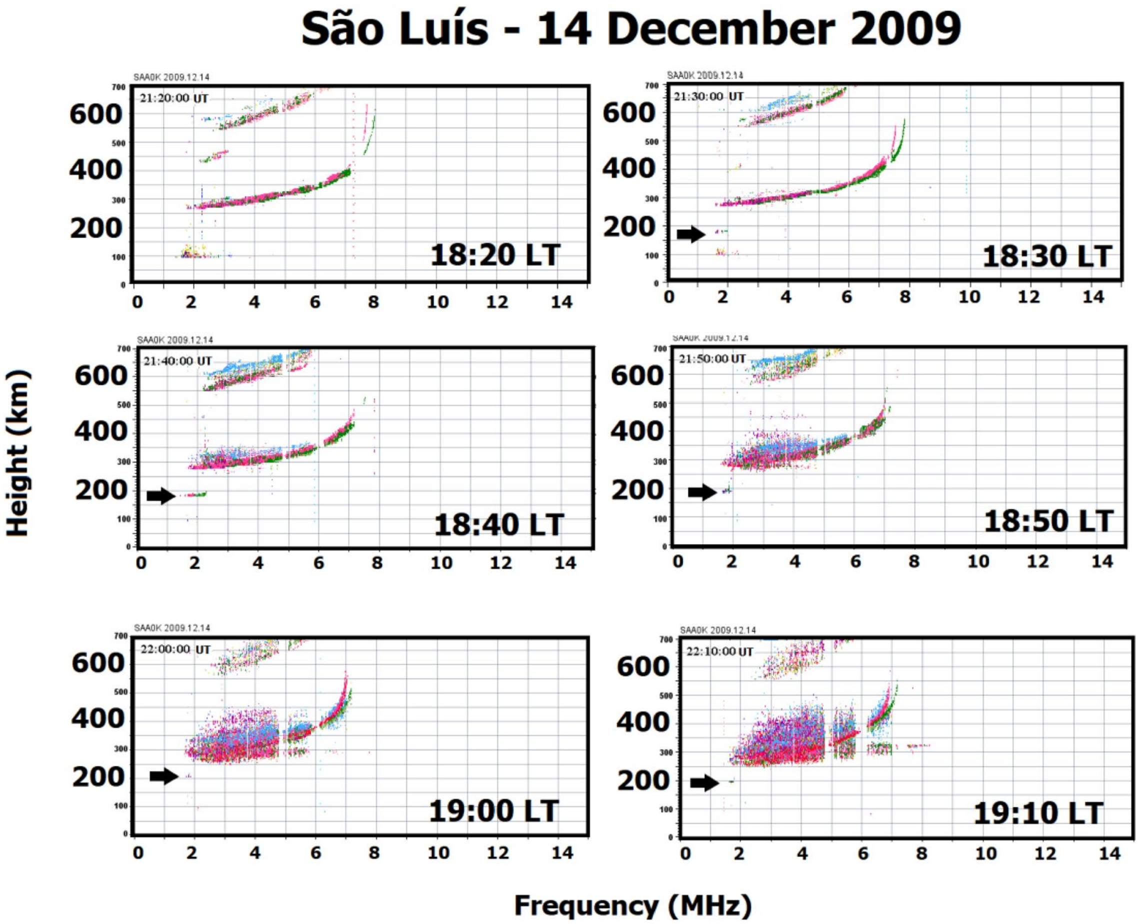

Figure 5. Ionograms over SL on December 14, 2009. The black arrows indicate the ascending intermediate layer. SL, Sao Luis.

Table 1 shows that in general the initial height of the IL increases with increasing F10.7 (except for events 4 and 5b).

3. Discussion and Conclusions

Figure 1 showed the most common situation in which the ILs are weakened until becoming disrupted as the sunset approaches as well as their typical occurrence height which is about 150 km. On the other hand, for the events studied here, the ILs were initially observed at altitudes close to 180 km, and in most of the cases, they presented a weakening in the top frequency as they rose. We believe that there must be a height limit between the E and F regions within which the IL can respond to the electric fields of the F region, more specifically to the PRE, and that this limit should vary between ∼ 160 and 170 km. The results presented by A. M. Santos et al. (2020) reinforce this assumption since in 2003, the period in which most of the ascending ILs were observed, the tendency was that the layers located a little lower than this limit presented a movement that was downward (as the example of Figure 1 in this present work) and not upward as reported here. In 2009, almost all the ILs near the sunset times were already located at altitudes equal to or less than 130 km.

As mentioned previously, the PRE is produced by the intensification of the eastward zonal electric field at sunset times. It is believed that such intensification is mainly caused by the F-region dynamo which is more pronounced during the equinox and summer (I. S. Batista et al., 1996; B. G. Fejer et al., 1991) and has significant day-to-day and solar activity variability. The driver for the intensification of the zonal electric

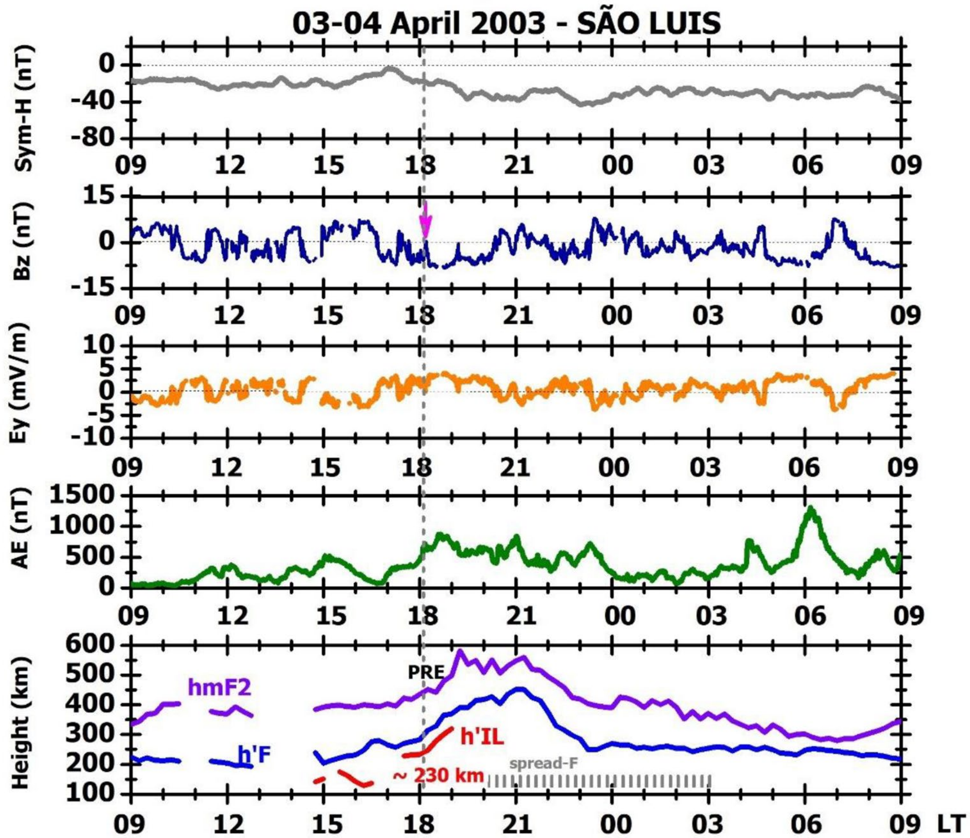

Figure 6. Similar to Figure 2, but for April 03, 2003.

field around sunset is the thermospheric wind blowing eastward under the condition of decreasing E-region conductivity (Farley et al., 1986). M. A. Abdu et al. (2010) showed that the higher the solar flux is, the higher the vertical drift peak/PRE will be (see also I. S. Batista et al., 1996; B. G. Fejer et al., 1979, 1991; A. M. Santos et al., 2013). This occurs because the conductivity local time/longitudinal gradient in the evening and the thermospheric eastward wind, responsible for the PRE intensity, are strongly affected by the solar activity condition. Based on model calculations, Goel et al. (1990) showed that the time decay of the electron density (dN_E/dt) at sunset during the equinox period, that is proportional to N_E^2, varied by a factor of 2 from high ($N_E^2 = 2.13 \times 10^9$ cm $^{-6}$), to low ($N_E^2 = 1.05 \times 10^9$ cm $^{-6}$) solar activity. A similar dependence was found for the thermospheric winds over Arequipa, Peru (16.5°S, 71.4°W), where the eastward zonal wind presented an increase of 100 m/s between 21 LT and 23 LT, for a variation of ∼100 SFU. It is interesting to observe that the rise of the ILs occurred during equinox and summer, the periods in which the PRE intensity is higher. No event was observed in June solstice, when the PRE reaches the lowest values (see e.g., I. S. Batista et al., 1996). As shown by M. A. Abdu et al. (2010), during the months of October, November, and December, the prereversal drift amplitude and also the spread-F intensity becomes closer to their yearly maximum in the Brazilian longitudinal sector. In agreement with this, four out of the seven ILs' rise events studied here occurred in those months. As summarized in Table 1, it is possible to note a relation between the initial height (h_0) of the IL and the F10.7 index. Except for some cases, it was observed that the higher the solar flux is, the higher the h_0 will be. As the PRE/V_{zp} is strongly dependent on F10.7, it is probable that the more intense electric fields during 2003 have been effective in both the dynamics and in the formation of the ILs. The upward rise of the ILs is a very unusual characteristic since its normal movement is expected to be downward, as it is caused probably by the action of the atmospheric tides (Lee et al., 2003; Niranjan et al., 2010; A. M. Santos et al., 2020; Szuszczewicz et al., 1995). Thus, it is possible that the ascending

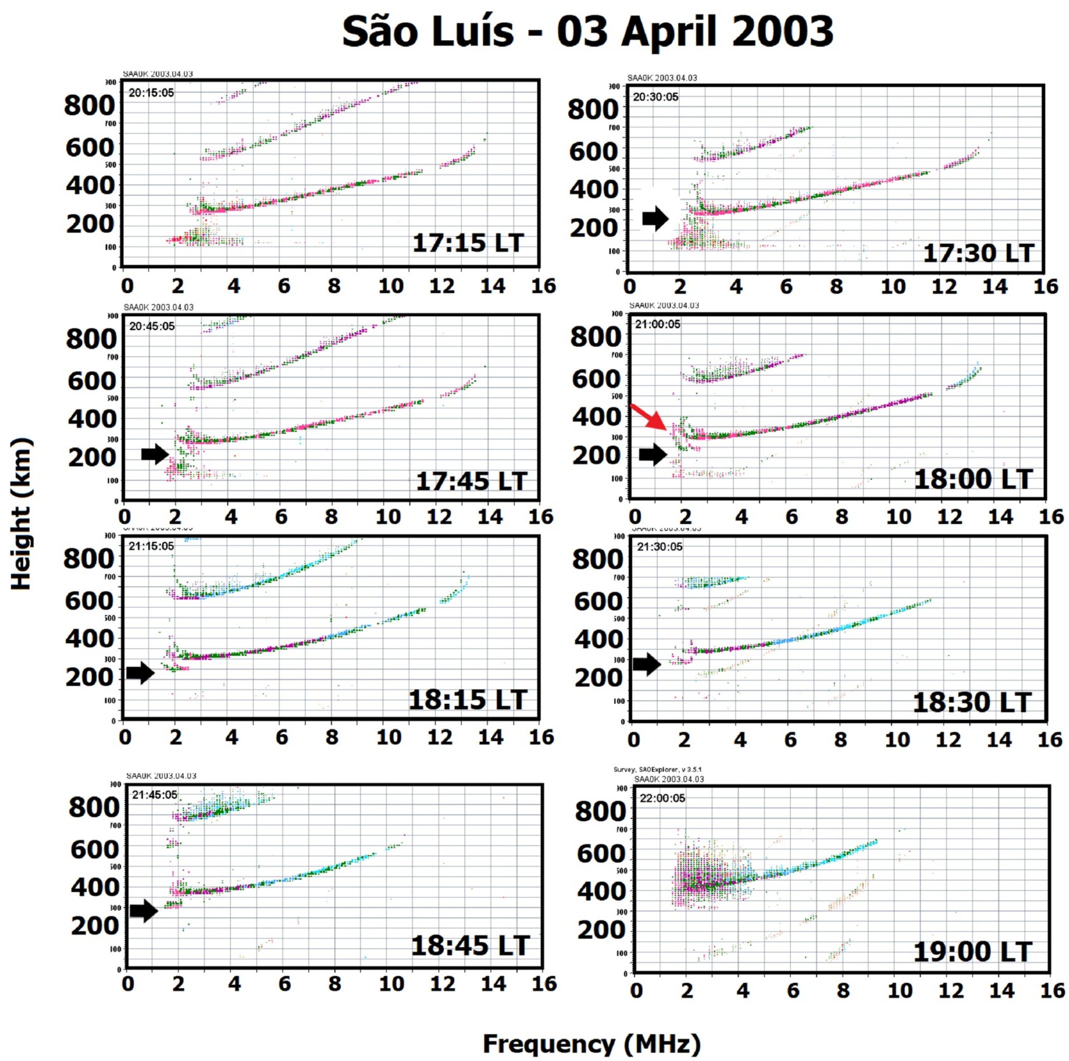

Figure 7. Ionograms over SL on April 03, 2003. The black arrows indicate the ascending intermediate layer. The red arrow in the ionogram at 18:00 LT shows the retardation in the low frequency end of the IL. IL, intermediate layer; SL, Sao Luis.

movement of ILs studied here has resulted from a competition between the electric fields generated by tidal winds and the PRE.

As shown in Table 1, the ILs were initially detected before or at the V_{zp} time, except for event 2, which was the only event that occurred during the solar minimum period. In this case, a delay of ∼20 min was observed between the IL's formation and the V_{zp} occurrence time. Besides that, the ionograms in Figure 5 show that the ILs' formation on December 14 occurred simultaneously with the beginning of the spread-F. According to Abdu et al. (2012), there are some key factors that control the spread-F development, such as the F region plasma vertical drift/PRE and the initial perturbation (or precursor seed) in electron density at the F layer bottom side gradient region. It is believed that the gravity waves originating from the tropospheric conditions are the seed perturbations required for the spread-F development. Considering that the IL on this day appeared simultaneously with the beginning of the spread-F and that some authors have discussed the role of the gravity waves in the ILs over the equatorial sector (see e.g., Chu & Wang, 1997; Niranjan et al., 2010; A. M. Santos et al., 2020), it is possible that the IL on December 14, that was initially located in the F region limits (175 km), has been influenced by the same gravity waves which seeded the spread-F on

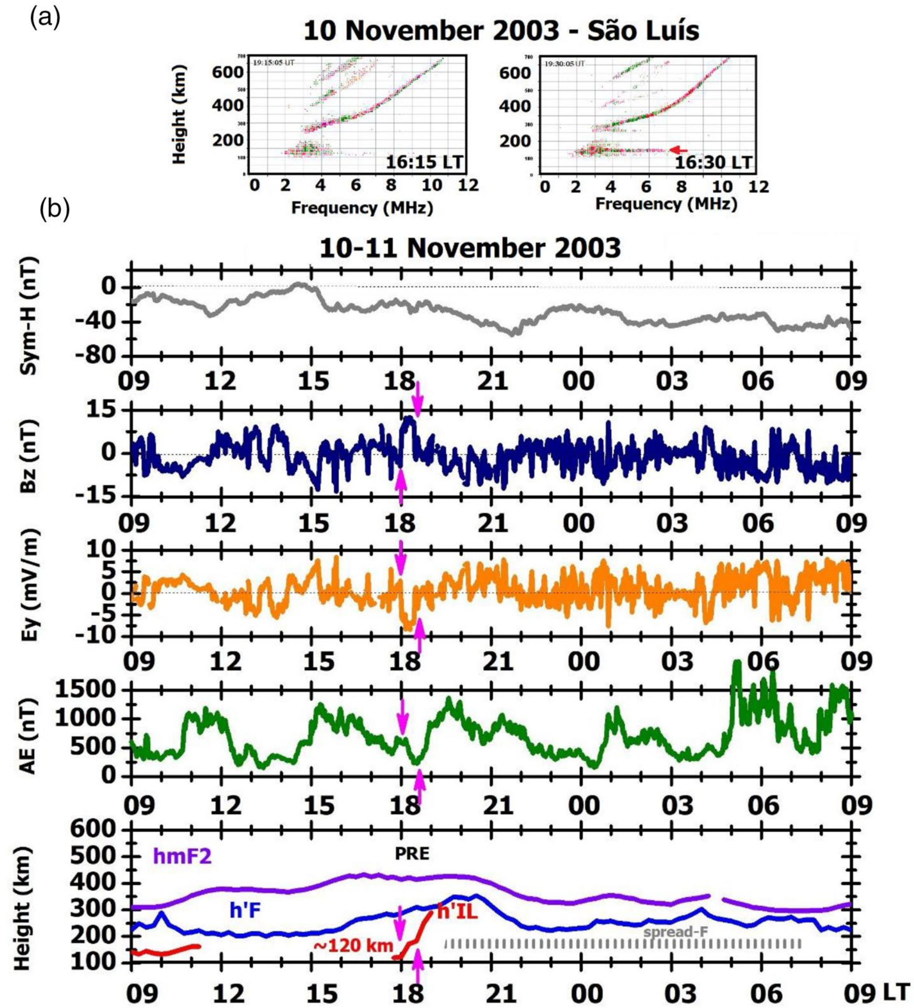

Figure 8. a) Ionograms over SL on November 10 showing the presence of dense Es layer simultaneously with the Esq as indicated by the red arrow at 16:30 LT. (b) Same as Figure 2 but for November 10, 2003. IL, intermediate layer; SL, Sao Luis.

this evening. However additional studies are necessary in order to comprehend the possible relationship between spread-F and ILs.

The impact of the evening zonal electric field enhancement in the sporadic-E layers have been discussed in the literature (see e.g., M. A. Abdu et al., 2003; Carrasco et al., 2007; Rastogi et al., 2012). It was observed that the Es layer formation during the post-sunset hours can be disrupted or enhanced depending upon the vertical structure of the electric field arising from the sunset electrodynamic process. Whilst a downward electric field induced by a westward electric field can favor the Es formation or even intensification, an upward vertical electric field of Hall conduction induced by an eastward electric field is capable of disrupting an ongoing sporadic-E layer. However, M. A. Abdu et al. (2003) mentioned that depending on the intensity of the PRE, such interruption may not occur. They showed that a peak in vertical plasma drift (V_{zp}) of ∼25 m/s cannot be enough to interrupt an ongoing Es layer over Fortaleza. In the case of the ILs, such dependence with the V_{zp}/PRE intensity was not clear. As shown in Table 1, V_{zp} varied from ∼16 to 47 m/s, which corresponds to zonal electric field variation from ∼0.4 to 1.1 mV; however, the IL's uplift and the subsequent weakening/disruption was observed in all the cases. Besides that, the IL did not reappear at later time as generally is observed for the Es layer. Another interesting characteristic is related to IL's lifetime. Differently from the sporadic-E layers, that are composed of long-lived metallic ions, the upper ILs are located in a region where

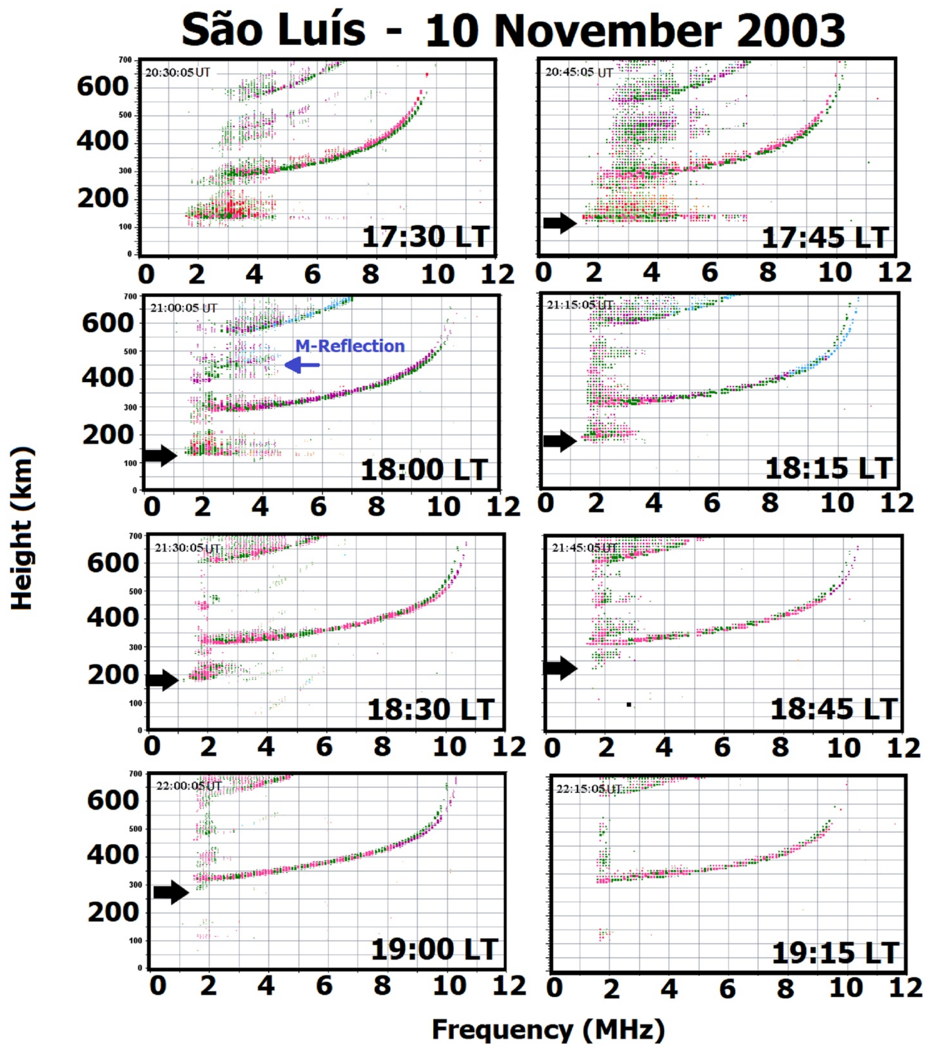

Figure 9. Ionograms over São Luis showing the ascending movement of the IL (black arrows). IL, intermediate layer.

Table 1
Ionospheric Parameters of the ILs, Vzp Information and F10.7 Index

Event number	Day	t_o (LT)	t_f (LT)	Duration (hour)	h_o (km)	h_f (km)	f_o (MHz)	f_f (MHz)	Vzp (m/s)	Time of Vzp (LT)	F10.7 (SFU)
1	October 12, 2003	16:45	18:30	1.75	188	306	3.8	3.2	40	18:30	87.8
2	December 14, 2009	18:30	19:20	0.8	175	201	2.0	1.9	21	18:10	78.6
3	April 03, 2003	17:30	19:00	1.5	230	320	3.1	2.1	47	18:45	155.7
4	November 10, 2003	17:45	19:00	1.25	120	289	7.1	2.0	18	18:15	94.6
5a	April 08, 2003	18:15	18:45	0.5	200	214	2.2	1.7	16	18:30	112.3
5b	April 08, 2003	18:30	19:30	1	253	259	2.5	3.8	16	18:30	112.3
6	January 29, 2003	17:00	18:30	1.5	209	295	3.9	3.7	40	18:30	124.4
7	November 08, 2003	18:00	18:30	0.5	185	211	2.5	1.8	34	18:30	92.7

Abbreviations: IL, intermediate layer; SFU, Solar Flux Units.

the layer ionization is dominated by O^+ and some combinations of NO^+, O_2^+, N_2^+. The convergence and accumulation of ions in these heights can lead to their loss through the dissociative recombination. Therefore, the durability of the upper ILs is in general lower than the Es layers (Wilkinson et al., 1992).

As mentioned by B. G. Fejer et al. (2007), the PPEFs in the ionosphere depend on some factors, such as the solar wind and magnetospheric driving mechanisms, the potential distribution penetrating to middle and low latitudes, and the global distribution of the ionospheric conductance. As indicated in the ionograms of Figure 9, as the layer rose, its top frequency decreased and attained a value of ∼2 MHz before being disrupted. Probably, this abrupt change in the Es-IL height was caused by a PPEF, however, it is interesting to note that this disturbance electric field affected more effectively the Es-IL layer than the F region. It was observed that the F layer also rose, but with slower velocity than that of the IL. As the efficiency of the PPEF is dependent on the ionospheric conductivity, the differences observed could be due to the lower conductivity at the intermediate heights between the E and F regions. In this range of altitude, the geomagnetic field lines get fully immersed in the night side earlier than at higher altitudes, therefore in a region of lower conductivity. The lower is the conductivity, the higher will be the eastward electric field and, consequently, stronger and faster will be the Es/IL rise. It is important to emphasize that other mechanisms may have contributed to this anomalous behavior of the Es-IL, so that additional studies are necessary in order to better understand the behavior of the IL on this day. Dos Santos et al. (2019) showed also a case in which the uplift of the IL was caused by PPEF and gravity waves, but differently from the present case, the rise was observed during the daytime. Event 4 was very interesting because different from the other cases, it refers to the uplift of a dense sporadic-E layer, probably formed by the wind shear mechanism, as evidenced by the multiple reflections in some ionograms. The Es got displaced from ∼120 to 290 km in ∼1 h 15 min time interval. Besides that, this was the only event for which the Es/ILs uplift was faster when compared with the F layer elevation. It is important to emphasize the unprecedented result reported here both for the ILs as well as for the Es layer that is: *the PRE not only seems to modify the intensity of these layers but also cause them to move up*.

In summary, the unusual uplift of the equatorial ILs located at altitudes above 170 km close to sunset during the PRE was discussed in this work. The outstanding results of this study may be summarized as follows:

1. The uplift of the ILs located at altitudes higher than 170 km can be caused by the prereversal electric field PRE and in some cases by an additional contribution from the PPEF during the main phase of a weak magnetic storm
2. Most of the cases of IL's rise near the PRE occurrence time were observed in 2003, a period in which the variability of the solar and geomagnetic activity was different from that of 2009
3. The uplift of the ILs was observed only in the equatorial region during the years of 2003 and 2009
4. Eastward PPEFs can be one of the factors that cause ascending movement of the sporadic layers

Additional studies involving the observational data and numerical simulation are needed for a better understanding of the PRE effects on the ascending movement of the ILs.

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Data Availability Statement

The indices Sym-H, Bz, Ey, and the AE were obtained from the website https://omniweb.gsfc.nasa.gov/form/omni_min.html (last access: March 12, 2019). The ionosonde data used here can be found in Zenodo (https://doi.org/10.5281/zenodo.4237755).

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