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Occurrence of the blanketing sporadic E layer during the recovery phase of the October 2003 superstorm

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Abstract

We have routinely monitored the total frequency (*ft*Es) and the blanketing frequency (*fb*Es) of sporadic E layers with the digital sounder under the magnetic equator in the Brazilian sector. Sporadic layers appear in the equatorial region (Es_q) at heights between 90 and 130 km, mainly due to irregularities in the equatorial electrojet current. However, during the recovery phase of the October 2003 superstorm, an anomalous intensification of the ionospheric density that exceeded the normal ambient background values for local time and location was observed. The parameter *fb*Es rose to almost 7.5 MHz during this event, due to a type "c" blanketing sporadic layer (Es_c), which is driven by wind shear. This result is discussed in terms of the atmosphere dynamics based on magnetic signature of the equatorial electrojet current using magnetometer data. Also, using data measured by sensors onboard the Geostationary Operational Environmental Satellite (GOES) 10 we analyze the possible influence of the solar flare-associated X-ray flux as an additional source of ionization.

Keywords: Space weather, Sporadic layers, Equatorial dynamics

Introduction

Ordinary sporadic E (Es) layers are very narrow ionization enhancements, typically 2–10 km in height. They are normally observed in the E region at heights between 90 and 130 km, and are quite horizontally extensive, covering tens to hundreds of kilometer. They have large day-to-day variability and distinct features relative to altitude and latitude of observation. The electron density of the Es layers can be up to an order of magnitude greater than the background densities. Due to their longer lifetime compared to the dominant species (O^+, NO^+, O_2^+) at the E region heights, the primary species of these layers are the metallic ions: Fe^+, Mg^+, Ca^+, and Na^+ (Kopp 1997).

The sporadic layers are classified into several types according to the different mechanisms of formation and the latitudes at which they are observed. The development of Es layers is strongly associated with particle precipitation at high latitudes (Kirkwood and Nilsson 2000). At middle and low latitudes, a comprehensive study by Whitehead (1989) has shown that the E region ionization enhancements can be formed due to vertical shear caused by opposite horizontal neutral winds, which in turn can be driven by gravity waves (Hook 1970; Lanchester et al. 1991; Jayachandran 1991) or tidal motions (Chimmonas 1971). The Es layers formed by wind shear lead to ionization enhancements that block the upper ionosphere to low-frequency radio soundings (Devasia et al. 2004) and may lead to amplitude scintillations at gigahertz (GHz) frequencies (Seif et al. 2015). Therefore, these layers are classified as blanketing layers (Es_b) (e.g., Reddy and Devasia 1973, 1981; Rastogi 1997; Devasia et al. 2004). The characteristics of the different types of Es layer observed in different latitudinal sector are summarized by Resende et al. (2013).

The type of Es layer most frequently observed in the equatorial region is the type "q" (Es_q). However, Es_q is not a layer in the sense of producing enhancements of the electron density. It does not also block the radio signal propagation to the upper regions (Piggot and Rawer

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1978). Indeed, the Es_q layer is associated with the equatorial electrojet (EEJ) plasma irregularity (Fejer and Kelley 1980; Forbes 1981). Specifically, the presence of the Es_q is associated with the gradient drift instability driven by the vertical polarization Hall electric field, as well as by the vertical density gradient and/or the two-stream instability (Whitehead 1989). The signature of the Es_q appears in ionograms as a scattering of the radio signal that covers most frequencies during the daytime, since the plasma irregularities in the EEJ are stronger in this period (Knecht and Mcduffie 1959).

Despite the Es_q being the dominant type of sporadic layer at the magnetic equator, blanketing types of Es layers (Es_b) can also be identified in the equatorial region during particular periods during the day. In these cases, such Es_b layers are usually associated with periods of reversed electrojet currents (CEJ events) (Rastogi 1997, 1999; Denardini et al. 2009), normally associated with storm periods due to the solar–terrestrial activity interaction.

In addition to the enhancements to electron density from the formation of sporadic layers, Afraimovich et al. (2001) established that extreme solar flares may cause sudden changes in the ionospheric ionization, leading to global distribution changes. They showed that the increases in X-ray and UV radiation intensity observed during chromospheric flares cause sudden increases in the process of ionization, although only increasing the electron density in the F region of the ionosphere. Manju and Viswanathan (2005) reported cases where changes in the direction of electric fields lead to the disappearance of the Es_q layer during intense solar flare events. In a more recent study, Sripathi et al. (2013) described the effects of an intense X class solar flare in the ionosphere of the equatorial regions and low latitudes. They show the disappearance of echoes of the ionograms during the flare event, indicating absorption of radio signals in the D region. In addition, Sripathi et al. (2013) observed a strong equatorial blanketing type Es layer in the ionograms before a flare that persisted for several hours, although it weakened during the flare.

Over the Brazilian sector, Batista and Abdu (1977) carried out a study of the presence of Es layers during disturbed periods covering several magnetic storms during solar cycle 20. They also computed the *ft*Es and the *fb*Es parameters which showed well-defined enhancements of the electron density of an appreciable magnitude, which were observed 1–3 days after the initiation of the storms. At that time, they had classified the sporadic layers associated with the *fb*Es enhancements as being of the type "a." After, a careful study of winds and recombination rates, they associated the electron density sudden enhancement to particle precipitations from the Van Allen radiation belt.

In the present study, we analyzed the evolution of the *ft*Es and the *fb*Es in Es layers during a magnetically disturbed period over São Luís, a Brazilian equatorial region. We identified peaks of *fb*Es which accompanied changes in the type of sporadic layers being observed by the digital sounder in the equatorial region. We assumed that these peaks are indicative of the Es_b layers presence during the recovery phase of the October 2003 superstorm. We show that peak in the *fb*Es parameter occurred on November 3, 2003, was correlated with a CEJ event. In addition, we verified the possibility of intense solar flares to causing an additional source of ionization, leading to the false impression that an Es layers have been formed.

Methods

We have used data from two separate types of ground-based equipment: a digital ionosonde and two magnetometers, installed under, and close to, the dip equator in the Brazilian sector. The digital ionosonde placed at São Luís (SLZ, 2.3°S, 44.2°W, dip −3.3°), under the magnetic equator, took a measurement every 15 min, sending consecutive pulses in the frequency range from 0.5 to 30 MHz, with a frequency step of 0.5 MHz. After careful manual reprocessing of all ionograms covering the desired period, we determine the ionospheric parameters *ft*Es and *fb*Es. The first parameter is the total frequency, which corresponds to the maximum frequency of the sporadic trace observed in the ionogram. The other parameter is the blanketing frequency which can be determined in two different ways: (1) When the Es_b layers are present, the *fb*Es correspond to the first frequency observed at the upper layer, and (2) when we observe Es_q layers only, the *fb*Es is obtained at the point where the F layer reflections begin to be observed (*fmin*F).

We also used data from magnetometers installed at the two sites, one under dip equator at SLZ and another close to dip equator at Vassouras (VSS, 3.9°S, 38.4°W, dip −13.3°). These sample the Earth's magnetic field at the rate of one measurement per second. However, we have only used the 1 min average of the H component measurements from these two sites so that we could determine the strength of the magnetic effect of the EEJ current at the ground level (named EEJ ground strength for simplification). The basic treatment of the magnetic data at each station is to eliminate outlier values from the measured components based on a third-order polynomial fitting. Then, the five quietest days of the month are chosen and their local midnight values are averaged ($\langle H_{00LT} \rangle$). Thereafter, the H component variation is normalized to the difference between the H component values and the mean midnight values for the five quietest days; providing ΔH, i.e., $\Delta H_{SLZ} = H_{SLZ} - \langle H_{SLZ00LT} \rangle$. Finally, the diurnal variation of the EEJ ground strength is estimated by taking the difference between the ΔH values at a station at the dip equator (ΔH_{SLZ}) and the ΔH values at a station near the dip equator but outside the influence of the EEJ (ΔH_{VSS}). A more detailed explanation on the magnetic data treatment and on the use of these two stations is explained by Denardini et al. (2009).

In addition, we looked for solar flare occurrences that match the time of each Es_b occurrence using measurements of X-ray radiation in the range 0.5–4.0 and 1.0–8.0 Å. Data were collected using the X-ray sensor (XRS) onboard the GOES 10 satellite located 6.6 Earth radii from the center of the Earth (Aschwanden 1994). Using these data, solar flare signatures (Taylor and Watkiks 1970) that occurred few minutes before the *fb*Es enhancements were identified and the evolution of the Es traces as seen in the ionograms was investigated.

Results and discussion

Figure 1 shows the variation of the Dst index in its top panel, the variation of both the *fb*Es (green line) and *ft*Es (brown line) at SLZ in the middle panel, and the variation of the X-ray solar radiation intensity measured in the range 0.5–4.0 Å (red line) and 1.0–8.0 Å (blue line) in the bottom panel. All these data are presented in UT and were observed from October 26 to November 3, 2003. Please note that the local time (LT) for the Brazilian sector is GMT-3 (or UT-3). The intensity of Dst is given in nT, and its linear scale is shown in the left vertical axis of the top panel. Both *fb*Es and *ft*Es are given in MHz, and their linear scale is shown in the left vertical axis of the middle panel. The X-ray solar radiation intensity in both bands is given in W/m^2, and a logarithmic scale is shown in the left vertical axis of the bottom panel. On the right vertical axis of the bottom panel, there is also a classification of the flare according to the intensity reached by the peak X-ray flux (Somov and Syrovatskii 1972).

A recent study by Resende et al. (2013) of the frequency parameters associated with Es layers in the equatorial ionosphere during disturbed periods revealed that the typical behaviors of *ft*Es and *fb*Es in the Brazilian sector (GMT-3) are characterized by enhancements during the morning period after about 9:00 UT reaching their maximum values at around 15:00 UT. These parameters then decrease to their quiescent values after around 21:00 UT. Resende et al. (2013) also found that the normal baseline for *ft*Es ranges between 4 and 6 MHz, while the normal baseline for *fb*Es (considering *fb*Es as a proxy of the *fo*E)

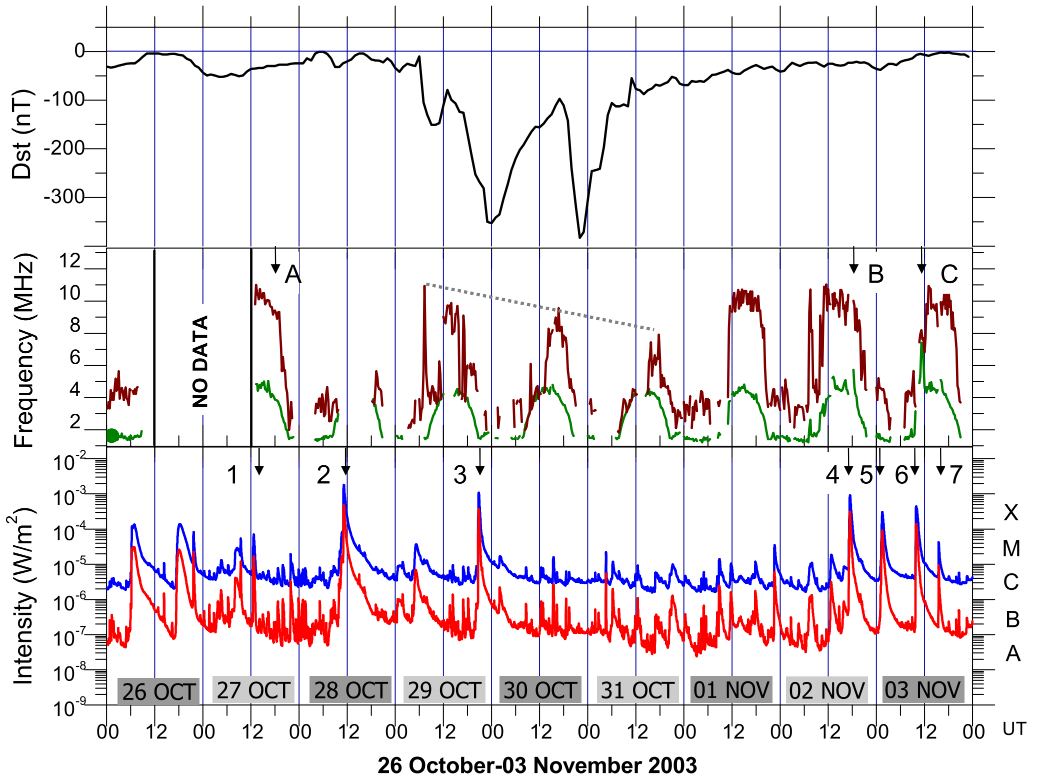

Fig. 1 Temporal evolution of (*top panel*) the Dst index, (*middle panel*) the *fb*Es (*green line*) and *ft*Es (*brown line*) at SZL, and (*bottom panel*) the X-ray solar radiation flux measured in the range 0.5–4.0 Å (*red line*) and 1.0–8.0 Å (*blue line*)

is below 2 MHz (close to 1.5 MHz in the present period of analysis). The largest values of *fb*Es were observed to be around 4.5 MHz close to the local midday (corresponding to an electron density around 25.1 × 10^4 electrons/cm^3), and top values of *ft*Es of about 11 MHz were reached in the time range between 13:00 and 15:00 UT.

During the magnetic superstorm that occurred in October 2003, the behavior of these frequency parameters was altered in an attention-grabbing way. The digisonde registered sequentially smaller values for the *ft*Es maximum daily peak from October 29 to 31, 2003 (identified by the dotted line in the middle panel of Fig. 1). Also, anomalous intensifications of the ionospheric density (determined from the *fb*Es) that exceeded the normal ambient background values for local time and location could be seen for a few days after the main phase of the magnetic storm (identified in the middle panel of Fig. 1 by the arrow labeled with the letters B and C).

The sequentially smaller values of the *ft*Es maximum daily peak started on the initial phase of the magnetic storm and lasted until the beginning of the recovery phase. On October 29, 2003, the *ft*Es maximum daily peak reached 10 MHz around midday, decreasing to 9.5 MHz on October 30, 2003, and decreasing to 8 MHz on October 31, 2003. Following this, the value of the *ft*Es maximum daily peak returned to the typical level of 11 MHz. Despite the remarkable characteristics of the frequency parameters measured during this event, we were not able to collect enough evidence to provide a definitive explanation for the declination in the *ft*Es maximum daily peak measured during the main phase of the superstorm. We only identified that the EEJ current was very weak during the period when the declination in the *ft*Es maximum daily peak was measured, implying a weak EEJ polarization electric field. This effect is shown in Fig. 2 through the EEJ ground strength (calculated from $\Delta H_{\mathrm{SLZ}} - \Delta H_{\mathrm{VSS}}$) from October 28 to 31, 2003. We suggest that an electromagnetic rearrangement of the $\mathrm{S_q}$ system, i.e., disturbance dynamo effects, was dominant in the equatorial environment in the E region during that period. This assumption is reasonable since the *ft*Es is a parameter taken from the $\mathrm{Es_q}$ layer, that is associated with EEJ plasma instabilities, which are in turn driven by the EEJ electric field, that we have stated was weak during that period.

The anomalous intensifications of the ionospheric density were determined from the sudden peaks in the *fb*Es. After double checking our ionograms and our data analysis, we confirmed that this intensification was a real effect that appeared superposed to the normally expected behavior for the *fo*E. These significant increases of *fb*Es (green line) are identified by arrows with capital letters A, B, and C in the middle panel of Fig. 1. The *fb*Es reached 5 MHz on October 27, 2003 (during the recovery phase of a minor storm which started on October 26, 2003) when the value was supposed to be around 4 MHz (letter A). This means there was an additional ionization of 9.1 × 10^4 electrons/cm^3 over the normal 21.9 × 10^4 electrons/cm^3, i.e., a 42 % increment [please note that the electron density can be calculated from $n = 1.24 \times 10^4 \left(fb\mathrm{Es}\right)^2$]. However, the most prominent events were observed during the recovery phase of the October 2003 superstorm. On November 2, 2003, during the first day of the recovery phase, a peak of 6 MHz in the *fb*Es is clearly observed close to 19:00 UT (letter B), doubling the electron density with an additional 22.8 × 10^4 electrons/cm^3 (104 %). On November 3, 2003, the rise of the *fb*Es to 7.5 MHz (letter C) represented an additional 37.7 × 10^4 electrons/cm^3 (146 %), i.e., one and a half times the expected electron density for the corresponding location, height, and time. Another aspect associated with the *fb*Es is that the values before the last two peaks were not computed due to the absence of the Es layer (both $\mathrm{Es_q}$ and $\mathrm{Es_b}$) from the ionograms.

In order to investigate this behavior of Es layers, we considered the influence of the X-ray flux due to solar flares in the ranges of 0.5–4.0 and 1.0–8.0 Å using measurements taken by XRS at the GOES 10 (arrows 1–7 in the bottom panel of Fig. 1). We identified the characteristics of high-intensity flares (M and X class) in events indicated by the numbered arrows. These identified events preceded the observed *fb*Es peaks (arrows with letters). The first event (arrow 1) was classified as M class and was followed by a small raise in the *fb*Es, 5 MHz (arrow A). The second event (arrow 2) could not be related to any ionospheric disturbance due to the lack of digisonde data. The events numbered 3 and 5 occurred at night (44°W) and did not affect the observation of the E region in the same way as those occurring during daytime. The more obvious cases (arrows 4 and 6) are X-ray flux due to X class flares and occurred just in time for the increases in the *fb*Es (letters B and C). Finally, the M class (arrow 7) occurred before a minor intensification in the *fb*Es that rose to 5.1 MHz.

For the present study, we took the peak in the *fb*Es parameter occurring on November 3, 2003, to a closer analysis. Figure 3 shows a sequence of ionograms obtained at SLZ on November 3, 2003, between 09:00 and 13:15 UT. Here we can identify the different types of Es layers during this period. The presence of the $\mathrm{Es_q}$ layer (associated with the EEJ irregularities and identified on black arrows) lasted until 09:30 UT (identified with black arrows in Fig. 3). There is no Es layer in the ionogram acquired at 09:45 UT, up to the point that the E layer trace is perfectly identified. Afterward, as seen in the ionograms from 10:00 to 10:30 UT, a strong ionospheric

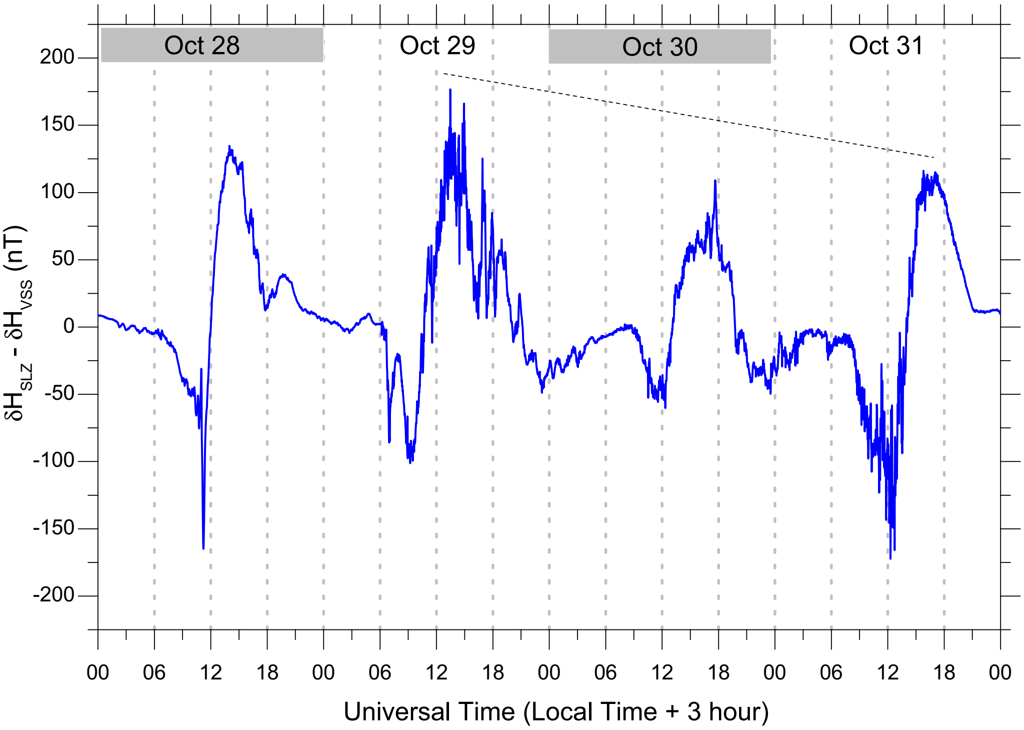

Fig. 2 Temporal evolution of the EEJ ground strength obtained from 00:00 UT (LT + 3) on October 28 to 24:00 UT on October 31, 2003

absorption took place hiding all the ionospheric traces of the E and F regions. Subsequently, the ionogram acquired at 10:45 UT revealed a typical Es_c layer (identified with red arrows in Fig. 3) with its characteristic "cusp," which matches with the frequency increase in the *fb*Es to 7.5 MHz (identified with letter C in Fig. 1). At around 12:30 UT, the Es_c (associated with wind shear caused by neutral winds, a common feature at the middle latitudes, but rare at the equator, as described in Whitehead 1989) seems to emplace the Es_q that dominated the ionogram from then on.

In relation to absorption of the layers on ionograms, we know that the solar radiation X-ray with wavelengths between 2 and 8 Å is responsible for the ionization of all the atmospheric constituents, while the EUV with wavelengths ranging from 1027 to 1118 Å is responsible for the ionization of the minor constituents present at the D region heights. Therefore, an extra amount of solar radiation could have increased the D region density leading to an increase in its opacity to shorter wavelength electromagnetic signals propagating upward (Abdu 1966; Abdu et al. 1967, 1973). In this case, the lower frequencies of the digisonde would be blocked. Therefore, the disappearance of the Es layers and E and F regions could be a response of the D region density to sudden X-ray and/or EUV solar radiation. We have no measurement of the D region density or of the opacity to prove that it was directly affected by the solar flares during these events. However, based on the short time period between the solar event observation and the observed effect in the *fb*Es, it seems plausible to assume that an X-ray additional ionization flux imposed on the ionosphere due to the solar flares would have blocked the lower frequencies of the digisonde. Also, our results agree with that reported by Sripathi et al. (2013) showing the sudden disappearance of echoes of the ionograms during the flare event, indicating absorption of radio signals in the D region.

In discussing augmentation of the *fb*Es, we should recall that we observed a sudden appearance of the Es_c layer in replacement of the normally observed Es_q layers (identified with black arrows in Fig. 3). Also, the presence of Es_c layer means that the wind shear mechanism is dominant (Abdu et al. 1997). Such increases in the *fb*Es were previously reported in low latitudes by Batista and Abdu (1977). The authors published a study where they analyzed some magnetic storms which occurred between 1973 and 1975 in which the *fb*Es reached values greater than 7 MHz 2–3 days after the storm. They stated that after having performed a careful study of winds and recombination rates, these *fb*Es increases can be attributed to particle precipitations from the Van Allen radiation belt. Therefore, these observed layers were classified as Es_a layers. We see no sporadic layers of type "a" in our study. However, we believe that there is evidence that the neutral winds

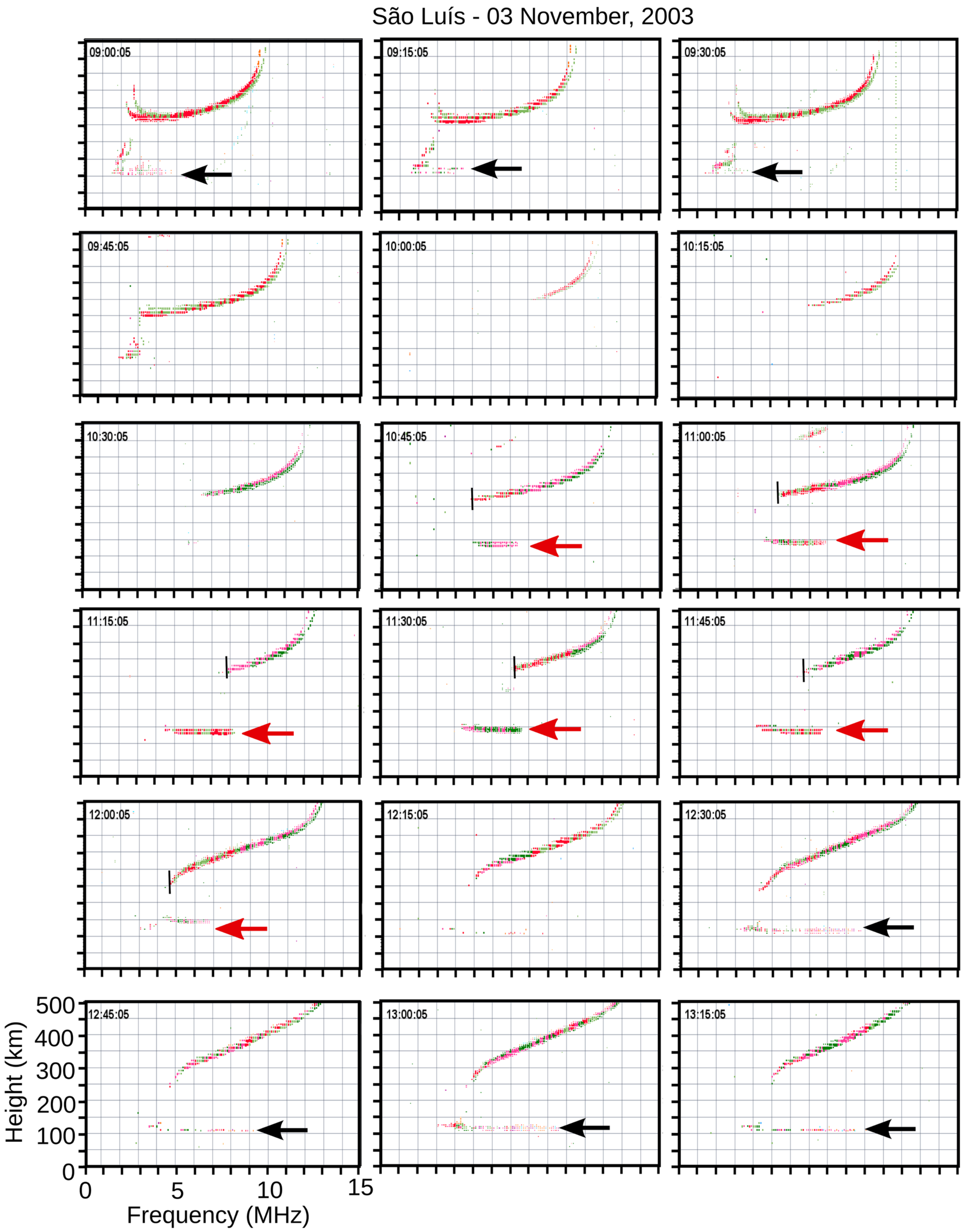

Fig. 3 Sequence of ionograms obtained at SLZ on November 3, 2003, between 09:00 and 13:15 UT when different types of sporadic E layer were identified

play an important role in the Es formation process during sudden density intensification, as in the study performed by Batista and Abdu (1977). Therefore, we looked for the influence of the dynamics of the E region on the formation of the $\mathrm{Es_c}$ layer through investigation of the EEJ ground strength as an indirect measurement of the E region electric field strength, that is a measurement of the $\mathrm{S_q}$ system, which in turn is driven by the atmospheric neutral wind.

Figure 4 shows the evolution of the *fb*Es (given in MHz) from 00:00 UT on 2 November to 24:00 UT on 3 November (red line in the upper panel). Also, the EEJ ground strength for the same time period is placed in the bottom panel of the same figure, identified as $\Delta H_{\mathrm{SLZ}} - \Delta H_{\mathrm{VSS}}$ (red line). The mean quiet-time values obtained from 3-day averaged values acquired few days before the superstorm (blue lines) are also superposed on both graphs.

This figure clearly shows that the sudden increase in the electron density on November 3, 2003, occurred during a counter electrojet (CEJ) event, meaning that a downward polarization electric field was dominant in the E region during this period (Crochet et al. 1979). Therefore, since the electric field mechanism was no longer acting and the $\mathrm{Es_c}$ layer is present, we have enough arguments to say that the neutral wind mechanism is the only acting force influencing the Es formation. In fact, Devasia et al. (2006) studied the dependence of the appearance of sporadic layers in equatorial latitudes over a solar cycle. They had shown several events where radio signal propagation was blocked and the upper layers could not be identified. It should be noted that all CEJ events reported by Devasia et al. (2006) occurred under magnetically quiet conditions (Ap < 10) contrary to the present case, where the presence of the $\mathrm{Es_c}$ layer occurred during the recovery phase of a magnetic storm (Dst index around −30 nT), i.e., a moderately disturbed period. Nevertheless, Denardini et al. (2009) reported that CEJ events may occur during both quiet and moderately disturbed magnetic conditions in the Brazilian territory. Their work also includes an introductory review where they show the importance of the atmospheric neutral wind (tide and gravity waves) for the development of CEJ events on both local and global scales, supporting our assumption that the neutral wind mechanism is the only acting force dominating the Es formation in this study. Tsunoda (2008) analyzed the $\mathrm{Es_b}$ layers in equatorial regions and suggested that these layers are anti-correlated with the EEJ intensity. Recently, Yadav et al. (2014) studied the $\mathrm{Es_b}$ layer occurrence in equatorial regions in the Indian sector for the years 2007 and 2009 and also concluded that the $\mathrm{Es_b}$ layers are linked with the CEJ events.

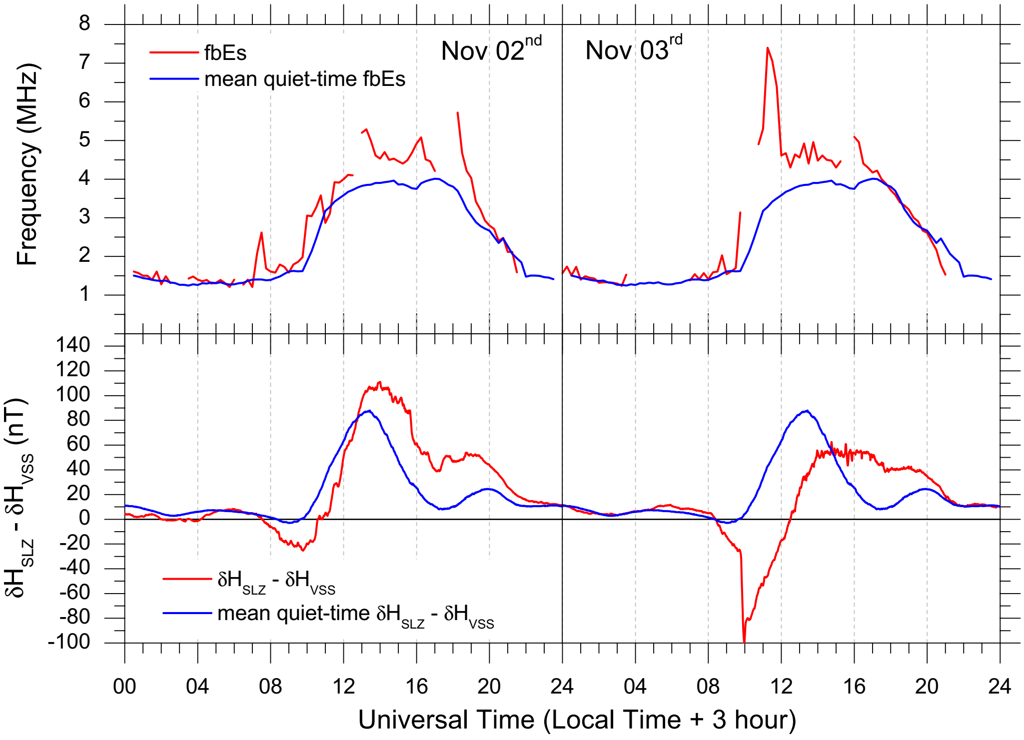

Fig. 4 Temporal evolution of the *fb*Es (*upper panel*) and of the EEJ ground strength (*bottom panel*) obtained from 00:00 UT on November 2 to 24:00 UT on November 3, 2003. The *red lines* show the quantities measured during this interval with *blue lines* showing the mean quiet-time quantities calculated from 3-day average values acquired a few days before the superstorm

Therefore, due to the similar characteristics between our example and those reported by other authors, mainly Devasia et al. (2006), we infer that the abnormal enhancement of the equatorial sporadic E layer density (indicated by the *fb*Es peak) and appearance of the $\mathrm{Es_c}$ layer are related to the CEJ event. Moreover, the radio wave absorption (below 5–8 MHz) occurred in the D region that happened some minutes before the abnormal enhancement of the E layer density is attributed to the additional X-ray ionization due to solar flare events.

Figure 4 demonstrates that another enhancement of the *fb*Es may have occurred after 18:00 UT on November 2, although we have not thoroughly investigated this occurrence in terms of the dominant type of sporadic layer. Therefore, we could not provide a conclusion on the mechanism of formation in that case. However, judging by the excursion of the EEJ ground strength for the same time period we can certify that there was no CEJ event taking place at that moment. We should remember that this observation occurred during a time of disturbance, when several ionospheric effects can take place, e.g., disturbance dynamo and participle precipitations. So, to elucidate this matter we would need to look more closely at the ionograms as well as other sources of data obtained for that period, without discarding the competing wind shear mechanism.

Conclusions

By attributing the additional X-ray ionization flux to the solar flare that occurred minutes prior, we used radio wave absorption observed with a digital sounder at São Luís—MA, Brazil, to identify solar activity effects in the ionospheric D region. We have shown sequentially smaller values for the *ft*Es maximum daily peak between from October 29 to 31, 2003. The observed reduction started in the initial phase and lasted until the beginning of the recovery phase of the 2003 superstorm. The *ft*Es measured close to midday did not exceed 10 MHz on October 29, 9.5 MHz on October 30, and 8 MHz on October 31. We also observed that the EEJ current was very weak during the period when the decline in the *ft*Es maximum daily peak was measured, meaning a weak EEJ polarization electric field. Therefore, we assumed that an electromagnetic rearrangement on the $\mathrm{S_q}$ system to be dominant in the equatorial environment in the E region during that period. In addition, we showed the presence of peaks in the *fb*Es, i.e., peaks of electron density that suddenly appeared superposed to the normal behavior of the E region electron density diurnal variation. The most remarkable peak (meaning impressive increases of about 146 % in the electron density) was observed on November 3, during the recovery phase of the magnetic superstorm, when *fb*Es registered 7.5 MHz. We showed that this abnormal enhancement of the *fb*Es appears due to an $\mathrm{Es_c}$ layer development which occurred during CEJ conditions. These results were similar to studies reported by other authors. We infer that the *fb*Es enhancement and appearance of the $\mathrm{Es_c}$ layer are related to the CEJ event. Moreover, the radio wave absorption (below 5–8 MHz) occurred in the D region some minutes before the abnormal enhancement of the E layer density which can be attributed to the additional X-ray ionization from solar flare events.

Authors' contributions

CMD conceived the study, participated in its design and coordination, carried out the magnetic data processing, performed part of the data analysis, participated in the sequence alignment, and drafted the manuscript. LCAR helped design and coordinate the study, also carrying out the ionosonde data processing and performing part of the data analysis, participating in the sequence alignment and drafting the manuscript. JM carried out all the electron density calculations, actively participated in the discussions, and helped to draft and review the manuscript before submission. SSC carried out the acquisition, cleaning, and processing of the magnetic data. He also helped revise the manuscript and participated in drafting the discussions. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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