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On the characteristics of 150-km echoes observed in the Brazilian longitude sector by the 30 MHz São Luís radar

F. S. Rodrigues[1], **E. R. de Paula**[2], **and J. L. Chau**[3]

[1]Atmospheric & Space Technology Research Associates – ASTRA, Boulder, CO, USA
[2]Instituto Nacional de Pesquisas Espaciais, INPE, São José dos Campos, Brazil
[3]Radio Observatorio de Jicamarca, Instituto Geofísico del Perú, Lima, Peru

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Abstract. We present long-overdue details about the intensity and spectral characteristics of 150-km echoes observed by the São Luís radar in Brazil. The São Luís observations show that the echoes usually come from multiple scattering layers that descend in altitude before local noon, and ascend during afternoon hours, similar to what has been found in observations made in other longitude sectors. The layers are usually 3–5 km thick and located, mostly, between 130 and 170 km altitude. The measurements also show variations in echo intensity that are similar to observations made at other equatorial and off-equatorial sites. Analysis of observations made during 2008 shows significant (>37 %) monthly occurrence rates for every month. Reduced occurrence rates were observed around March Equinox. We associate this reduction in occurrence rate, however, to a non-geophysical factor. An increase in the daytime sky noise in the months around March Equinox causes a decrease in the signal-to-noise ratio (SNR) of the echoes, which makes them less distinguishable in our analysis. A higher occurrence of weaker echoes around March Equinox was confirmed by an statistical analysis of the seasonal variation of echo intensities. Strong, long-lasting and, therefore, more noticeable echoing layers, however, were observed between June and early September compared to other months in 2008. Spectral analyses show that most of the echoes have negative mean Doppler shifts indicating upward velocities. The echoes also have narrow spectral widths of only a few m s^{-1}. Finally, we also found that the mean Doppler shift of the observed echoes can vary noticeably with altitude at times. Using spaced antenna measurements we show that this is caused by the wide field-of-view of the radar and the spatial distribution of the scatterers within the radar beam.

Keywords. Ionosphere (Equatorial ionosphere)

Correspondence to: F. S. Rodrigues
(frodrigues@astraspace.net)

1 Introduction

Observations of non-thermal scattering of radio waves occurring at approximately 150-km altitude in the equatorial ionosphere were first reported by Balsley (1964) based on measurements made with the Jicamarca radar in Peru. Jicamarca measurements made by Royrvik (1982) almost twenty years later showed that the echoes were caused by field-aligned electron density irregularities. These echoes are observed during daytime only and are commonly referred to as 150-km echoes. Despite being known for many years, an explanation for the origin of these echoes is still topic of current investigation. The difficulty to explain the origin of these echoes is caused by the absence of any obvious source of free energy that could be responsible for the generation of density irregularities at those altitudes (e.g. Tsunoda and Ecklund, 2000). However, it has been hypothesized that the ionospheric irregularities causing 150-km echoes could be generated by a gravity wave driven interchange instability (Kudeki and Fawcett, 1993) or by polarization electric fields generated off magnetic equator by a sporadic E layer instability (Tsunoda, 1994). More recent results indicate that 150-km echoes can be related to naturally enhanced ion acoustic waves (Chau et al., 2009).

A renewed interest in these echoes was motivated by the high time and range resolution observations made by Kudeki and Fawcett (1993) using the Jicamarca radar. Their observations showed that the echoing region descends during morning hours reaching a minimum altitude around local noon and ascends in the afternoon. This creates a necklace-like pattern in Range-Time-Intensity (RTI) radar maps and has been associated with the daily variation of the solar zenith angle (Kudeki and Fawcett, 1993). Kudeki and Fawcett (1993) also showed that the intensity of the echoes was modulated in time with periods between 5 and 15 min. Similar modulation, however, was not detected in the magnitude of the Doppler shifts of the echoes. More importantly, they pointed out

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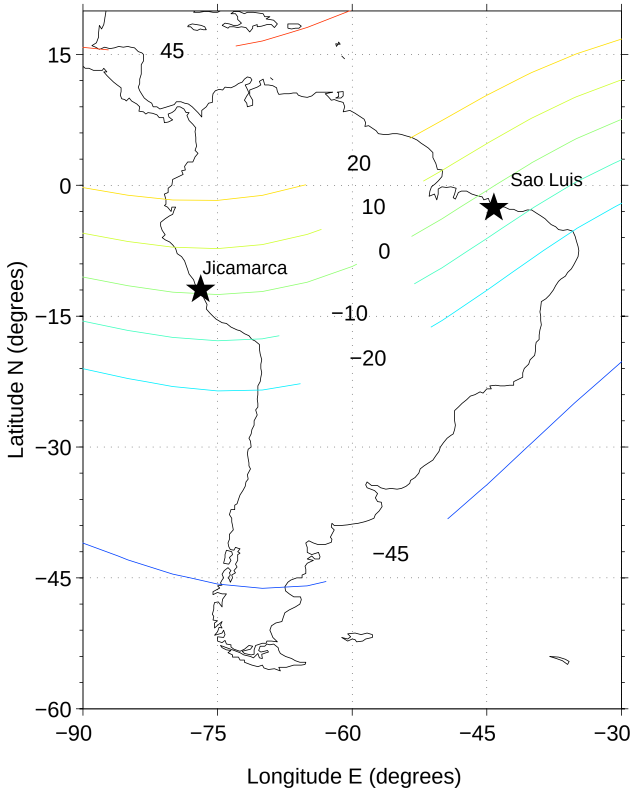

Fig. 1. Location of the São Luís radar. Contours of magnetic inclination and the location of the Jicamarca radar in Peru are also shown for reference.

that the Doppler velocities followed the intensity of the electrojet current measured by latitudinally-spaced magnetometers. They suggested that observations of 150-km echoes could be used to estimate the magnitude of the equatorial zonal electric field, an important driver of the low-latitude ionosphere. They also suggested that smaller radar systems could detect these 150-km echoes and therefore could be used for monitoring equatorial electric fields. Using simultaneous incoherent and coherent scatter radar observations at Jicamarca, Woodman and Villanueva (1995) and Chau and Woodman (2004) confirmed that the vertical Doppler velocity of 150-km echoes is in fact a good proxy of the vertical F-region $\boldsymbol{E} \times \boldsymbol{B}$ plasma drift. Routine measurements of vertical plasma drifts are now made at Jicamarca using observations of 150-km echoes.

Analysis of the characteristics of the 150-km echoes measured at different longitude sectors can help us better understand the underlying processes responsible for the field-aligned irregularities producing scattering. The occurrence of 150-km echoes have already been detected, for instance, in the Peruvian sector (e.g. Kudeki and Fawcett, 1993; Chau and Kudeki, 2006), in Pohmpei, Micronesia (e.g. Kudeki et al., 1998; Tsunoda and Ecklund, 2004), in Indonesia (Patra et al., 2008; Yokoyama et al., 2009), and in the Indian sector

Table 1. Main radar parameters for observations of 150-km echoes.

Parameter	Value
Peak power	4 kW
Code length	28 bauds
Baud length	1-km
IPP	600 km
Number of samples	120
Initial sampling height	90 km
Number of coherent integrations	16
Number of incoherent integrations	10
Number of FFT points	64

(Choudhary et al., 2004; Patra and Rao, 2007). de Paula and Hysell (2004) also reported the detection of 150-km echoes in the Brazilian sector during initial observations made by a small, low-power coherent backscatter radar deployed in the equatorial site of São Luís. Here, we examine more carefully the observations of equatorial 150-km echoes made by the São Luís radar with emphasis on the comparison of these observations with similar measurements made elsewhere. We point out similarities and differences in the characteristics of the echoes observed over São Luís and other sites. While this comparative analysis does not explain the origin of the 150-km echoes, it provides additional information that must be considered when developing theories to explain the origin of the 150-km echoes. Our results also provide further insights on utilizing small radar systems for detection of 150-km echoes and interpreting these observations. This report is organized as follows: information about the experimental radar setup used for observations of 150-km echoes are provided in Sect. 2. Details about the observations and analyses are given in Sect. 3. The results of the observations and analyses are discussed in Sect. 4. Section 5 contains a summary and final remarks for this study.

2 Experimental setup

A 30 MHz coherent backscatter radar is installed near the geomagnetic equator in São Luís, Brazil (2.59° S, 44.21° W, −2.35° dip lat) and is operated by the Brazilian National Institute for Space Research (INPE). Figure 1 shows the location of the São Luís radar. The location of the Jicamarca radar in Peru where measurements of equatorial 150-km echoes were first made, and contours of magnetic inclination are also shown for reference. The São Luís radar has being used mainly for studies of equatorial spread *F* (e.g. Rodrigues et al., 2004; de Paula et al., 2004; Rodrigues et al., 2008) but observations of the equatorial electroject and 150-km echoes have also been made (de Paula and Hysell, 2004). The São Luís radar is equipped with two 4 kW transmitters and four independent antenna sets. Each antenna set is formed by a 4 × 4 array of Yagi antennas. The four sets

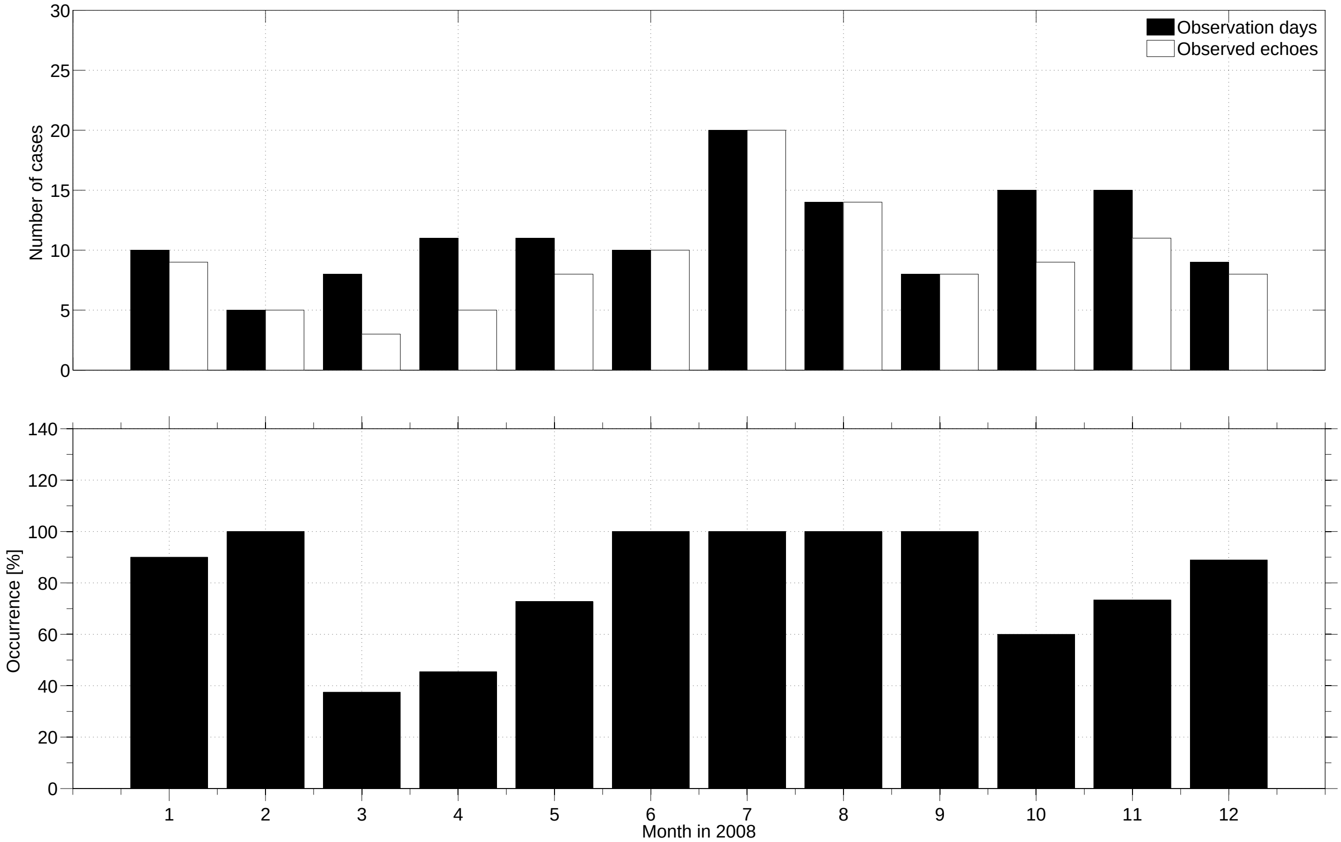

Fig. 2. Top panel shows the number of observation days for every month in 2008 and the number of days when 150-km echoes were observed in the RTI maps. The bottom panel shows the occurrence rate for each month computed using the information shown in the top panel.

are aligned in the magnetic East-West direction. One or two antenna sets can be used for transmission. Observations of 150-km echoes are usually made using only one antenna set for transmission and one transmitter. Soundings were made with 28-bit coded pulses giving a range resolution of 1 km. The inter-pulse period is 600 km and voltages are sampled every 1 km for ranges between 90 to 210 km altitude. Table 1 summarizes the specifications of the radar mode used for 150-km echoes observations.

3 Observations and analysis

Figure 2 shows a summary plot of the 150-km echoes observations made by the São Luís radar in 2008. In order to create this plot, we carefully examined Range-Time-Intensity (RTI) maps created right after each observation, and before raw data (voltage samples) were written into magnetic data tapes. The RTI maps were visually inspected to identify the occurrence of echoes. We used the following criteria to estimate the monthly occurrence frequency of 150-km echoes:

1. We considered an "observation day" only those days with, at least, 4 h of upper E-region observations between 09:00 and 16:00 LT.

2. We considered 150-km echoes to have occurred on a given observation day if echoes were clearly identified (usually with SNR $\gtrsim -10$ dB) in the RTI maps between 09:00 and 16:00 LT and between 130 and 170 km altitude.

3. Consequently, we considered that 150-km echoes did not occur in a given observation day if no echoes were identified in the RTI maps between 09:00 and 16:00 LT and between 130 and 170 km altitude.

Figure 2 indicates a significant occurrence rate of 150-km echoes for every month in 2008. The occurrence rates were computed using the criteria described above and, therefore, did not take into account variations in the intensity or duration of the observed echoes. We only evaluated whether echoes were detected or not. Nevertheless, Fig. 2 provides an useful overview of the occurrence of 150-km echoes in the Brazilian longitude sector, which until now had yet to be provided. We will limit our statistical analysis here to observations made during 2008. A comprehensive multi-year analysis of the occurrence of 150-km echoes over São Luís is under way (A. Kherani, personal communication) and is outside the scope of this paper. We must point out that, at

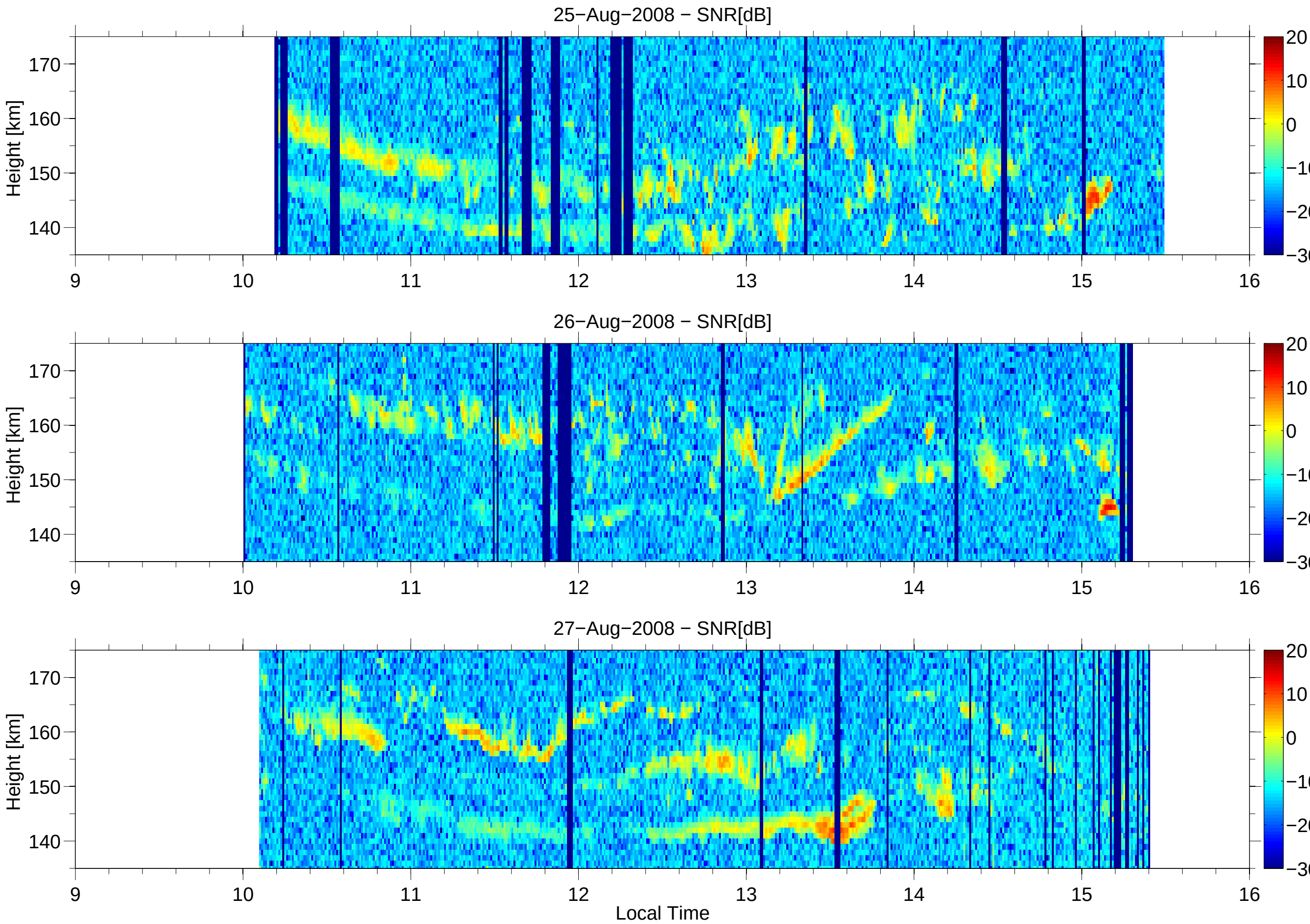

Fig. 3. Range-Time-Intensity (RTI) maps of upper E-region observations made by the São Luís radar in Brazil on three consecutive days during 25–27 August 2008.

least for observations made in 2008, the echoes observed between June and September seem to be stronger than echoes observed in other months based on our visual inspection of the RTI maps. More details about the variability in echo intensity and implications are given in the following section.

Figure 3 shows Range-Time-Intensity (RTI) maps illustrating typical upper E-region observations made by the São Luís radar. Daytime observations in São Luís usually started around 10:00 LT and finished around 15:30 LT. On these observations, moderate to strong echoes were observed between 135 and 170 km altitude. Vertical dark blue bands in the RTI maps indicate data gaps caused by either technical problems with the acquisition system or by intermittent radio interference sources located near the radar site. The Doppler spectrum of observations such as those shown in Fig. 3 were also computed using the Fast Fourier Transform (FFT) algorithm. The spectra were computed using 64 data points obtained using 16 coherent integrations and 10 incoherent integrations. Therefore, a Doppler spectrum for each range gate was obtained every ∼40 s. Mean Doppler shifts and spectral widths for each spectrum were estimated by fitting a Gaussian function to the measured spectrum. The left-side panels in Fig. 4 show the mean Doppler shifts of the observations showed in Fig. 3, while the right-side panels in Fig. 4 show the full spectral widths. Note that the convention in these plots is that a negative Doppler shift indicates motion away from the radar. Also, the full spectral width is twice the standard deviation parameter of the fitted Gaussian function.

As mentioned earlier, after observations are made and a figure with the quick-look RTI map is produced and saved, data is written into magnetic data tapes. In order to carry out spectral analyses of the echoes observed by the São Luís radar, raw data (voltage samples) written in the tapes must be read again. This is a time-consuming and tedious process, one of the main reasons for a report of 150-km echoes measured by the São Luís radar to be long overdue. In addition to this difficulty, during the data reduction process we also found that some of the tapes were damaged, and the data could no longer be retrieved from these tapes. While a set of 136 observation days could be used to produce the histogram

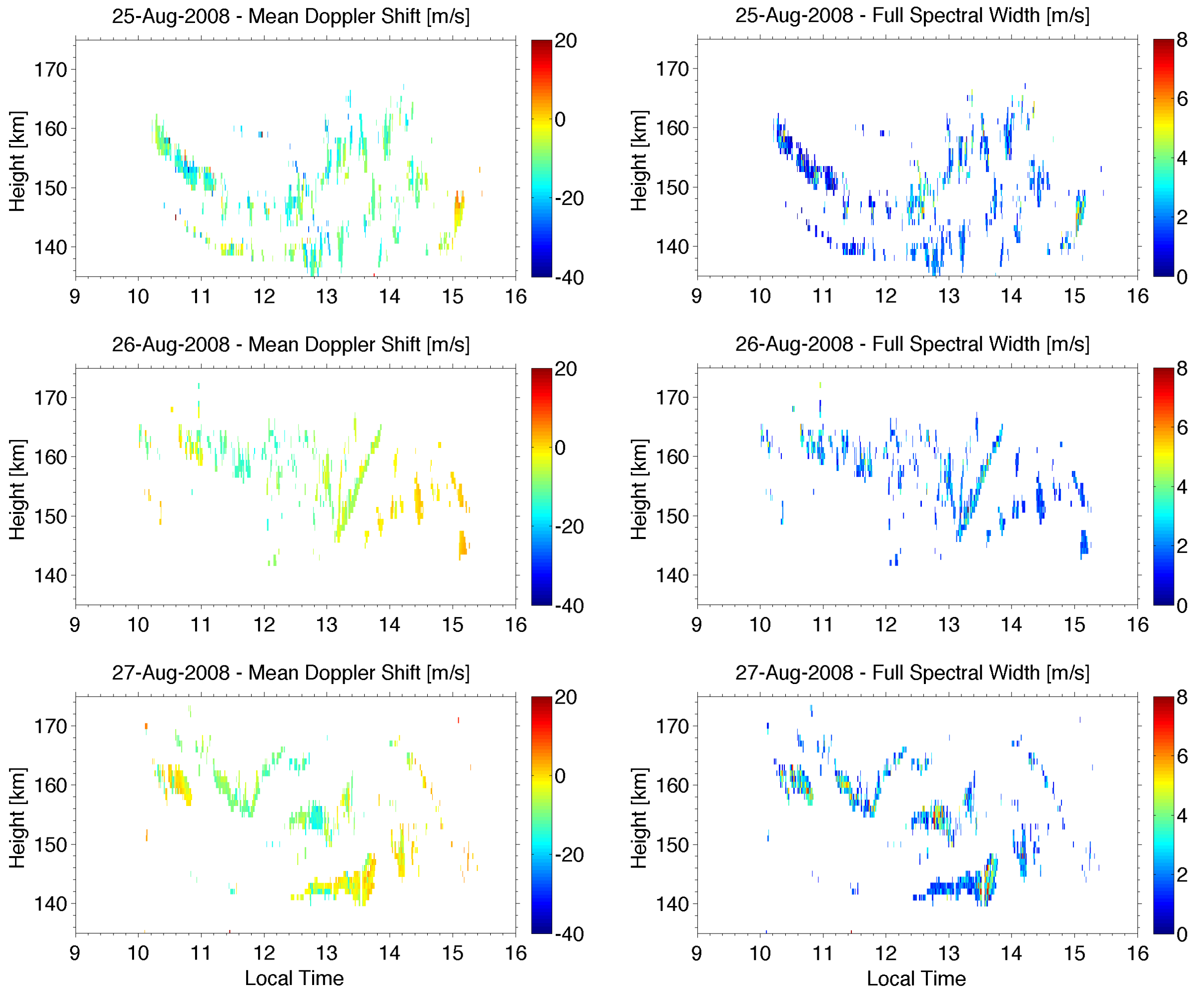

Fig. 4. Mean Doppler velocities (left-side panels) and full spectral widths (right-side panels) for SNR > −5 dB echoes observed on 25, 26 and 27 August 2008.

of 150-km echoes occurrence shown in Fig. 2, only measurements from 81 observation days were available for spectral analyses. Fortunately, a large number of observations of 150-km echoes was still available for each season. Once the tapes were read and the spectra of the echoes were calculated, we grouped the observations into height versus local time bins for each season in 2008 (March Equinox: February/March/April; June Solstice: May/June/July; September Equinox: August/September/October; and December Solstice: November/December/January). The bins were 5 km wide in height and 15 min wide in local time. The number of observations in each bin were then calculated and are shown in the left-hand side panels of Fig. 6. The occurrence rate of echoes with SNR > −5 dB was also calculated for each season. The results are shown in the right-hand side panels of Fig. 6, and will be discussed in the following section.

4 Discussion

Tsunoda and Ecklund (2004) were the first to investigate seasonal variations in the occurrence of 150-km echoes. They analysed observations made between 1999 and 2003 by a low-power 50 MHz radar located under the magnetic equator in Pohnpei (6.96° N, 158.19° E, 0.3° dip lat). They showed that the occurrence frequency of 150-km echoes over Pohnpei has a clear maximum during Northern Hemisphere Summer months and minimal (nearly absent) activity during other months. Because of the similarity with the seasonal variation of sporadic E layers (E_s) in that longitude sector, they suggested that the ionospheric irregularities causing 150-km echoes could be created by an off-equator E_s instability (Cosgrove and Tsunoda, 2002). Using observations made by the JULIA (Jicamarca Unattended Long-term Investigations of the Ionosphere and Atmosphere) mode of the Jicamarca radar, Chau and Kudeki (2006) investigated the seasonal variation of 150-km echoes in the Peruvian (Western

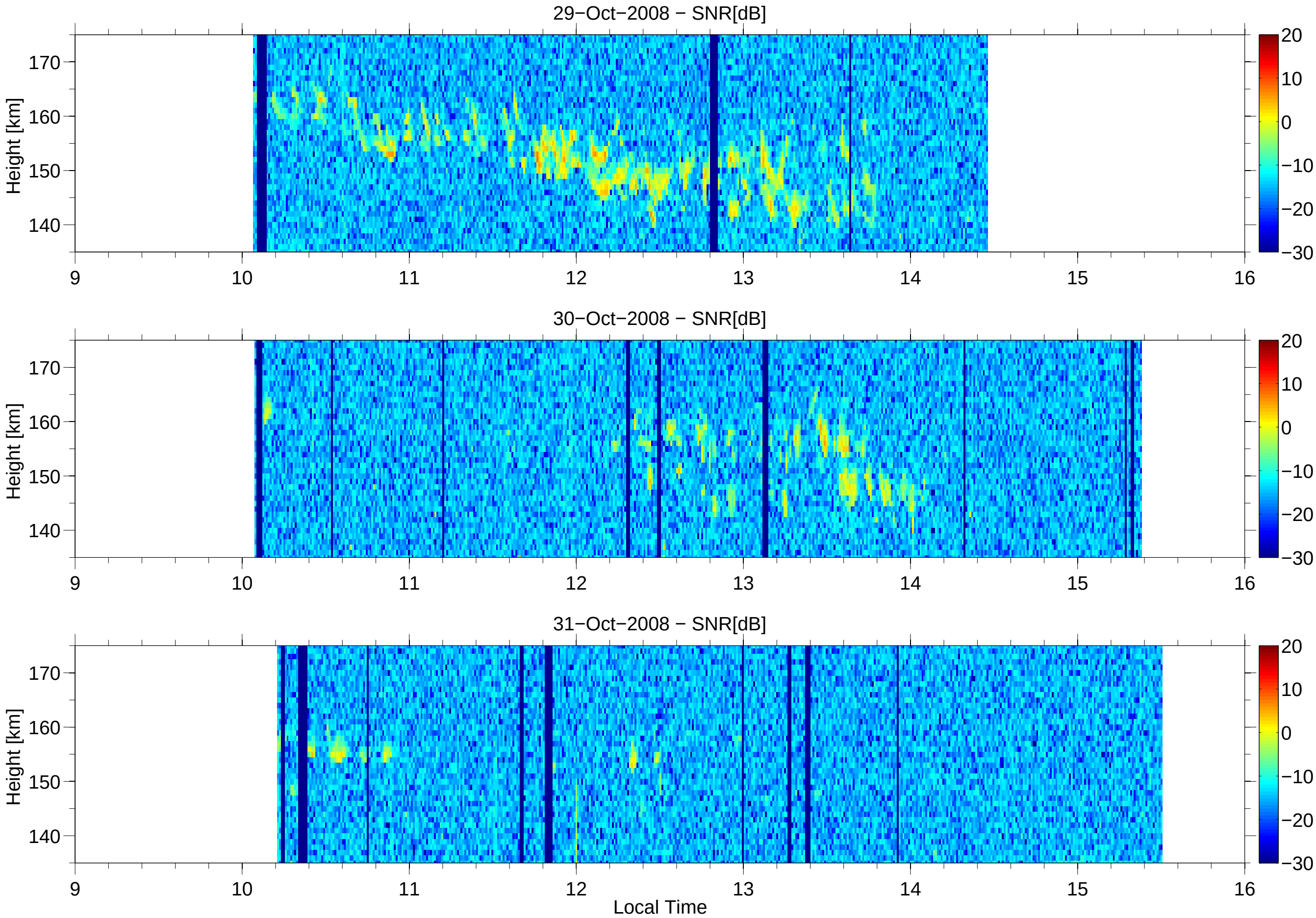

Fig. 5. Range-Time-Intensity (RTI) maps of upper E-region observations made by the São Luís radar in Brazil on three consecutive days during 29–31 October 2008.

South American) sector. They found that 150-km echoes are observed virtually every day over Jicamarca. Their results indicate a high occurrence (>70 %) of echoes for all seasons but with slightly higher occurrence (>85 %) during June Solstice months. Chau and Kudeki (2006) results challenge the hypothesis of Tsunoda and Ecklund (2004) about the control of E_s layers over the occurrence of 150-km echoes since off-equatorial E_s layers occur more frequently during the December solstice in the Peruvian sector. Statistics of the occurrence of off-equatorial 150-km echoes in the Indian sector were also presented by Patra and Rao (2007). They studied observations made by the Gadanki MST radar (2.33° S, 44° W) between July 2005 and August 2006. The radar probes the upper E-region around 6.5° S magnetic latitude. Their analysis did not show clear evidence of a seasonal variability in echo occurrence in the Indian longitude sector.

Figure 2 shows that 150-km echoes were observed over São Luís with significant occurrence rates (>37 %) in every month of 2008. We did not observe the conspicuous maximum in the occurrence of 150-km echoes around June Solstice and nearly absence of echoes during other months as found by Tsunoda and Ecklund (2004) in the Pacific sector. However, we must point out again that the analysis of the occurrence rate of 150-km echoes whose results are shown in Fig. 2 does not take into account the intensity (SNR) of the echoes. A more quantitative statistical analysis of the variability in echo intensity will be presented and discussed in the following section. Nevertheless, our inspection of the RTI maps indicated that echoes observed between June and September were stronger and consequently more distinguishable in the RTI maps than in other months of 2008. To illustrate this, Fig. 5 shows RTI maps of upper E-region observations made during three consecutive days in October 2008. The RTI maps in Fig. 5 serve to exemplify the occurrence of weaker echoes compared to those observed in August (see Fig. 3). Fewer echoes can be seen in the October RTI maps and the "necklace" pattern cannot be clearly identified in some days.

In order to better quantify the occurrence of 150-km echoes in the Brazilian longitude sector and its seasonal

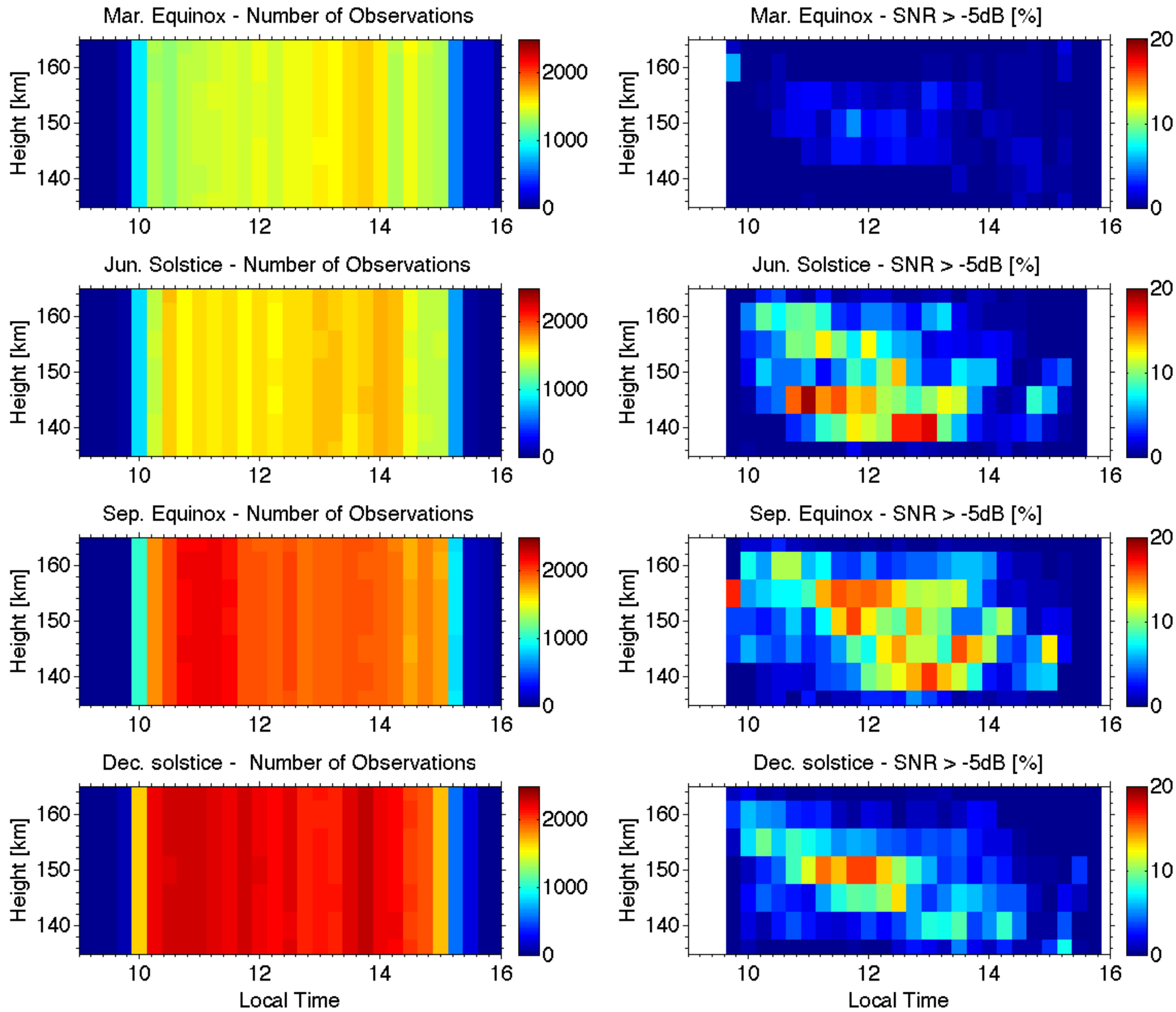

Fig. 6. Left-hand side panels show the number of observations versus height and local time for each season. Right-hand side panels show the occurrence rate of echoes with SNR greater than −5 dB.

variability, we grouped the observations by seasons (see description of the methodology in the previous section). The left-hand side panels in Fig. 6 show that a large number of observations were available for analysis in each height/local time bin. The right-hand side panels show the occurrence rate of moderate to strong echoes (SNR > −5 dB). The most striking feature shown in this analysis is the somewhat low occurrence rate of echoes with SNR > −5 dB during March Equinox compared with other seasons. This is in good agreement with the results shown in Fig. 2, which indicates a low occurrence of 150-km echoes in March and April. Figure 2 shows a high occurrence of 150-km echoes in February but only a few days of observations were available on that month. The variability in echo intensity throughout the year can be explained, in most part, by the variability in sky brightness. For the 30 MHz São Luís radar, the Galactic center can contribute with 6–8 dB of additional noise power. The Galaxy center, however, is only observed by the São Luís radar during daytime (09:00–18:00 LT) hours between January and June. Therefore, the low occurrence of moderate to strong echoes during the March Solstice months could be a direct result of the variability in the Galactic noise variation. The strong and long-lasting echoing layers observed between June and September also seem to manifest in the statistics shown in Fig. 6. A distinguishable higher occurrence of SNR > −5 dB echoes during June Solstice and September Equinox compared to other seasons can be observed.

Weaker and fewer echoes in the RTI maps during October and December Solstice months, for instance, could suggest that the conditions leading to the generation of 150-km

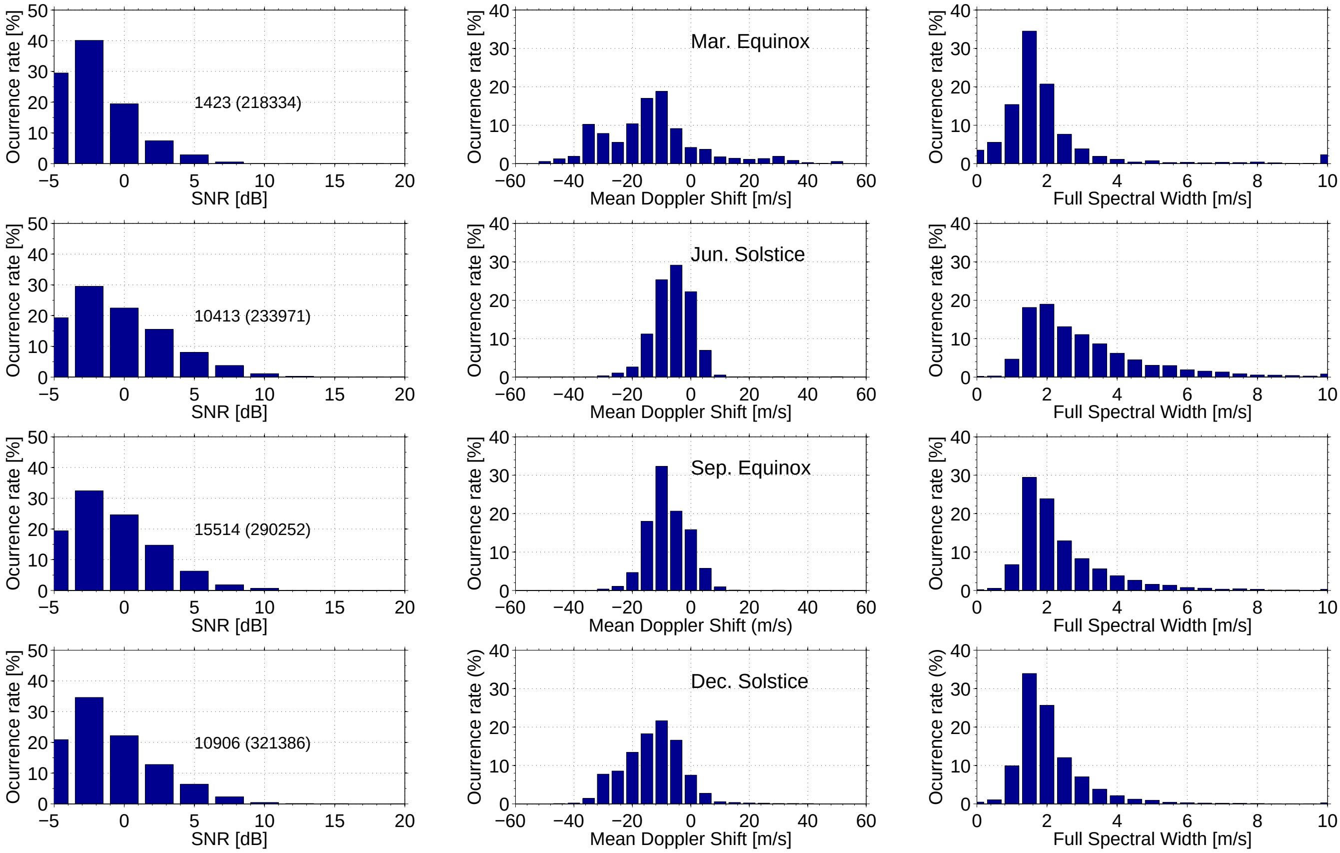

Fig. 7. Histograms of SNR (left side panels), mean Doppler shift (middle panels) and spectral width values (right side panels) of 150-km echoes observed by the São Luís radar in 2008 as a function of season (rows).

irregularities might not be as optimal as those found during June–September. On the other hand, the conditions for irregularity development might be similar but, for some reason, irregularities with smaller amplitudes were generated in October (and other months) and the São Luís is not sensitive enough to detect the echoes scattered by these irregularities. Statistical analysis of 150-km echoes observed by a more sensitive radar like JULIA could provide support to the latter hypothesis. However, a more careful analysis of seasonal variations in echo intensity (not occurrence) would be necessary to fully test this idea. The changes in echo intensity observed over São Luís also make us ask ourselves whether the conspicuous maximum of 150-km echoes during Summer months observed by Tsunoda and Ecklund (2004) could be a result of the threshold SNR set in the criteria used for identifying and counting the echoes. Setting a SNR that is too high might lead to an underestimation of the echo counts during periods when only weak echoes are observed. Irregularities causing 150-km echoes could still be generated but detection would be limited by instrument sensitivity.

4.1 On the intensity characteristics of the observed echoes

As mentioned earlier, the RTI maps in Fig. 3 show typical moderate-to-strong 150-km echoes observed over São Luís. Echoes with SNR values greater than ∼0 dB can be seen around 10:00 LT or earlier and last until around 15:30 LT. The first echoes appear between 150 and 170 km altitude during morning hours. The scattering regions appear as echoing layers in the RTI maps. These layers are usually 3 to 5 km thick in altitude. Two layers can be clearly seen throughout most of the observations on 25 August. Three layers can also be detected at times. A clear example of three layers can be seen on 27 August between 12:00 and 13:00 LT. The echoing layers descend in altitude during morning hours reaching the lowest altitude (∼140 km) around 12:30 LT. After reaching its lowest altitude, the layers start to ascend, reaching their initial altitude around 150–170 km.

Changes in the altitude of the echoing regions in a shorter period of time (from a few minutes up to several tens of minutes) are also observed. For instance, on 26 August, starting at about 13:15 LT, a relatively strong echoing region seems to start to gain altitude with time. The echoing center moves from about 150 km altitude to about 165 km in approximately 45 min, a height change rate of about $5.5\,\mathrm{m\,s^{-1}}$. Another example of altitudinal variability with short time-scale can be seen in the uppermost echoing layer observed on 27 August between 11:00 and 12:30 LT. Around 11:00 LT, the height of echoing layer varies quasi-periodically with a period of a few minutes and then starts to descend until reaching about 155 km altitude around 11:45 LT. After that, the layer starts to ascend again reaching 165 km altitude. The intensity of the echoes also seems to be modulated at times. For instance, fluctuations in the intensity of the echoes with a period of about 5 min are seen on the lowermost layer on 25 August between 10:30 and 12:15 LT. Fluctuations with longer periods (12–15 min) are also seen on 26 August between 10:00 and 11:00 LT and between 13:30 and 15:00 LT.

The RTI maps show examples of moderate-to-strong 150-km echoes over the São Luís site in Brazil. The echoes follow the same pattern observed at Jicamarca and other equatorial sites. The echoing layers in the RTI maps form a "necklace" shape, which is believed to be related to the daily variation of the solar zenith angle, and is considered the most striking feature of 150-km echoes (Kudeki and Fawcett, 1993; Kudeki et al., 1998; Tsunoda and Ecklund, 2004; Chau and Kudeki, 2006). Fluctuations in the intensity of the echoes with periods of a few minutes are also observed at Jicamarca (e.g. Kudeki and Fawcett, 1993). We point out, however, that the echoes over São Luís are more patchy and intermittent than the echoes observed with the Jicamarca radar. In the example shown by Chau and Kudeki (2006), for instance, the echoing layers in the RTI map are nearly continuous with time throughout the entire period of observations. Additionally, the Jicamarca echoes are stronger than the echoes observed in São Luís. They commonly exceed SNR = 10 dB at Jicamarca. In São Luís, however, only a few cases exceed this threshold as shown in Fig. 7 (left-hand side panels). The differences in the intensity of the echoes observed over São Luís and Jicamarca are caused, in most part, by differences in the experiment setup (number of coherent integrations, transmitted pulse length and shape) and hardware (transmitters and antenna arrays) of these two radar systems. Figure 7 shows histograms of SNR (left panels), spectral width (middle panels) and mean Doppler shift values (right panels) for each season. The number in each panel indicates the number of observations/echoes with SNR greater than −5 dB. The number between parenthesis indicates the total number of observations available for this analysis. Again, the histograms show that echoes with SNR > −5 dB were observed less frequently during March Equinox compared with other seasons, which, as explained in the previous section, is believed to be linked to the increased sky noise during this period.

Finally, the right-hand side panels of Fig. 6 also offer useful insights on the intensity characteristics of the 150-km echoes observed in Brazil. They show that, for any season, high-altitude echoes with SNR > −5 dB were more frequently observed in the morning sector than in the afternoon sector. Only a limited number of SNR > −5 dB echoes are observed after approximately 14:30 LT.

4.2 On the spectral characteristics of the observed echoes

The middle panel of Fig. 7 presents histograms of the mean Doppler velocities of the observed echoes with SNR > −5 dB as a function of season. It shows that most of the echoes have negative Doppler shifts, indicating upward velocities. This is, again, in good agreement with what is expected for 150-km echo observations. The vertical Doppler velocity of the 150-km echoes follow the vertical F-region plasma drift (e.g. Chau and Woodman, 2004) and, under geophysically quiet conditions, daytime vertical plasma drifts are expected to be upward (e.g. Fejer et al., 2008). Patra and Rao (2007) also examined the spectral characteristics of the off-equatorial 150-km echoes observed by the 53 MHz Gadanki radar. They found that most echoes had upward Doppler velocities with magnitudes below approximately $40\,\mathrm{m\,s^{-1}}$.

The left-hand side panels in Fig. 6 shows histograms of the (full) spectral widths of the observed echoes with SNR > −5 dB. Most of the observed echoes have spectral widths larger than $1\,\mathrm{m\,s^{-1}}$ but less than $7\,\mathrm{m\,s^{-1}}$, and with a maximum around $2\,\mathrm{m\,s^{-1}}$. Our results seem to be similar to what was observed in the Pohnpei spectral measurements. Tsunoda and Ecklund (2004) found that 150-km echoes observed by the Pohnpei radar are characterized by narrow spectral widths (a few $\mathrm{m\,s^{-1}}$ or less). Chau and Woodman (2004) and Chau and Kudeki (2006) also emphasized that 150-km echoes observed by Jicamarca have narrow spectral widths (less than $15\,\mathrm{m\,s^{-1}}$). The example shown by Chau and Kudeki (2006) (Fig. 1 in their paper) shows that most spectral widths are between 5 and $15\,\mathrm{m\,s^{-1}}$. We must clarify that the comparisons made in this paper refer to Jicamarca observations made with the JULIA radar mode, with antenna beams pointing perpendicular to the magnetic field. New off-perpendicular observations made at Jicamarca (Chau, 2004; Chau et al., 2009) also show echoes around 150-km altitude with spectra as wide as the ion line of the incoherent scatter spectrum (spectral width larger than $1000\,\mathrm{m\,s^{-1}}$). Finally, Patra and Rao (2006) also found that most spectral widths of off-equatorial 150-km echoes fall within 2 and $8\,\mathrm{m\,s^{-1}}$ with a maximum occurrence around $4\,\mathrm{m\,s^{-1}}$.

High-resolution observations at Jicamarca show that the vertical Doppler velocities of the 150-km echoes do not vary with altitude (Kudeki and Fawcett, 1993). However, looking again at Fig. 4 (left-hand side panels) we see that the Doppler shifts over São Luís seem to show some height variability at times. This observation is, perhaps, more obvious in the lowermost echoing layer on 27 August between 10:30 and 13:30 LT, for instance. We hypothesized that the variation in mean Doppler shift as a function of height could be a result of echoes coming from different localized scattering

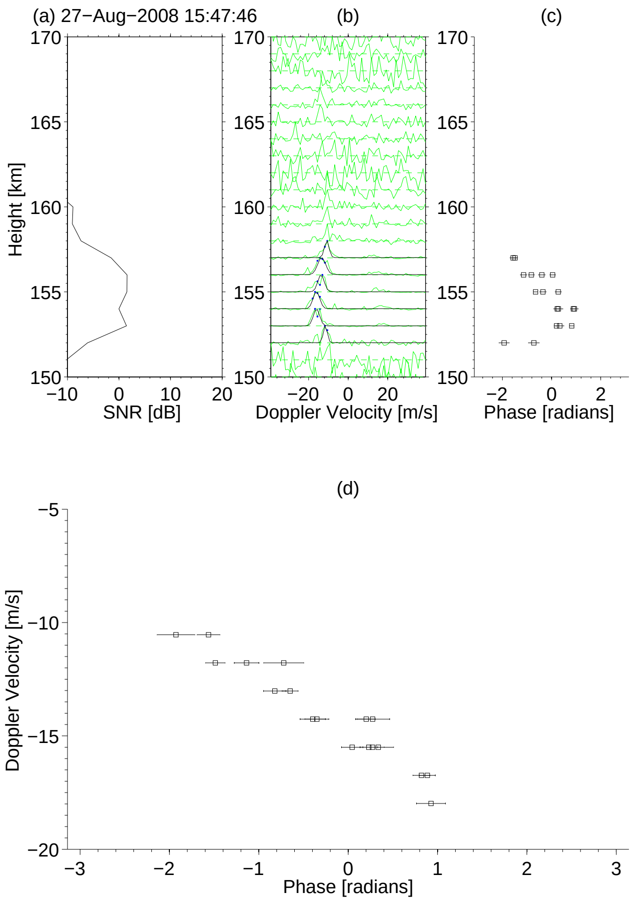

Fig. 8. Example of 150-km echoes observed over São Luís on 27 August 2008 at 12:47 LT. **(a)** SNR profile. **(b)** Measured (green solid lines) and fitted (black solid lines) spectra as a function of height. **(c)** Differential phase estimated from spaced antenna observations (see text). **(d)** Estimated phases versus corresponding Doppler velocities.

centers within the radar beam. The São Luís radar uses small antenna arrays with somewhat wide beamwidths (~15° in the zonal direction). To test this hypothesis we used measurements made by a pair of antennas spaced by 25 m. The measurements allow us to compute complex spectra, and estimate the normalized coherency and phase difference of the echoes as a function of Doppler velocity (e.g. Farley et al., 1981). Figure 8 shows an example of the results of our analysis. Panel (a) shows the SNR vertical profile indicating echoes around 155 km altitude. Panel (b) shows measured (solid green lines) and fitted (solid black lines) spectra as a function of altitude. Only spectra for echoes with SNR > -10 dB and with normalized coherency greater than 0.7 are fitted and show here. Note that, as we mentioned earlier, the mean Doppler velocity varies somewhat with altitude. In this particular example, it varies more than 10 m s^{-1} in less than 10 km altitude. Panel (c) shows the phase differences computed for the high coherency (>0.7) spectral bins. Uncertainties for the computed phases are also shown. The variability in the phases shown in panel (c) indicate that echoes come from different zenith angles (in the magnetic zonal plane) above the radar. Panel (c) even suggests a tilted scattering structure that resemble those suggested by Tsunoda and Ecklund (2004). Radar imaging observations at Jicamarca also suggest that most 150-km echoes measured by JULIA are caused by non-localized (or beam-filling) scattering structures, but localized scattering structures have also been seen in the interferometric images.

The phases of the echoes shown in panel (c) are shown again in panel (d) versus their respective Doppler velocities. The variation of the Doppler velocity as a function of arrival phase shown on panel (d) indicates that the measurements represent radial (not vertical) velocities of localized scattering regions within the field-of-view of the radar. The vertical velocity component can be estimated directly from Fig. 8d just by looking at echoes with zero phase angle (echoes from overhead) and is about 15 m s^{-1} in this example. In fact, measurements of localized scattering structures such as those shown in Fig. 8 can provide enough information to estimate both the vertical as well as the zonal components of the Doppler velocity of 150-km echoes over São Luís. Details about this estimation and results, however, are outside the scope of this report.

5 Summary and final remarks

We presented long-overdue details about equatorial 150-km echoes observed in the Brazilian longitude sector. While this study does not explain the origin of the 150-km echoes, it provides new information that must be taken into account when developing theories to explain the origin of these echoes.

The upper E-region echoes observed by the São Luís radar in Brazil show the regular “necklace” pattern in the RTI maps, which is the most striking feature of the 150-km echoes. Two or three scattering layers could be observed at times. The layers descend in altitude during morning hours and ascend in the afternoon. Echoes are observed, mostly, between 135 and 165 km altitude and at any given time during the period of the observations, which generally runs from about 10:00 LT until approximately 15:30 LT. Fast changes in the altitude of the echoing layers were noticed. We also noticed that the echoes observed by the São Luís radar are more “patchy” than the echoes observed by the Jicamarca radar. Quasi-periodic variations in the intensity of the layers were detected with periods ranging from a few to 15 min. For any season, most of the observed echoes have negative Doppler shifts indicating upward velocities, which is a result of the ionospheric plasma drifts, which are predominantly upward during daytime. The echoes also have narrow spectral widths. Most of the echoes have (full) spectral widths between 1 and 7 m s^{-1} with a peak in the occurrence rate around 2 m s^{-1}.

Analysis of over 130 RTI maps of radar observations made during 2008 show that 150-km echoes could be detected with significant monthly occurrence rates (>37 %). The lowest occurrence rates were found around March Equinox. Analysis of the RTI maps also show that stronger and more long-lasting echoing layers were observed during the period between June and September. Weaker and less distinguishable echo layers were seen in the RTI maps of observations made during other months. Statistical analysis of the SNR values of the observed 150-km echoes (Figs. 6 and 7) show that moderate-to-strong echoes occurred less frequently during March Equinox. This is, most likely, a result of an increase in the background noise during this period. The São Luís radar was pointing towards the Galactic center between approximately 09:00 LT and 15:00 LT (when most echoes are observed) between February and April. The occurrence of stronger echoes during the period between June and September also shows in the statistical analysis of the 150-km echoes as a function of season. A higher occurrence rate of echoes with SNR > -5 dB was observed during June Solstice and September Equinox months than what was observed during March Equinox and December Solstice months.

Finally, we detected some height variability in the mean Doppler shift of the 150-km echoes measured by the São Luís radar. Observations at Jicamarca, however, show that the mean Doppler shift of the 150-km echoes does not vary much with altitude. We used spaced antenna observations to verify that the variability in the São Luís measurements were caused by the wide beamwidth of the antennas. The variability in the mean Doppler shift measured by the São Luís radar is a result of the spatial distribution of the localized scattering structures within the radar beam.

Future work includes a more detailed analysis of the changes in echo intensity as a function of season and solar flux and how this variability relates to the new findings of Chau et al. (2009). Their results indicates that some of 150-km echoes might not be produced by field-aligned irregularities, but by naturally enhanced ion acoustic waves. An initial analysis of observations made in 2010 showed lower monthly occurrence rates than those observed in 2008. Additionally, the spaced antenna observations whose results were presented here motivate to us to investigate the estimation of both the zonal and vertical components of the Doppler velocities of the 150-km echoes measured by the São Luís radar.

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References

Balsley, B. B.: Evidence of a stratified echoing region at 150 kilometers in the vicinity of the magnetic equator during Daylight Hours, J. Geophys. Res., 69, 1925–1930, 1964.

Chau, J. L.: Unexpected spectral characteristics of VHF radar signals from 150-km region over Jicamarca, Geophys. Res. Letters, 31, L23803, doi:10.1029/2004GL021620, 2004.

Chau, J. L. and Kudeki, E.: Statistics of 150-km echoes over Jicamarca based on low-power VHF observations, Ann. Geophys., 24, 1305–1310, doi:10.5194/angeo-24-1305-2006, 2006.

Chau, J. L. and Woodman, R. F.: Daytime vertical and zonal velocities from 150-km echoes: Their relevance to F-region dynamics, Geophys. Res. Lett., 31, L17801, doi:10.1029/2004GL020800, 2004.

Chau, J. L., Woodman, R. F., Milla, M. A., and Kudeki, E.: Naturally enhanced ion-line spectra around the equatorial 150-km region, Ann. Geophys., 27, 933–942, doi:10.5194/angeo-27-933-2009, 2009.

Choudhary, R. K., St.-Maurice, J.-P., and Mahajan, K. K.: Observation of coherent echoes with narrow soectra near 150 km altitude during daytime away from the dip equator, Geophys. Res. Lett., 31, L19801, doi:10.1029/2004GL020299, 2004.

Cosgrove, R. B. and Tsunoda, R. T.: A direction-dependent instability of sporadic E-layers in the nighttime midlatitude ionosphere, Geophys. Res. Lett., 29, 1864, doi:10.1029/2002GL014669, 2002.

de Paula, E. R. and Hysell, D. L.: The São Luís 30 MHz coherent scatter ionospheric radar: System description and initial results, Radio Sci., 39, RS1014, doi:10.1029/2003RS002914, 2004.

de Paula, E. R., Iyer, K. N., Hysell, D. L., Rodrigues, F. S., Kherani, E. A., Jardim, A. C., Rezende, L. F. C., Dutra, S. G., and Trivedi, N. B.: Multi-technique investigations of storm-time ionospheric irregularities over the São Luís equatorial station in Brazil, Ann. Geophys., 22, 3513–3522, doi:10.5194/angeo-22-3513-2004, 2004.

Farley, D. T., Ierkic, H. M., and Fejer, B. G.: Radar Interferometry: A New Technique for Studying Plasma Turbulence in the Ionosphere, J. Geophys. Res., 86, 1467–1472, 1981.

Fejer, B. G., Jensen, J. W., and Su, S.-Y.: Quiet time equatorial F region vertical plasma drift model derived from ROCSAT-1 observations, J. Geophys. Res., 113, A05304, doi:10.1029/2007JA012801, 2008.

Kudeki, E. and Fawcett, C. D.: High resolution observations of 150 km echoes at Jicamarca, Geophys. Res. Lett., 20, 1987–1990, 1993.

Kudeki, E., Fawcett, C. D., Ecklund, W. L., Johnston, P. E., and Franke, S. J.: Equatorial 150-km Irregularities Observed at Pohnpei, Geophys. Res. Lett., 20, 1987–1990, 1998.

Patra, A. K. and Rao, N. V.: Radar observations of daytime 150-km echoes from outside the equatorial electrojet belt, Geophys. Res. Lett., 33, L03104, doi:10.1029/2005GL024564, 2006.

Patra, A. K. and Rao, N. V.: Further investigations on 150-km echoing riddle using simultaneous observations of 150-km and E region echoes from off-equatorial location Gadanki, J. Geophys. Res., 112, A09301, doi:10.1029/2006JA012204, 2007.

Patra, A. K., Yokoyama, T., Otsuka, Y., and Yamamoto, M.: Daytime 150-km echoes observed with the Equatorial Atmosphere Radar in Indonesia: First results, Geophys. Res. Lett., 35, L06101, doi:10.1029/2007GL033130, 2008.

Rodrigues, F. S., de Paula, E. R., Abdu, M. A., Jardim, A. C., Iyer, K. N., Kintner, P. M., and Hysell, D. L.: Equatorial spread F irregularity characteristics over São Luís, Brazil, using VHF radar and GPS scintillation techniques, Radio Sci., 39, RS1S31, doi:10.1029/2002RS002826, 2004.

Rodrigues, F. S., Hysell, D. L., and de Paula, E. R.: Coherent backscatter radar imaging in Brazil: large-scale waves in the bottomside F-region at the onset of equatorial spread F, Ann. Geophys., 26, 3355–3364, doi:10.5194/angeo-26-3355-2008, 2008.

Royrvik, O.: Drift and aspect sensitivity of scattering irregularities in the upper equatorial E-region, J. Geophys. Res., 87, 8338–8342, 1982.

Tsunoda, R. T.: Enhanced velocities and a shear in daytime E_{sq} over Kwajalein and their relationship to 150km echoes over the dip equator, Geophys. Res. Let., 21, 2741–2744, 1994.

Tsunoda, R. T. and Ecklund, W. L.: On the nature of 150-km radar echoes over the magnetic dip equator, Geophys. Res. Lett., 27, 657–660, 2000.

Tsunoda, R. T. and Ecklund, W. L.: On a summer maximum in the occurrence frequency of 150-km (F_1) radar echoes over Pohnpei, Geophys. Res. Lett., 31, L06810, doi:10.1029/2003GL018704, 2004.

Woodman, R. F. and Villanueva, F.: Comparison of electric fields measured at F region heights with 150 km irregularity drift measurements, paper presented at the 9th International Symposium on Equatorial Aeronomy, Bali, Indonesia, 1995.

Yokoyama, T., Hysell, D. L., Patra, A. K., Otsuka, Y., and Yamamoto, M.: Daytime 150-km echoes observed with the Equatorial Atmosphere Radar in Indonesia: First results, Geophys. Res. Lett., L06101, doi:10.1029/2007GL033130, 2009.