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Equatorial 150 km echoes and daytime F region vertical plasma drifts in the Brazilian longitude sector

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Abstract. Previous studies showed that conventional coherent backscatter radar measurements of the Doppler velocity of the so-called 150 km echoes can provide an alternative way of estimating ionospheric vertical plasma drifts during daytime hours (Kudeki and Fawcett, 1993; Chau and Woodman, 2004). Using observations made by a small, low-power 30 MHz coherent backscatter radar located in the equatorial site of São Luís (2.59° S, 44.21° W; −2.35° dip lat), we were able to detect and monitor the occurrence of 150 km echoes in the Brazilian sector. Using these measurements we estimated the local time variation of daytime vertical ionospheric drifts in the eastern American sector. Here, we present a few interesting cases of 150 km-echoes observations made by the São Luís radar and estimates of the diurnal variation of vertical drifts. These cases exemplify the variability of the vertical drifts in the Brazilian sector. Using same-day 150 km-echoes measurements made at the Jicamarca Radio Observatory in Peru, we also demonstrate the variability of the equatorial vertical drifts across the American sector. In addition to first estimates of the absolute vertical plasma drifts in the eastern American (Brazilian) sector, we also present observations of abnormal drifts detected by the São Luís radar associated with the 2009 major sudden stratospheric warming event.

Keywords. Ionosphere (Electric fields and currents; Equatorial ionosphere; Ionospheric irregularities)

1 Introduction

At F region heights, electric fields are responsible for the transport of plasma in the $\boldsymbol{E} \times \boldsymbol{B}$ direction, where $\boldsymbol{E}$ is the background ionospheric electric field vector and $\boldsymbol{B}$ is the geomagnetic field vector. Electric fields in the low-latitude ionosphere are created, in most part, by the dynamo action of atmospheric tides and thermospheric neutral winds blowing across geomagnetic field lines (e.g., Heelis, 2004). This atmospheric dynamo drives electrical current systems with vertical and horizontal components. In order to maintain the current divergence-free, large-scale polarization electric fields are created in the upper atmosphere.

Based on experimental and modeling studies, the zonal component of the background equatorial electric field, during the day, is expected to be in the eastward direction (Scherliess and Fejer, 1999; Anderson, 2006; Fesen et al., 2000; Fang et al., 2008; Shume et al., 2009). This component of the electric field causes an upward $\boldsymbol{E} \times \boldsymbol{B}$ drift of the ionospheric F region plasma. The upward drift, as a consequence, moves the F region plasma to higher altitudes. Subsequently, however, the ionospheric plasma moves along magnetic field lines under the action of plasma pressure and gravity and is deposited at low-latitudes creating what is known as the "Fountain Effect". This Fountain effect creates a trough of ionospheric plasma near the magnetic equator and makes the F region electron density to peak at low-latitudes. Therefore, large latitudinal gradients in electron density are created in the low-latitude ionosphere and the magnitude of these gradients is controlled by the magnitude of equatorial vertical drifts (e.g., Klobuchar et al., 1991). The action

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of trans-equatorial thermospheric neutral winds at F region heights also controls the deposition of plasma at low latitudes. It pushes the plasma from one hemisphere to another, and creates asymmetries in the distribution of the ionospheric plasma.

Despite the importance of the equatorial electric field for ionospheric modeling and specification, only the Jicamarca Radio Observatory (JRO) in Peru has been been able to provide routine ground-based measurements of equatorial plasma drifts. For about 50 yr, vertical (and zonal) plasma drifts have been measured at JRO using incoherent scatter radar (ISR) measurements. Jicamarca is the only equatorial facility capable of making ISR measurements. ISR observations, however, are expensive since they require the operation of high-power (MW) transmitters and large transmitting/receiving antenna systems. Therefore, only a limited number of observation hours per year is available, in general.

Recent studies, however, have shown that coherent scatter echoes caused by non-thermal ionospheric plasma waves located around 150 km altitude might provide an inexpensive way to monitor equatorial plasma drifts (Kudeki and Fawcett, 1993). Since the early observations made by the Jicamarca ISR in the 1960s, coherent scatter echoes have been observed from regions around 150 km altitude during daytime (Balsley, 1964). The origin of these echoes is still not understood since there are no obvious sources for plasma instabilities and, therefore, plasma irregularities in that region (Tsunoda and Ecklund, 2000; Patra et al., 2011).

Using radar observations with higher resolution than previously possible, Kudeki and Fawcett (1993) revisited the observations of the 150 km echoes and uncovered some important features. In particular, they found that the mean Doppler velocity of the echoes would follow the bulk velocity of the plasma at F region heights. Additionally, they pointed out that small, less expensive radar systems could be used to detect 150 km echoes and monitor the mean equatorial F region plasma drift. Measurements made by Kudeki et al. (1998) confirmed that 150 km echoes could be detected by smaller radar systems outside the Peruvian sector. Using concurrent incoherent and coherent backscatter radar observations at Jicamarca, Woodman and Villanueva (1995) and Chau and Woodman (2004) confirmed that 150 km-echoes Doppler velocities represent the bulk velocity of the plasma at 150 km altitude, and that they could be used as a good proxy of the equatorial vertical drifts.

Significant advances in our knowledge about the average behavior of ionospheric vertical plasma drifts have been made using several decades of incoherent scatter radar measurements and in situ satellite measurements (e.g., Scherliess and Fejer, 1999; Fejer et al., 2008; Stoneback et al., 2011). Currently, however, we seek a better understanding of the day-to-day and small-scale (say a few 10s of degrees in longitude) variability of the F region zonal electric field. New measurements of 150 km echoes and drifts made by low-power, low-cost radar systems have the potential to greatly improve our knowledge about the variability of the ionospheric electric fields.

Therefore, motivated by the importance of new equatorial plasma drift observations, we present results of an analysis of 150 km echoes observed by a coherent backscatter radar located in the magnetic equatorial site of São Luís in Brazil. We use these measurements to obtain, for the first time, estimates of the local time variation of daytime F region plasma drifts, at a given day, in the Brazilian longitude sector. Presentation of this study is organized as follows: first, in Sect. 2, we provide information about the experimental radar setup used for observations of 150 km echoes. Examples of measurements available and analyzed during this study are presented in Sect. 3. Results of analysis presented in Sect. 3 are discussed in Sect. 4. These results are compared with empirical model predictions and with similar type of observations made in the Jicamarca Radio Observatory in western side of South America. Section 5 contains a summary of our findings and final remarks for this study.

2 Experimental setup

The measurements used in this study were made by a 30 MHz coherent backscatter radar installed in São Luís, Brazil (2.59° S, 44.21° W; −2.35° dip lat), an observation site located near the geomagnetic equator in the eastern side of the South American sector. The measurements were made in 2008 and early 2009. Approximately 90 days of observations were available for this study. In several days, however, a reduced number of echoes were detected. The radar is operated and maintained by the Brazilian National Institute for Space Research (INPE). This ionospheric radar system has been used mainly for studies of F region ionospheric irregularities (e.g., Rodrigues et al., 2004; de Paula et al., 2004; Rodrigues et al., 2008; de Paula et al., 2011; Rodrigues et al., 2012) but it is also capable of observing E region irregularities (de Paula and Hysell, 2004; Shume et al., 2011).

de Paula and Hysell (2004) presented a description of the radar system with a few examples of different E and F region measurements made by the radar during its earlier years. In their description of the system, they showed observations indicating the occurrence of 150 km echoes over São Luís. Despite the successful detection of 150 km echoes by the São Luís radar, little had been done, so far, to derive estimates of vertical plasma drifts from these observations. In this study we examine the detection of 150 km echoes by the São Luís radar to estimate the daytime variation of vertical plasma drifts in the Brazilian longitude sector.

Instrumentation and analysis

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 antenna sets are aligned in the magnetic east–west direction. One or two antenna sets can be used for transmission. In general, observations of 150 km echoes are 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.

In order to estimate the mean Doppler velocity of the echoes we analyzed the radar returns using the Fast Fourier (FFT) algorithm. Prior to the FFT analysis, however, we coherently integrated 16 voltage samples. A total of 64 points were used for spectral analysis, and a total of 10 resulting power spectra were incoherently integrated before spectral parameters were estimated from the final power spectrum. Therefore, we were able to estimate unambiguously Doppler velocities between $-40\,\mathrm{m\,s^{-1}}$ and $+40\,\mathrm{m\,s^{-1}}$. The uncertainty of typical mean Doppler estimates is within $1\,\mathrm{m\,s^{-1}}$.

Full spectral widths and mean Doppler shifts (velocities) were estimated by fitting a Gaussian function to the final estimate of the power spectrum.

Table 1 provides a summary of the radar parameters used for 150 km-echoes observations. Figure 1 shows a map indicating the location of the São Luís radar. For reference purposes, the location of the Jicamarca Radio Observatory is also shown. Jicamarca is located across the American sector, approximately 30° of longitude to the west of São Luís. Jicamarca measurements of 150 km drifts, whenever available, are compared with São Luís measurements.

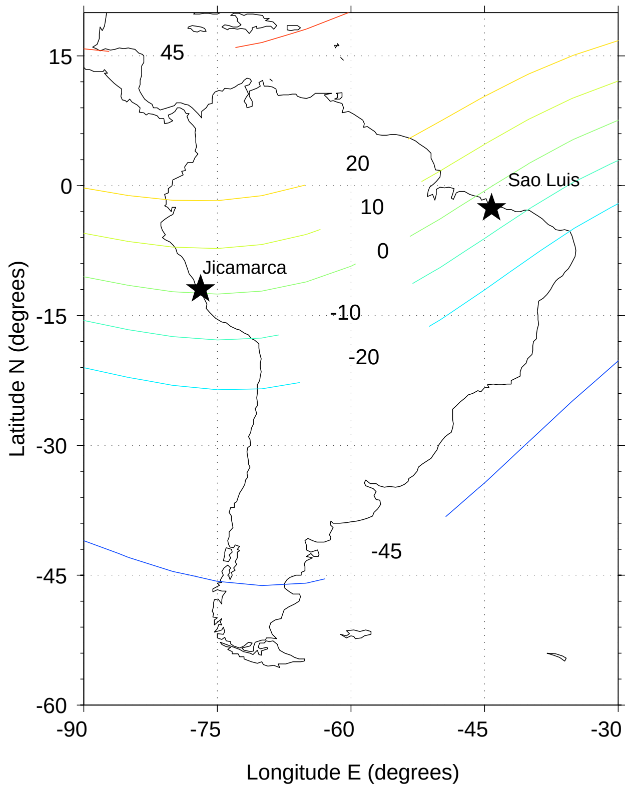

Fig. 1. Location of the São Luís radar whose measurements of 150 km echoes were used to derive vertical drifts in the Brazilian sector. The location of the Jicamarca Radio Observatory and the inclination of the geomagnetic field lines are are also shown for reference.

3 Results

Figures 2–6 present examples of observations made by the São Luís radar and the results of our analyses. We chose examples of observations that show 150 km echoes with significant signal-to-noise ratios (say SNR > -5 dB) occurring during four or more hours on each day. These examples are part of a set of measurements made during 2008 and early 2009 that have been available for this study. Additionally, these measurements were made during periods considered geomagnetically quiet. The 3 h Planetary K (Kp) index did not exceed 2+ during the observations. The eight 3 h Kp index values for each day are provided in each figure caption.

Panel a in each figure shows the range–time–intensity (RTI) map of the echoes. The vertical dark blue lines indicate data gaps caused by artificial clutter that has been observed from time to time in the radar measurements. The RTI maps show that 150 km echoes, in general, descend from higher altitudes during morning hours and ascend again in altitude in the afternoon as expected from typical observations made at Jicamarca and other sites (Tsunoda and Ecklund, 2004; Patra et al., 2008).

Panel b shows the mean Doppler velocity estimated from the echoes with SNR > -5 dB. The echoes, in general, have negative Doppler velocities, which indicates upward motion. High-resolution measurements at Jicamarca showed that the Doppler velocities of 150 km echoes do not vary much with altitude. In the measurements made with the São Luís radar, however, we found some variability in the mean Doppler velocity with height at times. We found that this variability is caused by the somewhat large beam width ($\sim 10°$) of the antennas used by the radar (Rodrigues et al., 2011b). Some of the echoes detected by the São Luís radar are caused by irregularities located a few degrees off zenith.

Panel c in each figure shows the full spectral width of the echoes. Similar to what has been observed in other sites (Royrvik and Miller, 1981; Chau and Kudeki, 2006; Patra et al., 2008), the 150 km echoes detected by the São Luís radar have, in general, narrow spectral widths (usually only a few $\mathrm{m\,s^{-1}}$). Careful analysis of São Luís echoes, however, show that double-peaked spectra could be observed at times. Again, this can be caused by the occurrence of multiple scattering centers within the radar field-of-view and within the same range gate (Rodrigues et al., 2011b).

Panel d shows the uncertainty in our estimates of the mean Doppler velocity. It can be seen that, in most cases, the uncertainty is well within $0.5\,\mathrm{m\,s^{-1}}$.

Table 1. Typical 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

Finally, panel e shows a curve (black markers) of the height and time averaged Doppler velocity of the echoes as a function of local time. The mean values were obtained by averaging all the Doppler velocities within 10 min time bins. The error bars represent the standard deviation of the values used in the average estimate. Therefore, they represent the temporal and spatial (height) variability of the estimated Doppler velocities. Note that the sign of the Doppler velocity has been converted so that positive velocities values represent away (upward) velocities. Consecutive bins do not overlap and running averages were not used to smooth the curves. We also only used echoes with full spectral widths that are less than 2 m s^{-1}. Observations from all the range gates within that time bin were used in the average. Panel e also shows model predictions (Scherliess and Fejer, 1999) of the vertical velocities for São Luís (solid black line) and Jicamarca (solid red line). Finally, whenever available, we include the vertical drifts in the western American sector estimated from 150 km echoes measured by the JULIA (Jicamarca Unattended Long-term Investigations of the Ionosphere and Atmosphere) mode of the Jicamarca radar.

4 Discussion

The previous section presented examples of measurements of 150 km echoes made by the São Luís radar and results of our analyses of these measurements. These examples are now examined and discussed individually. The most striking feature (or features) of these observations and analyses are pointed out.

4.1 30 January 2008: abnormally large drifts

Figure 2 shows results for observations made on 30 January 2008.

The RTI map (panel a) shows 150 km echoes occurring between approximately 140 and 170 km. Despite the data gaps caused by clutter, it is still possible to identify the "necklace" pattern in the RTI map caused by echoes descending in altitude during morning hours and ascending in the afternoon.

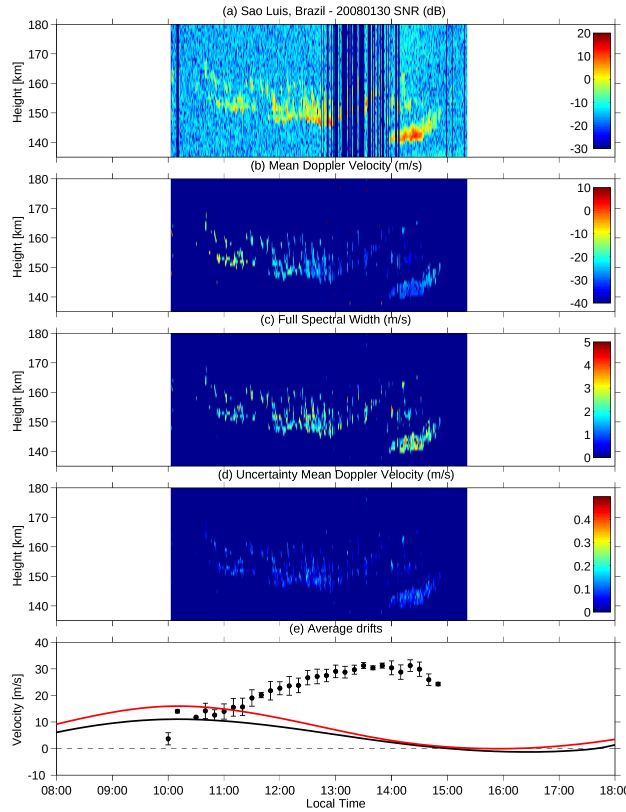

Fig. 2. **(a)** range–time–intensity (RTI) map of 150 km echoes observed by the São Luís radar on 30 January 2008. The vertical dark blue lines indicate data gaps caused by interference. **(b)** Mean Doppler velocity of the echoes. **(c)** Full spectral width of the echoes. **(d)** Uncertainty in the mean Doppler velocity. **(e)** The solid lines show the model prediction of vertical plasma velocities for São Luís (black) and Jicamarca (red). The markers show the estimated mean Doppler velocity of the 150 km echoes observed by the São Luís radar. The 3 h Kp indices for this day are 1, 2−, 0, 0+, 0, 0, 0, 0.

Panel b shows that the mean Doppler velocities vary only slightly (a few m s^{-1}) with height on this day. We remind that the negative velocities in this panel represent motion away from the radar. The magnitude of the velocities can be as large as 30 m s^{-1} or more on this particular day.

Panel c shows that most of the spectral widths are well within 2 m s^{-1} with only a few cases reaching $\sim$5 m s^{-1}.

Panel d shows that the uncertainties in the estimation of the mean Doppler velocity are really small, usually less than 0.5 m s^{-1} as mentioned earlier. Somewhat larger uncertainties were limited to a strong scattering region observed between 14:00 and 15:00 LT and 140 and 150 km altitude. The following examples (Figs. 3–6) confirm a noticeable tendecy of a low-altitude (below $\sim$150 km) scattering layer to appear after $\sim$14:00 LT.

Panel e shows the local time variation of the mean Doppler velocity averaged in time (every 10 min) and height. In this panel, positive values indicate upward velocities. Therefore, as expected, our results show mean upward drifts throughout the entire period of observations (between 10:00 LT and 15:00 LT). We also show predictions of vertical F region drifts made by the Scherliess and Fejer (1999) empirical model for São Luís (black solid curve) and Jicamarca (red solid curve).

The most striking feature on this day is that the measured drifts greatly exceed the Scherliess–Fejer model predictions for São Luís (and Jicamarca). The model only predicts an average value of the mean vertical drift. The measured drifts, however, are well outside the region of expected values even when the quiet-time day-to-day variability is taken into account. Using Jicamarca incoherent scatter radar (ISR) measurements, Fejer and Scherliess (2001) showed that the quiet-time variability is approximately 4–7 m s^{-1} during low solar flux conditions. At 14:00 LT, however, the model predicts $\sim$5 m s^{-1} drifts while the measurements show values exceeding 30 m s^{-1}.

We must point out that the Scherliess and Fejer (1999) empirical model of F region drifts was developed using a large set of local measurements made by the Jicamarca ISR between 1968–1992, but augmented by a limited set of global measurements made by the Atmosphere Explorer E satellite between 1977 and 1979. Therefore, it is not unreasonable to think that the limited data set outside the Peruvian sector might not be complete enough to describe well the behavior of the drifts in the Brazil sector. Continuous measurement of 150 km echoes can help the improvement of empirical and physics-based electric field (plasma drift) models.

Unfortunately, measurements of 150 km echoes were not made at Jicamarca on this day. Chau et al. (2008), however, conducted measurements of vertical drifts at Jicamarca between 17 and 26 January 2008 as part of an observational campaign that targeted the detection of the effects of sudden stratospheric warming (SSW) events in the low-latitude ionospheric electrodynamics. Drifts that were much larger than average were observed at Jicamarca between 21 January, when the SSW event started and 26 January, when observations ended. While we are inclined to hypothesize that the large drifts observed by the São Luís radar could have been a result of the 2008 SSW event, the example to be described next suggests that this might not be case. Abnormally large drifts during January can occur even during geophysically quiet times in the eastern American sector.

4.2 4 January 2008: longitudinal variability

Figure 3 shows results for observations made on 4 January 2008.

Panel a shows that, similar to the previous example, echoes were observed between 140 and 170 km altitude. In this example, however, we observed that the echoing region departs from the regular necklace pattern. Between approximately 12:00 LT and 13:30 LT, two layers (or regions) of echoes are perturbed from their regular necklace pattern and ascend and

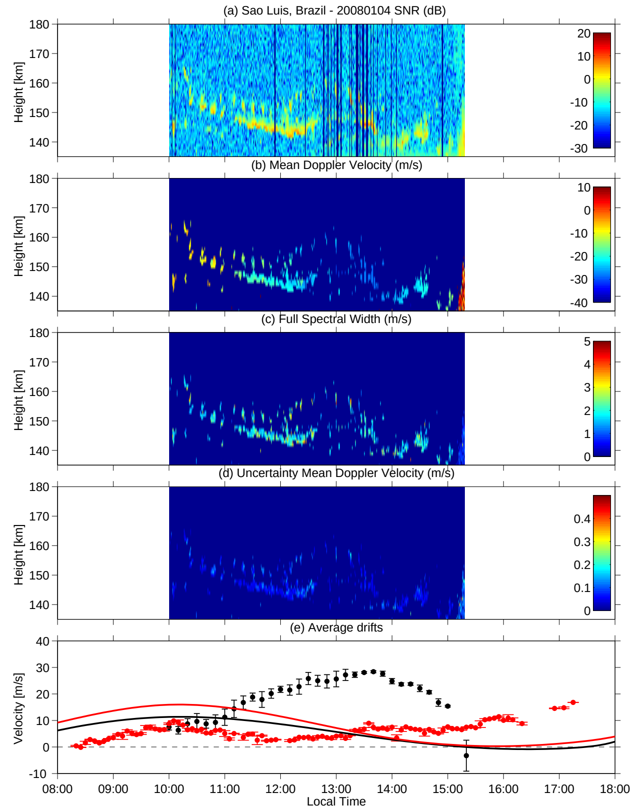

Fig. 3. Same as Fig. 2 but for 4 January 2008. The mean Doppler velocity of the 150 km echoes measured by the Jicamarca radar is also show in **(e)** as red markers. The 3 h Kp indices for this day are 0, 0, 0, 1−, 1−, 1, 0+, 2−.

then descend in altitude. Again, the removal of the clutter causes gaps in the RTI map, but the perturbation in the echoing layer behavior is still observable. Assuming that 150 km echoes are caused by irregularities generated by a plasma instability, perturbations in the echoing layer suggest a disruption in the underlying conditions controlling the instability growth rate. The disturbance in the height of the echoes (as seen in the RTI map), was not followed by any detectable variations in the mean Doppler velocities, which indicates that the underlying instability conditions are independent of the background zonal electric field.

Panels b–d show typical values of mean Doppler velocity, spectral width, and uncertainty in the estimated mean Doppler velocities for 4 January 2008.

Panel e shows that the amplitude and pattern of the estimated drifts are very similar to what was observed in the previous example (for 30 January 2008). They confirm that the unusually large plasma drifts seen on 30 January were not unique. On 4 January, however, 150 km echoes measurements were made at Jicamarca and drifts were available for comparison with the drifts measured over São Luís. The Jicamarca drifts are also shown in panel e as red markers. Despite geomagnetically quiet conditions, the local time variation and amplitude of the measured drifts (in São Luís and Jicamarca) depart significantly from the model drifts. The drifts measured over Jicamarca and São Luís depart significantly from each other as well. The drifts over São Luís reach amplitudes that are 3 times or more larger those observed at Jicamarca for the same local time.

The Scherliess–Fejer climatological model does not predict large zonal gradients in the daytime vertical plasma drifts in the American sector. A recent study of Araujo-Pradere et al. (2012) using C/NOFS satellite measurements, however, indicated that a large zonal gradient might exist. They associated the zonal gradient in the vertical drifts with the longitudinal variation of the dynamo winds driven by non-migrating tides. Our observations provide unambiguous evidence of the occurrence of large longitudinal gradients in the values of vertical plasma drifts (for a given LT) over the American sector. These gradients can cause additional difficulties in the proper modeling of the equatorial and low-latitude ionosphere when using, as input, the current climatological models of vertical drifts.

4.3 5 August 2008: downward drifts

Figure 4 shows results for observations made on 5 August 2008.

In a previous study, Rodrigues et al. (2011b) found that the 150 km echoing layers observed by the São Luís radar between July and early September of 2008 were stronger and lasted longer than echoing layers observed during other months on that year. The observations for this day exemplify that finding. On 5 August 2008, in particular, echoes were observed throughout the entire period of observations, from about 10:00 LT to approximately 15:00 LT.

Similar to previous examples, panels b–d show typical values of mean Doppler velocity, spectral width, and uncertainty in the estimated Doppler velocity.

Panel e shows that the average drifts measured by the São Luís radar have amplitudes that are much smaller than those presented in the previous examples (from January 2008). The drift model, however, predicts larger drifts than what was measured. Once again, the model predicts very similar drifts for Jicamarca and São Luís. Measurements of 150 km echoes were not made at Jicamarca on this day.

The most interesting feature, for this day, is that negative drifts were observed early in the afternoon (∼ 14:00 LT). This is atypical based on theoretical expectations and climatological models. A recent investigation of vertical plasma drifts measured by the ion velocity meter (IVM) onboard the C/NOFS satellite, however, showed an unexpected high occurrence of negative plasma drifts, particularly during the 2008–2009 period when solar flux conditions were extremely low (Stoneback et al., 2011). While we did observe a few cases of negative daytime plasma drifts in our 150 km-echoes observations, they did not show values as large as those seen in the average curves computed by Stoneback et al. (2011).

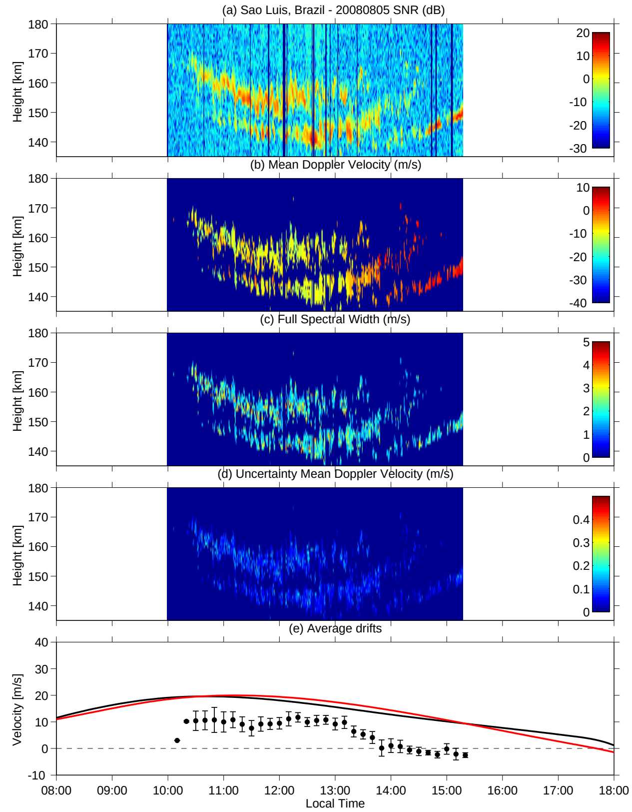

Fig. 4. Same as Fig. 2 but for 5 August 2008. The 3 h Kp indices for this day are 0+, 0+, 1−, 1, 1−, 0+, 0+, 0.

Our results resemble drift estimates obtained by Patra et al. (2012) using Gadanki radar (13.5° N, 79.2° E, 6.5° N mag. lat.) measurements of 150 km echoes. Their analysis show downward drifts of a few m s^{-1} in the afternoon. See, for instance, the drifts for 5 July 2008 in Fig. 6 of their paper.

4.4 2 September 2008: typical drifts

Figure 5 shows results for observations made on 2 September 2008.

Again, strong and long-lasting echoes were observed on this day (panel a). Similar to 5 August 2008 two echoing layers could be distinguished in the RTI map during most of the observations.

Panel b shows, before 12:00 LT, some height variability in the mean Doppler velocity of the echoes. It is unclear why we have more height variability on some days than others. We found, however, that we can use this height variability, together with spaced-antenna radar measurements, to estimate not only the direction of the scattering centers but also the vertical and zonal component of the drifts. Preliminary results are promising but are outside the scope of this study, and will be reported at a later time.

Panel c shows values of spectral widths that are similar to what was seen in the previous examples. Panel d

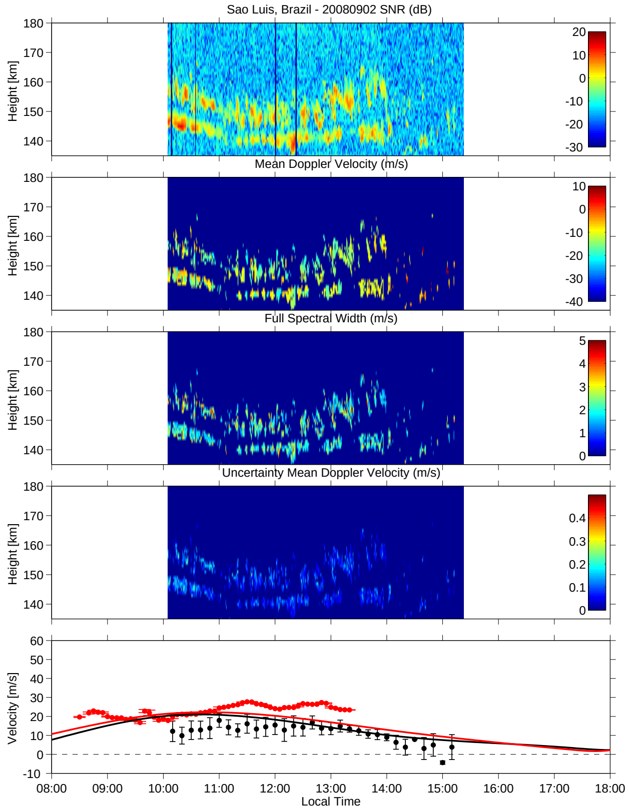

Fig. 5. Same as Fig. 2 but for 2 September 2008. The mean Doppler velocity of the 150 km echoes measured by the Jicamarca radar is also show in **(e)** as red markers. The 3 h Kp indices for this day are 1−, 0+, 1−, 1, 1, 0+, 0+, 1.

shows typical values of the uncertainty of the estimated mean Doppler velocities with a few larger values before 11:00 LT.

Jicamarca measurements of 150 km echoes were available on this day. Panel e shows the average measured drifts for Jicamarca and São Luís. Like in most cases when we have data from both sites, the drifts over São Luís and Jicamarca have different magnitudes. The relatively large error bars in the height and time averaged drifts for São Luís are a result of variability (in height – panel b) of the mean Doppler velocities.

This example illustrates typical vertical drifts measured in São Luís. Typical refers to the fact that the drifts indicate mostly upward plasma motion, with magnitudes no larger than 20 m s^{-1}. Additionally, the local time variation of the São Luís drifts also do not generally follow the drifts seen at Jicamarca.

Recently, Patra et al. (2012) analyzed observations of 150 km echoes made by radars in Gadanki (13.5° N, 79.2° E; 6.5° N mag. lat.) and Kototabang (0.2° S, 100.32° E; 10.36° S mag. lat.). They found that, despite being spaced by only 20° in longitude, the two sites observed a distinct behavior in the daytime vertical drifts. Not only drifts could be different over the two sites, but their day-to-day variability was also distinct. The day-to-day variability reached 15 m s^{-1} at Gadanki and only 7 m s^{-1} at Kototabang. The observations in São Luís and Jicamarca confirm that the local time variation of the drifts over two sites can be very distinct even if they are spaced by only a few 10s of degrees in longitude. We point out that the São Luís and Jicamarca are equatorial sites and both observe electric fields around the same apex height (∼ 150 km). As stated earlier, this longitudinal variability of the drifts could be caused, at least in part, by the variability in non-migrating tides such as those responsible for the wavenumber-4 structures observed in low-latitude ionospheric total electron content – TEC (e.g., Immel et al., 2006; Araujo-Pradere et al., 2012).

Another factor contributing for the differences in vertical drifts observed at Jicamarca and Sao Luis could be the location of these sites with respect to the geographic equator. The equatorial electric fields are a result of the E/F region dynamos. The winds and tides driving the dynamos are known to vary with geographic latitude. Therefore, the neutral winds and tides over (and near) Sao Luis and Jicamarca are expected to be distinct as a result of their latitudinal differences. While Sao Luis is located near the equator (0.2° S), Jicamarca is at a low geographic latitude (11.95° S). The differences in the magnetic equatorial drifts seen at Jicamarca and Sao Luis can be due to differences in their geographic latitudes. Furthermore, winds from different local times contribute to the dynamo electric field over Sao Luis due to the large magnetic declination in the eastern American sector (∼ −20°).

4.5 29 January 2009: SSW event

Finally, Fig. 6 shows results for observations made on 29 January 2009.

Panel a shows that only after ∼ 12:00 LT two distinct layers were observed on this day. Panel b shows large values of mean Doppler velocities. Panels c and d show typical values of spectral widths and uncertainties for the estimated mean Doppler velocities, respectively.

Panel e shows the mean vertical drifts for São Luís. Measurements of 150 km echoes were also made at Jicamarca on this day, and the resulting average drifts in the Peruvian sector are shown as well. The most interesting features of the drifts observed on this day are the large magnitudes and the high similarity between the local time variation of the drifts over São Luís and Jicamarca. Upward drifts as large as 45 m s^{-1} were observed in Jicamarca and drifts as large as 35 m s^{-1} were observed in São Luís. We point out the difference in the range of the vertical axis for this example compared to previous examples.

Previous experimental studies have already shown that the daytime zonal equatorial electric field can be severely disturbed during what is called sudden stratospheric warming (SSW) events (e.g., Anderson and Araujo-Pradere, 2010; Chau et al., 2008; Fejer et al., 2010; Rodrigues et al., 2011a).

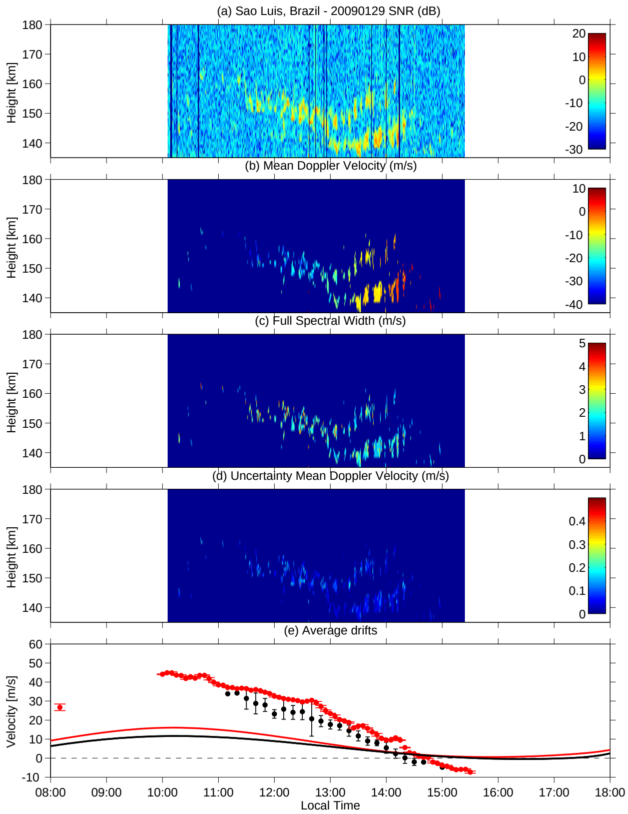

Fig. 6. Same as Fig. 2 but for 29 January 2009. The mean Doppler velocity of the 150 km echoes measured by the Jicamarca radar is also show in **(e)** as red markers. The 3 h Kp indices for this day are 0, 2, 2+, 1+, 1+, 0+, 0+, 0.

The mechanism linking the variations in the high latitude stratosphere and the low-latitude ionosphere are being investigated and new measurements can prove very useful to test/validate proposed theories.

SSW events are large meteorological events taking place in the high latitude stratosphere. During Northern Hemisphere winter, a deceleration of the eastward stratospheric winds has been observed. A sudden increase in the stratospheric temperature is also observed during SSW events hence the name of this meteorological event. When a reversal of the zonal wind is observed (at 10 hPa geopotential height and 60° N geographic latitude), the SSW is classified as major. This is the case of an event observed in January 2009 (e.g., Fejer et al., 2010; Fang et al., 2012; Rodrigues et al., 2011a). During a SSW event, the atmospheric circulation is altered from its normal pattern. This change in circulation affects the propagation of tidal waves; a result of a complex interaction between different tidal modes, interaction with the mean flow and with stationary planetary waves (e.g., Fang et al., 2012).

Chau et al. (2008) has already reported that, during the January 2009 SSW event, the vertical plasma drifts over Jicamarca were severely disturbed. Abnormally large upward drifts were observed during morning hours and unexpected downward drifts were seen in the afternoon. The effects of SSW events on the ionospheric electrodynamics exemplify a complex coupling between the high-latitude lower atmosphere and the low-latitude ionosphere.

Using vertical drift measurements made by the Ion Velocity Meter (IVM) instrument on-board the C/NOFS satellite, Rodrigues et al. (2011a) had already found that the magnitude and local variation of drifts did not vary much over a large range (10s of degrees) of longitude during the 2009 SSW.

The observations at Jicamarca and São Luís on 29 January 2009 provide measurements without the space–time ambiguity associated with satellite observations. The radar measurements, nevertheless, confirm the satellite measurements showing a large spatial (zonal) correlation length of the equatorial vertical drifts during the 2009 SSW event at least for the American sector.

5 Summary and final remarks

We presented results of first estimates of the daytime vertical ionospheric drifts in the Brazilian sector. These estimates were obtained from measurements of 150 km echoes measured by the 30 MHz low-power coherent backscatter radar installed in São Luís, Brazil (2.59° S, 44.21° W; −2.35° dip lat). São Luís measurements were compared against empirical model (Scherliess and Fejer, 1999) predictions of equatorial F region drifts. The measurements were also compared against same-day measurements of 150 km-echoes drifts made by the JULIA radar in the Peruvian sector, only 30° to the west of the São Luís site (see Fig. 1). Our measurements and comparisons show that equatorial drifts can be highly variable, departing severely from model predictions and changing dramatically in longitude for the American sector at a given day. Previous studies (Fejer et al., 2008) have already indicated large longitudinal gradients in the averaged (climatological) drifts measured by satellites. Combining Jicamarca and Sao Luis radar observations, we have now shown absolute measurements of the drifts across South America, which quantify the longitudinal gradient for a given day.

The São Luís observations show that, even during geomagnetically quiet conditions, vertical drifts can vary significantly across the American sector (over 30° longitude). We found, for instance, that daytime drifts can be as large as 30 m s^{-1} over São Luís and not exceed 10 m s^{-1} over Jicamarca on the same day. This is likely a result of a longitudinal variability in the E region dynamo winds. Differences in latitude of those sites are likely to play a role as well, since Sao Luis is approximately 10° closer to the geographic equator than Jicamarca.

On the other hand, we also found that during a day in the 2009 sudden stratospheric warming (SSW) event, the local time variation and magnitude of daytime drifts over São Luís and Jicamarca were very similar. Furthermore, in both sites, the drifts were abnormally large compared to quiet-time expectations. Joint radar measurements confirm previous satellite observations that indicated that drifts could be nearly the same (for a given LT) over a wide range of longitudes during the 2009 SSW.

Previous studies indicated the occurrence of unexpected daytime downward drifts during the 2008–2009 period when solar flux were abnormally low (Stoneback et al., 2011; Patra et al., 2012). We did find cases of downward drifts, usually after 16:00 LT, in the limited set of measurements available to this study. The magnitude of these drifts, however, were much smaller than those reported by Stoneback et al. (2011), and were in better agreement with the values observed by Patra et al. (2012).

Finally, we also presented an example where the height vs. time variation of the 150 km echoes in the RTI map could deviate, for a few tens of minutes, from the typical "necklace" pattern. This indicates that the underlying conditions for the generation of 150 km-echoes irregularities can be disturbed momentarily. The mean Doppler velocity of the echoes, however, were not affected by the changes in the underlying plasma conditions, which suggests that the background electric field does not play a role in the instability responsible for the irregularities causing 150 km echoes.

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References

Anderson, D. A.: Global, low-latitude, vertical $\boldsymbol{E} \times \boldsymbol{B}$ drift velocities inferred from daytime magnetometer observations, Space Weather, 4, S08003, doi:10.1029/2005SW000193, 2006.

Anderson, D. A. and Araujo-Pradere, E. A.: Sudden stratospheric warming event signatures in daytime $\boldsymbol{E} \times \boldsymbol{B}$ drift velocities in the Peruvian and Philippine longitude sectors for January 2003 and 2004, J. Geophys. Res., 115, A00G05, doi:10.1029/2010JA015337, 2010.

Araujo-Pradere, E. A., Fang, T.-W., Anderson, D. N., Fedrizzi, M., and Stoneback, R.: Modeling the daytime, equatorial ionospheric ion densities associated with the observed four-cell longitude patterns in $\boldsymbol{E} \times \boldsymbol{B}$ drift velocities, Radio Sci., 47, RS0L12, doi:10.1029/2011RS004930, 2012.

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. 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., Fejer, B. G., and Goncharenko, L. P.: Quiet variability of equatorial ExB drifts during a sudden stratospheric warming event, J. Geophs. Res., 36, L05101, doi:10.1029/2008GL036785, 2008.

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.

de Paula, E. R., Kherani, E. A., Cueva, R. Y. C., and Camargo, L. A.: Observations of pre-midnight 5-m irregularities in the equatorial F-region over Sao Luis, Brazil: Solar flux dependence and seasonal variations, J. Atmos.-Sol. Terr. Phys., 73, 1544–1554, 2011.

Fang, T.-W., Fuller-Rowell, T., Akmaev, R., Wu, F., Wang, H., and Anderson, D.: Longitudinal variation of ionospheric vertical drifts during the 2009 sudden stratospheric warming, J. Geophys. Res., 117, A03324, doi:10.1029/2011JA017348, 2012.

Fang, T. W., Richmond, A. D., Liu, J. Y., Maute, A., Lin, C. H., Chen, C. H., and Harper, B.: Model simulation of the equatorial electrojet in the Peruvian and Philippine sectors, J. Atmos.-Sol. Terr. Phys., 70, 2203–2211, 2008.

Fejer, B. G. and Scherliess, L.: On the variability of equatorial F-region vertical plasma drifts, J. Atmos. Sol.-Terr. Phys., 63, 893–897, 2001.

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.

Fejer, B. G., Olson, M. E., Chau, J. L., Stolle, C., Lühr, H., Goncharenko, L. P., Yumoto, K., and Nagatsuma, T.: Lunar-dependent equatorial ionospheric electrodynamic effects during sudden stratospheric warmings, J. Geophys. Res., 115, A00G03, doi:10.1029/2010JA015273, 2010.

Fesen, C. G., Crowley, G., Roble, R. G., Richmond, A. D., and Fejer, B. G.: Simulation of the pre reversal enhancement in the low latitude vertical ion drifts, J. Geophys. Res., 27, 1851–1854, 2000.

Heelis, R. A.: Electrodynamics in the low and middle latitude ionosphere: a tutorial, J. Atmos.-Sol. Terr. Phys., 66, 825–838, 2004.

Immel, T. J., Sagawa, E., England, S. L., Henderson, S. B., Hagan, M. E., Mende, S. B., Frey, H. U., Swenson, C. M., and Paxon, L. J.: Control of equatorial ionospheric morphology by atmospheric tides, Geophys. Res. Lett., 33, L15108, doi:10.1029/2006GL026161, 2006.

Klobuchar, J. A., Anderson, D. N., and Doherty, P. H.: Model studies of the latitudinal extent of the equatorial anomaly during equinoctial conditions, J. Geophys. Res., 26, 1025–1047, 1991.

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., 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.

Patra, A. K., Chaitanya, P. P., and Tiwari, D.: Characteristics of 150 km echoes linked with solar eclipse and their implications to the echoing phenomenon, J. Geophsy. Res., 116, A05319, doi:10.1029/2010JA016258, 2011.

Patra, A. K., Chaitanya, P. P., Mizutani, N., Otsuka, Y., Yokoyama, T., and Yamamoto, M.: A comparative study of equatorial daytime $\boldsymbol{E} \times \boldsymbol{B}$ drift in the Indian and Indonesian sectors based on 150 km echoes, J. Geophsy. Res., 117, A11312, doi:10.1029/2012JA018053, 2012.

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.

Rodrigues, F. S., Crowley, G., Azeem, S. M. I., and Heelis, R. A.: C/NOFS observations of the equatorial ionospheric electric field response to the 2009 major sudden stratospheric warming event, J. Geophys. Res., 116, A09316, doi:10.1029/2011JA016660, 2011a.

Rodrigues, F. S., de Paula, E. R., and Chau, J. L.: On the characteristics of 150 km echoes observed in the Brazilian longitude sector by the 30 MHz São Luís radar, Ann. Geophys., 29, 1905–1916, doi:10.5194/angeo-29-1905-2011, 2011b.

Rodrigues, F. S., Moraes, A. O., and de Paula, E. R.: Imaging equatorial spread F irregularities with the São Luïs coherent backscatter radar interferometer, Radio Sci., 47, RS0L03, doi:10.1029/2011RS004929, 2012.

Royrvik, O. and Miller, K. L.: Nonthermal scattering of radio waves near 150 km above Jicamarca, Peru, J. Geophys. Res., 86, 180–188, doi:10.1029/JA086iA01p00180, 1981.

Scherliess, L. and Fejer, B. G.: Radar and satellite global F-region vertical drift model, J. Geophys. Res., 6829–6842, doi:10.1029/1999JA900025, 1999.

Shume, E. B., de Paula, E. R., Maus, S., Hysell, D. L., Rodrigues, F. S., and Bekele, A.: Equatorial zonal electric fields inferred from a 3-D electrostatic potential model and ground-based magnetic field measurements, J. Geophys. Res., 114, A06305, doi:10.1029/2009JA014158, 2009.

Shume, E. B., de Paula, E. R., and Abdu, M. A.: Modulation of equatorial electrojet plasma waves by overshielding electric field during geomagnetic storms, J. Geophys. Res., 116, A08302, doi:10.1029/2010JA016353, 2011.

Stoneback, R. A., Heelis, R. A., Burrell, A. G., Coley, W. R., Fejer, B. G., and Pacheco, E.: Observations of quiet time vertical ion drift in the equatorial ionosphere during the solar minimum period of 2009, Geophys. Res. Lett., 116, A12327, doi:10.1029/2011JA016712, 2011.

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.