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Climatological study of the daytime occurrence of the 3-meter EEJ plasma irregularities over Jicamarca close to the solar minimum (2007 and 2008)

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We have developed algorithms for conducting a seasonal statistical study of the occurrence of plasma irregularities in the Peruvian sector as a function of height and local time, covering two years of data (2007 and 2008) close to the solar minimum. This study was performed based on radar measurements carried out at the Jicamarca Radio Observatory (JRO), which is located in Lima–Peru (11.57°S, 76.52°W, dip: 2°N), under the magnetic equator. The statistical analysis runs over daily Range Time Intensity (RTI) maps obtained with the radar operating in the Jicamarca Unattended Long-term Investigations of the Ionosphere and Atmosphere (JULIA) mode. Our results revealed relevant features of the diurnal variation of the plasma irregularities embedded in the equatorial electrojet, such as: a more often occurring presence of the 3-m irregularities during equinox, and a descent of the scattering profile in the morning hours, followed by its ascent in the afternoon.
Key words: Equatorial aeronomy, equatorial electrojet, plasma irregularities, coherent radar observation.

1. Introduction

During the last decades, theoretical and experimental research has been carried out to study the intense electric current that flows around the magnetic dip equator at ionospheric altitudes of about 105 km (E-region), referred as the equatorial electrojet (EEJ). Examples of theoretical considerations on the EEJ and plasma irregularities, such as the characteristic of these irregularities to be aligned with the magnetic field, and backscattered echoes obtained by radio soundings which occur only for radiation propagating nearly perpendicular (within about 1°) to the magnetic field, have been discussed by Fejer and Kelley (1980), Forbes (1981) and Kudeki *et al.* (1985). Experimental investigations of the equatorial plasma irregularities using VHF coherent and incoherent scatter radars were also carried out over Jicamarca by Cohen (1967), Fejer *et al.* (1975), Farley and Fejer (1975), and many others.

The basic features of the plasma irregularities as seen by VHF radars have been obtained from spectral analyses of the backscattered echoes, labeled as type 1 and type 2, after the plasma instabilities processes. The spectrum related with the type-1 irregularities shows a narrow spectral width, with its center of distribution close to the ion-acoustic speed (≈360 m/s). The spectra of the type-2 irregularities have a larger width than the type 1, and smaller Doppler velocities than the ion-acoustic speed. The center of the frequency distribution of type-1 irregularities is not sensitive to the beam inclination angle, while the type-2 center of distribution has a sinusoidal dependence within the elevation angle of the antenna beam (Cohen and Bowles, 1973). The most prominent type of spectra is type 1 when sounding over Jicamarca (Fejer and Kelley, 1980). However, this may not be the case for other longitudinal sectors (Denardini *et al.*, 2005).

Most of the authors referred to above have mentioned that the EEJ is mainly a diurnal phenomenon and, therefore, plasma irregularities should be most often observed during daytime. In order to determine the specific local time when such irregularities begin to be detected in the morning and cease to be observed in the afternoon, we have performed the present study based on radar measurements that were carried out at the JRO. Also, we have sought to verify the seasonal variability for the period covered in the present analysis. Furthermore, we have chosen data acquired during low solar activity periods in order to minimize the solar influences through the S_q system in our analyses. We based our statistics on daily Range Time Intensity (RTI) maps obtained with the Jicamarca radar operating in the JULIA mode during the years 2007 and 2008.

2. Radar System, Data Processing and Analysis

2.1 Main radar system characteristics

The Jicamarca radar system has already been described in some publications, e.g., Cohen (1967) and Woodman (1971). Therefore, we will restrict ourselves to briefly recalling some of its most important features that impact on the data we used. The measurements were made at a frequency of 49.92 MHz, corresponding to an irregularity wavelength of about 3 m. The data were acquired using the original transmitter that consists of four completely independent modules. Two of those modules have been converted into a new design using modern tubes. Each of these new modules can deliver a peak power of ≈20 kW with

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Table 1. List of days with JRO radar data selected for the statistical analyzes.

Data acquired in 2007					
D Months		**E Months**		**J Months**	
November	13–15, 21–27, 29, 30	September	04–10, 20–27	May	14–31
				June	01–06, 27–30
December	01–05, 20–31			July	01–04
				August	16–28
Data acquired in 2008					
D Months		**E Months**		**J Months**	
January	01–15	March	01–13	May	08–27
				June	26–30
February	06–11, 28, 29	September	01	July	01–07, 17–31
				August	01–05, 14–31

a maximum duty cycle of 6% and pulses as short as 0.8–1.0 μs. There are four phase-coherent (common oscillators) receivers for collecting the radar echoes, which are mixed to baseband (with two quadrature outputs each) with maximum output bandwidths of about 1 MHz. Filters are available with nominal impulse response time constants ranging from 1 to 500 s. Eight data channels (four complex pairs) simultaneously sampled at 125 m (0.83 μs) resolution and fed the signal to a large FIFO buffer/coherent integrator, and from there to the acquisition computer for storage. The antenna configuration used during the present study leaded a 2–3° beamwidth (N–S and E–W), since we have used all elements of the main JRO array.

2.2 Data processing

The basic radar data analysis starts with the pre-processing. It consists of: (1) reading the voltage values and grouping these per height range; (2) applying a Fast Fourier Transform (FFT) over the voltage data set to obtain a periodogram at each specific height and time; (3) integrating the power spectra to derive the total backscattered power for the corresponding time and height; and (4) grouping all the pre-process data acquired during that specific day. The data analysis consists of building one spectrogram per sample height, each spectrogram being a contour color map of spectral power plotted in a format of Doppler frequency versus local time. The time variation of the total received power from a given height can be obtained by frequency-integrating each spectrum of the corresponding spectrogram. A daily RTI map is then produced by organizing the time variation of the total received power according to the height that they were obtained.

To examine the seasonal variation of the occurrence of the EEJ plasma irregularities, we have selected the data collected during 196 days during the period 2007 to 2008. These data were grouped as shown in Table 1, in which: (1) the D months consist of November, December, January, and February, representing the local summer season; (2) the E months consist of March, April, September, and October, representing the equinoxes; and (3) the J months consist of May, June, July, and August, representing the local winter season (Aveiro *et al.*, 2009). Hence, we have selected 51 days of the D months, 34 days of the E months, and 111 days of the J months. The next step of the data processing is to perform the statistical analysis described in the following section.

2.3 Statistical analysis

We developed a routine that performs all the statistical analysis over the RTI matrices of each day belonging to the three groups. In the following, we briefly describe some important features of this analysis: (1) a matrix is created with the same dimension as the original matrix that generates the daily RTI maps; (2) binary values are applied to the cells of this new matrix, depending on a single test; (3) the daily RTI matrix is evaluated according to the signal-to-noise power level of every cell; (4) when the ratio (given in dB) is positive (negative), we assume that the irregularities are present (absent) and the binary value "1" ("0") is applied to the corresponding cell in the daily statistical matrix; (5) this procedure is performed individually to each daily RTI matrix; and, finally, (6) a matrix corresponding to the sum of all daily matrices is divided by the number of the days included in the analysis, leading to what we have labeled as a histogram matrix. In this matrix, each line represents the relative distribution of the occurrence of EEJ plasma irregularities with respect to the local time at a given height range. The columns represent the relative histogram with respect to the height at a given time. The format chosen for presenting the statistical results is a contour color map as shown in Fig. 1. We refer to this plot as the Range Time Histogram (RTH), and its color scale gives the percentage of occurrence of EEJ plasma irregularities for the specific local time and height of analysis, according to the season.

3. Results

The basic results of this study is presented in Fig. 1, which shows the RTH maps for the D months, the E months and the J months (from the top to the bottom), from 0600 to 1800 LT (76.52°W), covering the height range 70 to 140 km. Observing the maps, we can clearly see that the irregularities stay roughly confined to the region from 90 to 120 km during the entire day at any season. Also, there is some preferential local time for the EEJ irregularities

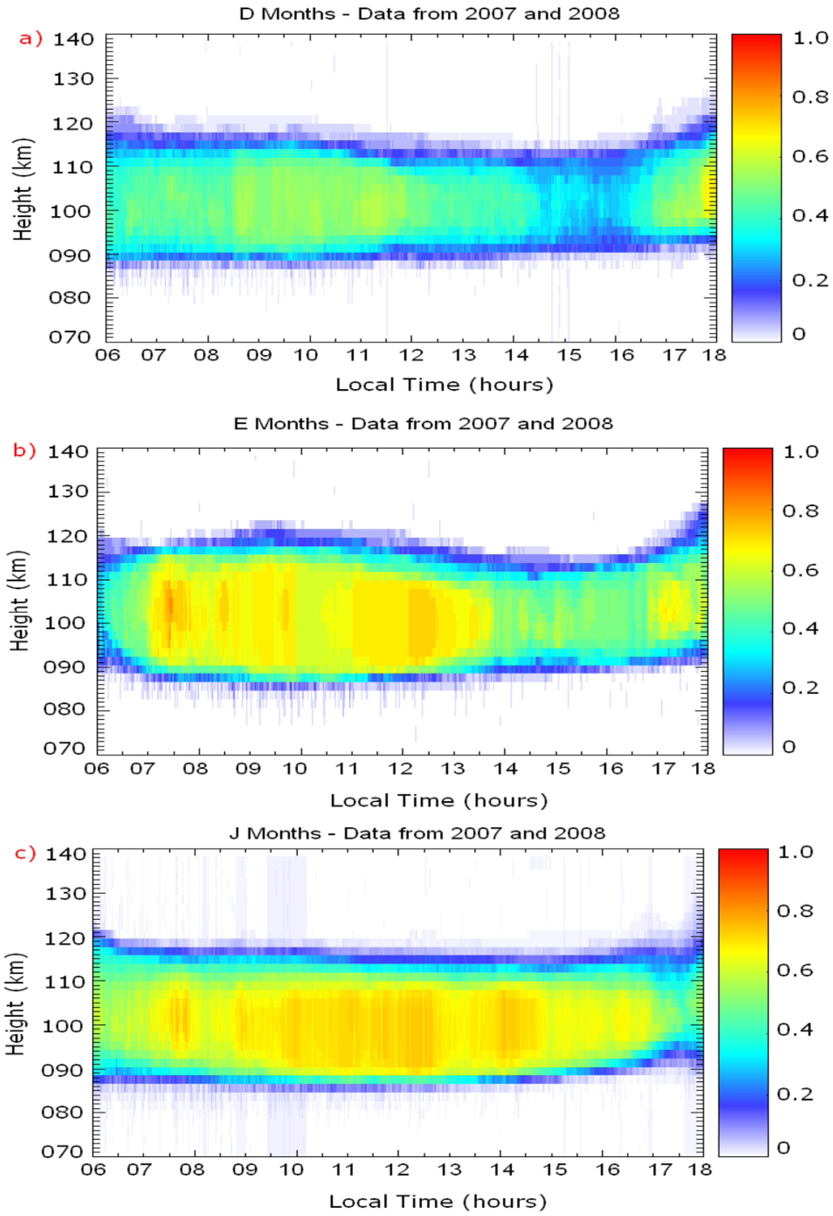

Fig. 1. RTH maps with the statistical occurrence of plasma irregularities for (a) D months, (b) E months and (c) J months, from 06 to 18 LT (76.52° W), covering the height range from 70 to 140 km.

to develop, which are clearly the morning hours and early afternoon. Moreover, there seems to be an ascent of the whole scattering region late in the afternoon. There also are some discrepancies in the occurrence of EEJ irregularities depending on the season, like the fading of the occurrence at around 1500 LT during the D months (summer season) and the E months (equinoxes). In order to investigate this in detail, we performed an analysis of the RTH maps based on curve fitting to obtain the time evolution of the occurrence distributions of the irregularities. The first parameter that we obtained is the fit center of the irregularities occurrence height distribution (EJC). The second parameter that we analyzed was the thickness of the region where the irregularities occurrence surpassed 20% of the cases (EJT). The third one was the percentual occurrence of irregularities at the EJC height, i.e., the value of the histogram for each column of the RTH map.

In the upper panel of Fig. 2, we present the time evolution of the EJC for the D months (red bullets), E months (green bullets), and J months (blue bullets). The "error bars" are not error, but the EJT. The errors in determining the EJC are presented in the right upper corner of this panel. The bottom panel of Fig. 2 presents the time evolution of the occurrence of irregularities at the EJC height for the three data sets evaluated in this study.

From the RTH map in Fig. 1, and with the help of the bottom panel of Fig. 2, we may say that the common features of the occurrence of EEJ plasma irregularities in the Peruvian sector are (at least, for the present period of analysis): (a) the development of irregularities is always present during daytime, but with different levels of incidents depending on the season—they occur more often during the E months (equinoxes), and less during the D months (summer); (b) after about 0630 LT there is a 25% possibility of irregularities

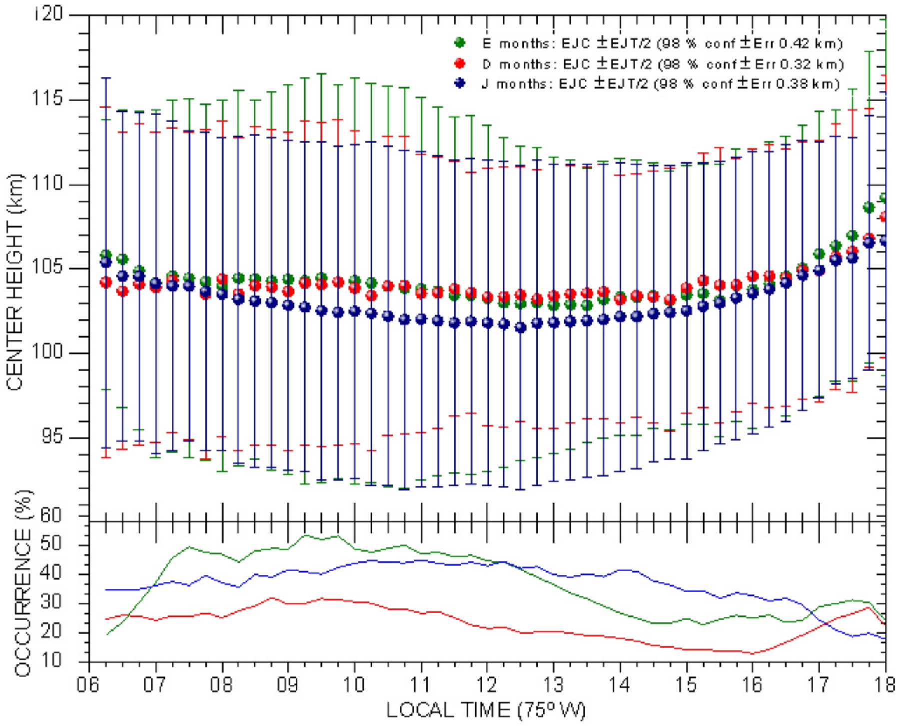

Fig. 2. The time evolution of (upper panel) the EJC for the D months in red bullets, E months in green bullets, and J months in blue bullets, within the corresponding EJT around the fit center; and the time evolution of (bottom panel) the irregularities occurrence at the EJC height for the three mentioned sets of data.

developing; (c) between 0730 and 1100 LT the chance of observing plasma irregularities over Jicamarca reaches its highest values, especially during the E months (equinoxes) and the D months (summer); (d) after about 1100 LT during the D months (summer) or E months (equinoxes), and after about 1400 LT during the J months (winter), there is a decreasing chance of observing the EEJ irregularities; (e) by the end of the measurement period (close to 1600 LT), the probability of irregularities development is lowest and then increases again, except in the J months; and (f) the probability of measuring EEJ irregularities at about 1800 LT (or even later) does not exceed 25%. Also, from the RTH map in Fig. 1, and with the help of the upper panel of Fig. 2, we may state that: (g) the scattering region containing the EEJ irregularities descends during the morning hours, the clearest example of which occurs in the J months (winter); (h) this region also ascends in the afternoon, after about 1230 LT for the J months (winter), but after about 1400 LT during the E months (equinoxes) or D months (summer); (i) the ascent is more pronounced in the E months (equinoxes), very clear, but less intense, during the D months (summer) and even less intense during the J months (winter); and (j) the height range where the irregularities are observed may be as broad as 23 km at around 1000 LT, but this usually reduces after 1100 LT to 10–15 km close to 1700 LT, mainly in the E months.

With regard to some of the most evident differences of the presence of EEJ plasma irregularities during the different seasons in our study, we may say that: (a) there is a gradual decrease in the intensity of the occurrence of plasma irregularities to values between 10–20% after 1400 LT, except for the J months, when the chance of observing plasma irregularities is quite persistent (>30%) up to 1700 LT; (b) the probability for observing plasma irregularities increases up to 30% after about 1600 LT for the D months, and after about 1630 LT for the E months, but it did not increase in the J months; and (c) the lowest probability for observing plasma irregularities between 1400 and 1700 LT was found in the D months, when their occurrence never exceeded 30%.

4. Discussions

Such a statistical study of the EEJ plasma irregularities observed with the Jicamarca 50 MHz radar alone is not a new result, since other authors have carried out similar studies for the American sector (Chau *et al.*, 2002; Denardini *et al.*, 2005); and for the Indian sector (Patra *et al.*, 2004; Kumar *et al.*, 2009) before. However, these previous studies did not cover the same sector during the same solar cycle period and, more importantly, differ in some aspect from our results. Chau *et al.* (2002) have focused their analysis on data from Piura radar (a 50-MHz radar at the Peruvian sector in South America) and have found that the echoes from E-region plasma irregularities were stronger in summer (Dec.–Mar.) than in winter (May–Jun.). However, most of their statistics is based on nocturnal echoes since the authors claim daytime echoes are not observed because the antenna at Piura radar has a low sensitivity (small antenna and low transmitted power). Also, they investigated the presence of the E-region irregularities observed close to the solar maximum (2000–2001). Denardini *et al.* (2005) have also investigated the E-region irregularities during the solar maximum (2002) based on the RESCO 50-MHz radar, but for the Brazilian sector in South America, which has a significantly different declination (around -20° at the RESCO site). They presented RTI maps like Chau *et al.* (2002) with stronger echoes during summer (Nov.–Jan.), and weaker echoes during winter (May–Jul.). But they also pointed out the frequent presence of echoes during equinoxes, with a relatively high strength during the entire daytime. Patra *et al.* (2004) based their study in the E-region echoes observed by the Gadanki 53-MHz radar and covered the period between 1994 and 2000, during the last solar minimum and most of the ascending phase of the solar cycle 23. However, the focus of their work was a night and day comparison rather than seasonal statistics. So, they did not cover all the seasons with their observations. They constrained their analysis to data acquired during spring and summer (Apr.–Aug.). Kumar *et al.* (2009) focused their work at low latitudes but outside the electrojet belt.

Despite some discrepancies in the data selection assumed for characterizing the seasons in these different studies, most of the periods are coincident in order to allow a direct comparison. Therefore, the divergence between our results, which shows that the occurrence of the irregularities is more often in the E months (equinoxes), and the result of Chau *et al.* (2002) and Denardini *et al.* (2005) for the American sector, showing the occurrence of stronger echoes during summer, may not be explained by the data selection. However, this discrepancy should be carefully analyzed with respect to three basic aspects: (1) the technique used to establish it; (2) the data selection with respect to the period of day; and (3) the data selection with respect to the period of the solar cycle. With respect to the first aspect, our work differs from that published by Denardini *et al.* (2005) because they based their analysis on the maximum intensity of the echo strength, while we have based ours on the threshold for irregularities to develop, i.e., Denardini *et al.* (2005) stated that summer is the season during which the irregularities are stronger, while we state that the E months (equinoxes) is the season during which the irregularities are most likely to be observed. Indeed, our observations did not contradict those made by Denardini *et al.* (2005). With respect to the second aspect, our work differs from that published by Chau *et al.* (2002) because they based their statistics on nocturnal echoes while we focused on daytime echoes only. Also, both Chau *et al.* (2002) and Denardini *et al.* (2005) performed their studies using radar data collected during a solar maximum, while we have based our statistics on measurements made during a solar minimum. These three basic differences between the above-mentioned studies highlight the originality of our results, at least with respect to the occurrence of irregularities in the American sector.

The explanations for the observations are not easy, however. Chau *et al.* (2002) raised an important point with respect to the need for knowledge about some important variables (density gradients, electric fields, etc.) to properly explain the statistical results. Patra *et al.* (2004) stated that a more homogeneous ionosphere in the zonal direction may impact on the type-2 irregularity developments, which, in turn, will reduce their observation and the general statistics since this type is expected to be observed even when the electric field is not strong enough to develop type-1 irregularities. Also, it must be noted that the development of type-2 irregularities is related to the parallel upward electric field and density gradient at the region of study. So, it is desirable to know about the background density gradient, as well as the wind system, which is capable of producing the density gradient which allows the development of type-2 irregularities. Since we have no such information about the above parameters we are not in a position to determine the origin of the observed seasonal characteristics. We may only speculate that the polarization electric field during the E months (equinoxes) should more frequently reach the level to surpass the minimum threshold for the development of irregularities over Jicamarca than the threshold reached during the other seasons. Also, we may suggest that future studies (based on magnetometers, for instance) confirm our results.

With respect to those items mentioned in the previous section regarding the height and local time of statistical observations, they are mostly consistent with the current knowledge of the mechanism of the generation of the type-1 (modified two stream) and type-2 (gradient drift) irregularities, as well as several other observations (Fejer and Kelley (1980), and references therein; Forbes (1981), and references therein). The descent of the scattering region containing the EEJ irregularities during the morning hours, followed by its ascent in the afternoon have also being reported before by Denardini *et al.* (2005).

Denardini *et al.* (2005) observed ascents after about 1400 LT during all seasons, irrespective of the magnetic condition, and they reported a seasonal dependence of the ascent degree. They assumed the ascent to be a characteristic of the daily behavior of the EEJ and mentioned that it is more pronounced during the summer, very clear but less intense during equinoxes, and not clearly defined during winter. Our observations revealed different results, however.

We did not consider the magnetic condition, but we clearly see that there is a more pronounced ascent in the E months (equinoxes), a very clear, but less intense, ascent during the D months (summer) and a clearly defined, but even less intense, ascent during J months (winter). Also, we observe a descent in the morning hours, which is not clearly identified, nor sufficiently discussed, in the previous work by Denardini *et al.* (2005). Another difference is the time when the ascent of the EJC starts. We observe this as early as after midday during the J months (winter).

We assume that the theory proposed by Denardini *et al.* (2005) is correct for explaining the ascent itself, since it partially explains this based on the α-Chapman behavior of the E-layer and on the variation of the collision frequencies from 1400 to 1700 LT, leading to the displacement of the region where the anisotropic factor is approximately equal to one-third ($\psi \approx 1/3$). However, as in the case of the discrepancy in the plasma occurrence, an explanation for the seasonal discrepancies is difficult since we have no information regarding the electric field, density gradient, wind system, and other important variables measured above the radar site at the moment of the measurements used in the present analysis. Again, we may only assume that our previous speculation is right so that the electric field (vertical) during the E months (equinoxes) should be strong enough to exceed the minimum threshold required to develop irregularities over Jicamarca, and this may result from a stronger primary field (zonal) which may lead to additional ascent effects due to the local electrodynamics, essentially $\mathbf{E} \times \mathbf{B}$ drifts. Indeed, just to mention a probably-unrelated fact, Fejer *et al.* (1991) have reported stronger $\mathbf{E} \times \mathbf{B}$ drifts at the F-region over Jicamarca during the E months (equinoxes).

5. Conclusions

This study showed a statistical occurrence of the 3-m plasma irregularities observed by the Jicamarca radar, in the Peruvian sector. We developed a routine that performed a statistical analysis over the RTI matrices of each day of radar data collected during 196 days during the period 2007 to 2008. The results are shown in plots referred to as RTH maps, where the color scale gives the percentage of occurrence of EEJ plasma irregularities for the specific period and height of analysis. From the RTH maps, we saw that the irregularities stay roughly confined to a region limited from 90 to 120 km during the entire day during any season, despite there being some preferential local time for the EEJ irregularities to develop. Also, the presence of the 3-m irregularities occurs more often during equinox and we clearly observe a descent of the scattering profile in the morning hours followed by its ascent in the afternoon. These results were compared with previous studies, but they did not cover the same sector during the same solar-cycle period. Notwithstanding the different data set, the ascent of the scattering profile in the afternoon found similarities with that reported by Denardini *et al.* (2005), explained through the α-Chapman behavior of the E-layer and the locus of one-third of the anisotropic factor. Nevertheless, our analysis revealed that the ascent is more pronounced during equinoxes, while the previous study showed that they should be is more pronounced during the summer. There are also other discrepancies among the present results with those published of other studies. The previous work revealed a preference for the occurrence of 3-m plasma irregularities in summer, in contrast with the often observed occurrence during equinox that is reported in the present study. Since we have no information on the electric field, density gradient, wind system, and other important variables measured above the radar site at the time of the measurements, we are not in a position to determine the origin of the observed seasonal characteristics. We may only speculate that the polarization electric field during the equinoxes more frequently reaches the level to exceed the minimum threshold for irregularities to develop over Jicamarca than during other seasons. If so, it may also be strong enough to impose additional ascent effects due to the local electrodynamics, essentially $\mathbf{E} \times \mathbf{B}$ drifts.

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