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Research

On the Ionospheric Variability of Critical Frequency along the Equator Anomaly Trough and Plausible Role of Vertical *E x B* Drift

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Abstract

The F2-layer critical frequency (foF2) variability was investigated over Jicamarca (11.9°S, 76.8°W, dip 1°N), a station along the equator anomaly trough during solar minima period. Diurnally, foF2 is more vulnerable to variability during the nighttime (13-27%) than the daytime (5-16%) having two characteristic peaks: pre-sunrise and post-sunset peaks. The highest values were attained during the pre-sunrise peak with a value range of 24-34%. Seasonally and annually, the pre-sunrise peak is higher than the post-sunset peak. The nighttime downward reversal value in vertical plasma drift coincides with the enhanced foF2 variability. The rapid faster electron drift away from the equator is responsible for the sharp drop in NmF2 and a subsequent rise in the percentage variability coefficient immediately after sunset in all seasons. Seasonal peaks in foF2 variability are suspected to be controlled by the enhanced E x B drifts and atmospheric wind which is consistent with some earlier results obtained in some stations in the African region during solar minima periods.

Keywords: *Pre-reversal enhancement; variability coefficient; foF2; solar minima; E x B drifts*

Introduction

The ionospheric F2-layer has been adjudged to be the most efficient layer for long-distance high frequency (HF) radio communication, since it contains both the highest electron density (NmF2) and highest height (hmF2). Therefore, a better understanding and interpretation of this layer will be of utmost advantage to radio communication experts. A good prediction of the foF2 variability is thus of great benefit in this respect as it holds a considerable feature of the complex subject of space weather, for both its practical applications and scientific importance. Akala et al (2011), Bilitza et al (2004), Forbes et al (2000) and Jayachandran et al (1995) are among the numerous researchers who have quantified and investigated the foF2 spread at different latitudes and solar cycles.

The equatorial anomaly on the other hand, characterized as the occurrence of a trough in the ionization concentration at the equator and crests at about 17^{o} in magnetic latitude in each hemisphere, has been well described as arising from the electrodynamics at the equator. Tidal oscillations in the lower ionosphere move plasma across the magnetic field lines which are horizontal at the magnetic equator. The resulting E-region dynamo sets up an intense current sheet referred to as the equatorial electrojet (Anderson et al., 2002). Though, these dynamo electric fi(e)lds are transmitted along the dipole magnetic field lines to F region altitudes, where the uplift of ionization takes place. The zonal current flows eastward during the day and westward at night. Since an electric field is established perpendicular to the magnetic field, an E x B/B^{2} drift moves the ionization vertically upwards during the day and downwards at night. This upward motion of ionization during the day is referred to as the equatorial fountain, since ionization rises above the magnetic equator until pressure forces become appreciable that it slows down and under the force of gravity moves along the field lines and is deposited at higher tropical latitudes.

This work examined the diurnal and seasonal variability of foF2 over an ionospheric station along the equator anomaly trough during a period of solar minima, as well as the plausible role of the vertical plasma drift in this variation.

Data and Methodology

The data used consists of ionospheric F2-layer parameters like the critical frequency (foF2), real height (hmF2), peak electron density (NmF2) and the vertical plasma drift (Vz). Hourly values of these parameters were taken over Jicamarca (Lat. 11.9^{o}S, Long. 76.8^{o}W, dip 1^{o}N), an ionospheric station along the anomaly trough in the American sector.The study is for the year 2010, a period of low solar activity (F10.7 = 82 sfu). The data sets for foF2 and hmF2 were obtained from the Space Physics Interactive data Resource (SPIDR) website (http://spidr.ngdc.noaa.gov). The NmF2 values were derived from the foF2 data using the relation in equation (i).

$$NmF2 = 1.24 \times 10^{10} (foF2)^2 \qquad (i)$$

where NmF2 is given in m^{-3} and foF2 in MHz

5-minute interval data from Jicamarca Incoherent Scatter Radar (ISR) for the year 2010 was extracted and converted into 1-hour interval data (see madrigal homepage at http://jrol.igp.gob.pe/madrigal/). The Jicamarca ISR measures direct vertical plasma drifts. Data were not available between 0000-0700 LT during summer. Following the example of Forbes et al. (2000), Rishbeth and Mendillo (2001), and others, the monthly mean (μ) and the standard deviation (σ) have been used for the evaluation. For the variability, we have used the coefficient of variability assuming that the variations represent real changes in electron density and not just a redistribution of the existing plasma. The foF2 variability coefficient (Vcoeff) is defined as

$$Vcoeff\,(\%) = [\text{standard deviation of the foF2 values/average value}]*100 \qquad (ii)$$

Vcoeff (%) is a statistical instrument for determining the degree of spread or deviance of each data point from the calculated average for the whole data set. Bilitza et al (2004) had indicated that the standard deviation is a good measure for describing the average variation from the monthly means. For the seasonal pattern of the foF2 variability coefficient, data for the months of March, June, September and December respectively represents the seasons of spring, summer, autumn and winter. Each set of data covers the entire 24 hours of the day for each of the four representative months of the year

Results and Discussion

3.1 Variability pattern in Ionospheric foF2

Figure 1 reveals the diurnal foF2 variability coefficient [Vcoeff (%)] pattern plotted against local time (LT) over Jicamarca F2-layer. On the average, the diurnal variations follow the same pattern during the entire four seasons. The variability is observed to be lowest during the day time (5-16%). At nighttime, the variability had increased (13-27%). However, the highest values were attained during sunrise (the pre-sunrise peak) with a value of 24-34%. For this pre-sunrise peak, the highest was observed in autumn (34%), followed by winter season (31%), then summer (27%) and the least in spring (24%). The second peak (the post-sunset peak) was observed between 2100 and 2200 LT for all seasons. In all the seasons, the pre-sunrise peak is higher than the post-sunset peak. Moreover, the nighttime variability coefficient observations were seen to be higher than the daytime observations. The differences in the daytime/nighttime observations were explained in part, to be due to the lower mean (μ) value during the night, which for comparable absolute variability give rise to higher variability percentage at nighttime (e.g Bilitza et al., 2004).

The two foF2 variability peaks observed, according to Chou and Lee (2008) are ascribed to abrupt electron density gradients triggered by the onset and turn-off of solar ionization, as well as the superimposition of spread-F on the background electron density. The pre-sunrise peak was reached earliest during summer and winter seasons, and latest in spring and autumn. The highest post-sunset peak value was yet again recorded during summer (26%). This observation is inversely related to the response of the seasonal electron density profile highlighted in figure 3 in which the lowest nighttime (1800-0600 LT) peak value was observed in summer. The inference from these observations is that much of the foF2 variations are observed during the summer season suggesting that there may be some other factors present during this season causing the variability which may not necessarily be present during other seasons.

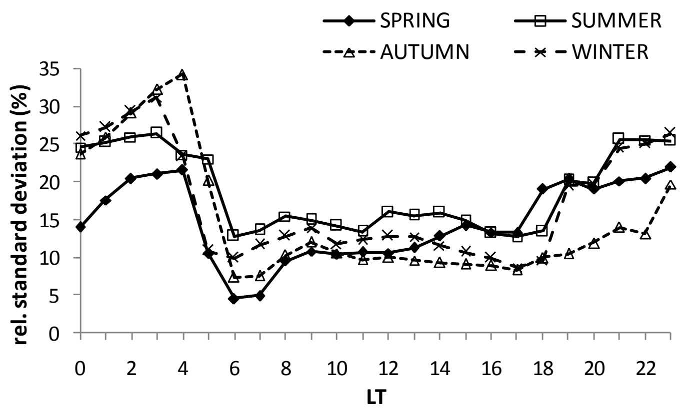

Figure 1: Diurnal variation of foF2 variability coefficient for all seasons over Jicamarca during period of solar minima.

The hourly annual plot of Vcoeff against local time (LT) is represented in figure 2. The plot revealed an average pre-sunrise peak of 28% around 0300 LT. The daytime value ranges from 8-13%, while the post-sunset peak recorded 23%. Annually, nighttime variability is higher than the daytime variation. Gravity waves had also been suggested to be another factor responsible for the nighttime ionospheric density gradient enhancement.

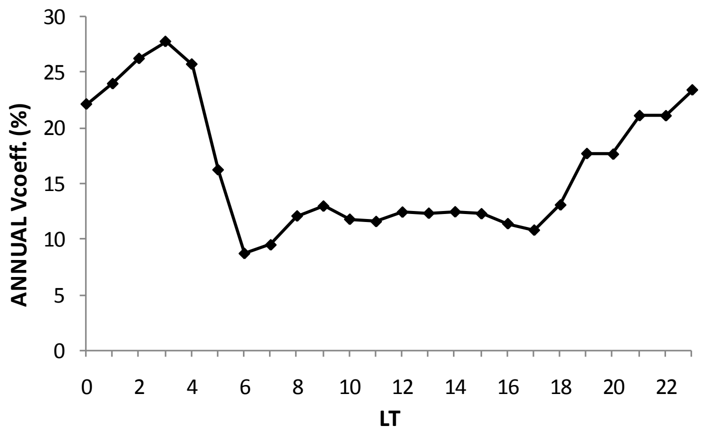

Figure 2: Annual variation of foF2 variability coefficient for all seasons

3.2 Response of Peak electron density (NmF2)

Figure 3 highlights the average seasonal variation of the peak electron density (NmF2) over Jicamarca. NmF2 increases from sunrise around 0500 LT and reaches a pre-noon peak before 1200 LT around 0700 – 0900 LT for all seasons. The least electron density concentration was observed in summer around this period. Thereafter, there is a general daytime reduction in electron density, creating a hollow and reaching a minimum between 1100 LT and 1200 LT. The least reduction was experienced in spring, while it is highest in summer. A second peak (the post-noon peak) was recorded between 1500 and 1600 LT. This condition of the appearance of peak electron density yet again is highest during the spring and lowest in summer. For this solar activity condition, the post-noon peak is greater than the pre-noon peak for the entire seasons. The above corollary are in total agreement with the results obtained for Ouagadougou (12.4^{o}N, 1.5^{o}E; dip 5.9^o) by Radicella and Adeniyi (1999) during a low solar activity period. At nighttime (1800 – 0600 LT), a general sharp drop in NmF2 is distinct immediately after sunset. This sharp drop was observed around 1700 LT. This decay is continuous during all season till around 0500 LT, at which time a pre-sunrise minimum occurs. For this nighttime event, the electron density is lowest in summer and highest during spring.

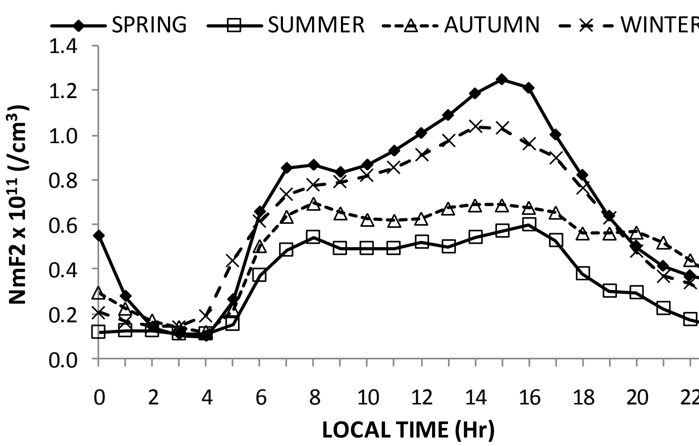

Figure 3: Average hourly diurnal peak electron density over Jicamarca for solar minima period

3.3 hmF2 Observations

Depicted in Figure 4 are the average seasonal real height profiles of the F2 layer. The observations for hmF2 for all the seasons indicate a sharp and gradual rise within the period of 0500-1000 LT. The variation range between the period 1000 and 1800 LT is much broader. Within this period, the magnitude of hmF2 is between 268-428 Km. During the daytime, the highest magnitude was observed in spring, while the least was recorded in summer. However, during the nighttime the highest hmF2 value was recorded in winter. On the average, two peaks were observed – the pre-noon peak and the post-sunset peak. The average post-sunset peaks are 428 Km (at 1800 LT), 343 Km (at 1800 LT), 419 Km (at 2000 LT) and 317 Km (at 1900 LT) respectively for spring, autumn, winter and summer. A sharp rise was noticeable between 1700-1800 LT at all season, indicating the presence of the F2-layer evening time pre-reversal enhancement (PRE). Immediately after this time, a sharp drop was experienced in the seasonal patterns up till around midnight period. The differences between the daytime peaks and the post-sunset peak values are not much pronounced except during spring and winter.

It is worthy to mention that the respective NmF2 and hmF2 observations in figures 3 and 4 are the mean values. However, the day-to-day variability of the ionosphere in terms of these two parameters can still be described in terms of their standard deviation. This is left open for future study. Through this, the different diurnal patterns like the noon-time bite-out, as well as NmF2 anomalous depletion can be realized even further.

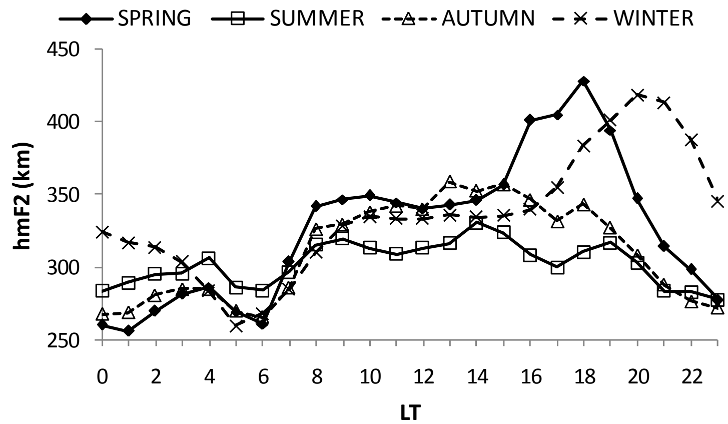

Figure 4: Seasonal hourly mean values of the F2 layer real height $(hmF2)$ over Jicamarca

3.4 Effects of vertical plasma drift

Figure 5 depicts the average hourly seasonal vertical plasma drifts pattern measured at Jicamarca for 2010. From the figure, the F2 ionosphere has attained dynamic equilibrium by both solar radiation and recombination, which makes up the production and loss processes respectively. The vertical drift is upward during the daytime and increases in velocity from around 0100 up till around 1100 LT with a wide peak around 1100 LT for all season. This shows that electrons are moving up and away from the equator in which case the electrons depletion during the daytime peaks around midday as seen from the NmF2 plot in figure 3. This condition allows for the formation of a maximum electron density before noon and a minimum around midday i.e. between 1030-1130 LT. Generally, depressions were observed nearly after the daytime peak till around 1700 LT.

Immediately after the maximum upward vertical drift was reached, the drift velocity takes a downward pattern and reach minimum before the post-sunset increase begins again. This indicates a reduction in the depletion of electron density after midday. Since the decrease in depletion begins some hours before sunset, when ionization production is still occurring, then one should expect the formation of a post-noon peak in the electron density. This agrees with the NmF2 post-noon peaks observed in figure 3, which is least in summer. At nighttime, the vertical drift is first characterized by an upward enhancement, so called the evening time pre-reversal vertical enhancement (PRE) around 1900 LT, then by a downward reversal. The PRE phenomenon is mainly driven by eastward electric fields and can significantly change the height of the ionosphere. The equatorial electric field and plasma drift vary with longitude at a given local time and affect the growth rate of the Raleigh-Taylor (RT) instability through the gravitational and electrodynamics drift terms and by controlling the electron gradient in the bottomside of the F-region after dusk. The post-sunset peak in upward plasma drift is indicative of a sudden faster depletion of electrons from the equatorial ionosphere. This is the reason for the sharp drop in electron density (figure 3) noticed immediately after sunset.

Some of the results of Fejer et al (1991) on plasma drift over Jicamarca that (i) the evening reversal of vertical drift occurs earlier at low than at high solar activity [when we compared our low solar activity [Rz = 16] results with that at high solar activity recorded in 1991 [Rz = 146] by Radicella and Adeniyi (1999)] and (ii) that the period of upward drift is shorter during low solar activity are in good agreement with the present work. On the average, the vertical drift is positive during the daytime (0600 -1800 LT) and negative for the entire nighttime period (1800 – 0600 LT). The enhancement was highest in spring with peak value of 24 m/s, and followed by winter season (13 m/s). However, the lowest was observed in autumn. This reveals that the drift is season dependent. The PRE is basically responsible for the large uplift of the F2 layer and the evening time resurgence of the Equatorial ionospheric anomaly (EIA). The vertical drift immediately after the PRE recorded downward reversal peak values of -39.6 m/s (at 0200 LT), -21.7 m/s (at 2200 LT), -17.4 m/s (at 0000 LT) and -12.7 m/s (at 2100 LT) for spring, autumn, winter and summer respectively.

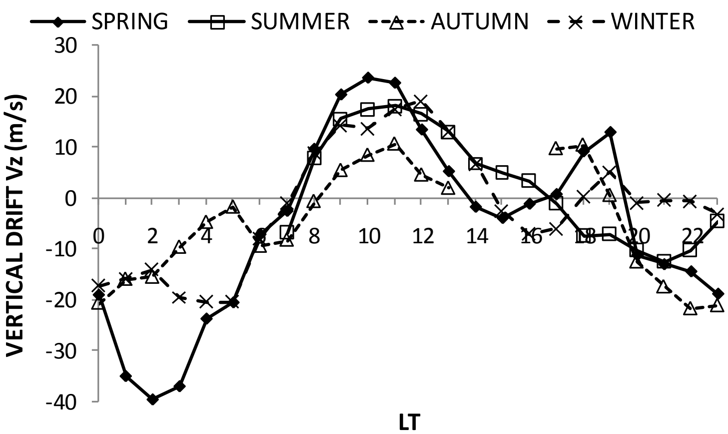

Figure 5. Average seasonal vertical plasma drifts measured at Jicamarca during low solar activity period of 2010.

The E x B field contributes to the vertical drift of ionization around the equator resulting in the depletion of ionization during the daytime in the equatorial region. Hence, such kinds of vertical plasma motions are primarily accountable for the deviations in the F2 layer parameters in the equatorial ionosphere. Rajaram and Rastogi (1977) have shown that the effect of E x B drift on the equatorial ionosphere commences from an altitude of about 200 Km upwards, which may have explain the variability observed in this study. Rishbeth (1971) had proposed that at evening time, the PRE is created from the combined F2 region dynamo action driven by the eastward thermospheric wind close to the dusk as well as the action of the E-region conductivity changes near the sunset terminator at conjugate magnetic latitudes. Sumod et al. (2012 and the reference therein) have also shown that lower atmospheric tides and waves can also make substantial changes to the PRE. Hence, a better understanding of the PRE and the pre-sunrise plasma drift would provide a clearer insight into the ionospheric variability of foF2.

The variation between the vertical plasma drift and the foF2 variability coefficient are highlighted in figure 6(a-d). Observe that during all the seasons in the daytime, the enhancement in the plasma drift is closely trailed by a corresponding depletion and thereafter a subsequent enhancement in the foF2 parameter signifying that the drift is a major role player in the foF2 heightening/depletion. In general vertical E x B plasma drift determines the extent of variability of the critical frequency foF2 effect. It is worthy to note that this may not hold all the time, as the plasma drift majorly controls the plasma density and hmF2, and not the variability directly. This is because, according to Adebesin et al. (2013a and reference therein), since the photo-ionization rate is proportional to atomic oxygen (O) and the loss rate is proportional to molecular nitrogen (N_2) and oxygen (O_2), a decrease in the mean molecular mass from downwelling through constant pressure surfaces would lead to increases in NmF2, while an increase in the mean molecular mass due to upwelling results in NmF2 decrease. A rise in hmF2 to regions of reduced loss due to equatorward winds would also generate increases in NmF2 if they occur while production is still occurring. Similarly, a drop in hmF2 due to poleward winds reduces NmF2. Consequently, ionospheric variability may also be attributed to the variability of other driving forces like tidal waves, equatorial zonal electric fields, which drives the equatorial electrojet (EEJ) and the equatorial ionization anomalies especially at low latitude regions (Adebesin et al., 2013b).

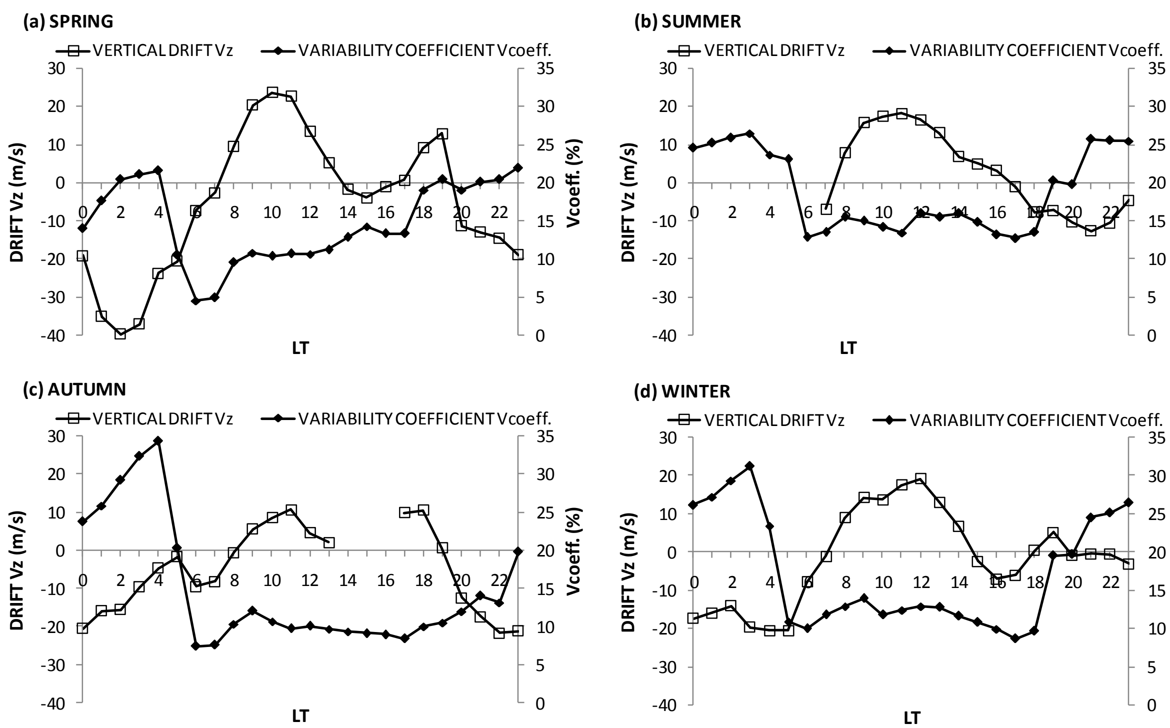

Figure 6: Response plot of (i) the average seasonal variation in vertical drifts (black diamond line) and (ii) foF2 variability coefficient (open square).

Downward foF2 depletions are as a result of increase vertical drifts. Ionospheric plasma is raised by this drift beginning from the F2 region, and then drifts along the magnetic field lines apart from the geomagnetic equator (known as the fountain effect). It must be noted that neutral composition changes observed at equatorial latitudes are not sufficient enough to cause depletion in foF2 variations, but an increase in atomic oxygen [O] may contribute to the enhancement in foF2 variability when E x B drifts are small. [O] is predominantly the largest atomic gas present in the F2 region. It is important to emphasize that the increase of absolute atomic oxygen concentration provides a background foF2 increase.

On the other hand, a very strong downward drift (or westward electric field) may also result in downward foF2 variability effect when F2 layer is pushed down to lower heights where recombination is strong (Mikhailov and Leschinskaya, 1991). At nighttime the corresponding depletion in the foF2 coefficient of variability as a result of a very strong downward drift are observed between 0400-0600 LT during the entire seasons. However, a decrease in the upward E x B drift carrying plasma from the topside to the F2-layer maximum will result in an enhancement in foF2 variability effect.

Vertical drifts during the daytime are therefore upward and have a sharp peak around 1000 LT (Fig. 6a-d). Moreover, this would make electrons to go up and away from the equator causing the maximum daytime electron depletion around local noon. Here, the respective vertical drift values at local noon are 13.5, 16.6, 5.8 and 19.1 m/s for spring, summer, autumn and winter seasons respectively. This condition encourages the creation of a pre-noon foF2 and a subsequent minimum around local noon as could be seen from the figure. The vertical drifts reversal immediately after the evening PRE in turn drives electrons to lower heights in the equatorial region. Observe also that the nighttime downward reversal value in vertical plasma drift coincides with the enhanced foF2 variability coefficient value. According to Bilitza et al. (2004), the greater variability values attained during the night compared to the daytime values have been attributed to lower value of the mean at night. This is because an almost similar absolute values were obtained for the standard deviation for both day and nighttime periods. Hence the denominator (average value) must have played a significant role in the higher variability observed at night. This is consistent with the result of Oladipo et al (2008). The sudden faster electron drift away from the equator as indicated by the PRE in rising plasma drift is responsible for the sharp drop in foF2 immediately after sunset.

4. Conclusion

This paper has presented ionospheric data from Jicamarca, a station located under the equatorial ionization anomaly (EIA). Summarizing the results of this work, the following were deduced:

- The diurnal observation revealed that foF2 is more vulnerable to variability during the nighttime (13-27%) than the daytime (5-16%) having two characteristic peaks: pre-sunrise and post-sunset peaks. The two peaks variability were ascribed to abrupt electron density gradients triggered by the onset and turn-off of solar ionization and superimposition of spread-F on the background electron density.
- The highest values of foF2 variability coefficient (Vcoeff (%)) were attained during the pre-sunrise peak with a value range of 24-34%. For this pre-sunrise peak, the highest was observed in autumn (34%), followed by winter season (31%), then summer (27%) and the least in spring (24%). The second peak (the post-sunset peak) was observed between 2100 and 2200 LT for all seasons. In all the seasons, the pre-sunrise peak is higher than the post-sunset peak. Annually, the average pre-sunrise peak of 28% magnitude was observed around 0400 LT. The daytime value ranges from 8-13%, while the post-sunset peak was 23% for the solar minima period.
- The nighttime downward reversal value in vertical plasma drift coincides with the enhanced foF2 variability. The sudden faster electron drift away from the equator as indicated by the pre-reversal enhancement (PRE) in rising plasma drift is responsible for the sharp drop in foF2 immediately after sunset in all the seasons.
- Seasonal peaks in foF2 are suspected to be controlled by the enhanced E x B drifts and atmospheric wind which agrees with the result of some previous works. The vertical drift immediately after the PRE recorded downward reversal peak values of -39.6 m/s (at 0200 LT), -21.7 m/s (at 2200 LT), -17.4 m/s (at 0000 LT) and -12.7 m/s (at 2100 LT) for spring, autumn, winter and summer respectively.

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