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ORIGINAL RESEARCH

COMPARISON OF DIURNAL AND SEASONAL VARIABILITY OF THE CRITICAL FREQUENCY OF THE F2 LAYER OVER ILORIN, JICAMARCA AND OKINAWA DURING MINIMUM SOLAR ACTIVITY

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Abstract:

Introduction: The ionosphere displays a wide range of variations ranging from diurnal, seasonal, annual and solar cycle variation. In this paper we present a study of the comparison of diurnal, seasonal and semiannual variation of the variability (VR) of the critical frequency of the F2 layer (foF2) over Ilorin (Lat. 8.47ºN, 4.6ºE, dip 4.1ºS) in the African sector,Jicamarca (Lat. 11.9ºS, Long.76.8ºW, dip 1ºN) in the American sector and Okinawa (26.3ºN, 127.8ºE, dip 36.8ºN) in the Asian sector during solar minimum period. These stations lie within the equatorial anomaly region of the ionosphere.

Aims: To compare the diurnal, seasonal and semi-annual variation of the variability (VR) of the critical frequency of the F2 layer (foF2) over Ilorin in the African sector, Jicamarca in the American sector and Okinawa in the Asian sector during solar minimum period.

Materials and Methods: foF2 relative variability (foF2 VR) is obtained by computing the ratio of the standard deviation (σ) to the monthly mean (μ) of each day at each hour express as a percentage.

Results: Diurnal analysis revealed that the critical frequency of the F2 layer is more prone to variability (VR) during the nighttime than the day time at these stations, with two characteristics peaks, post-midnight peak and pre-midnight peak. The peaks at Ilorin (20 - 43%; 16 - 25%) are observed to be highest in values than those at Jicamarca (17 - 27%; 15 - 22%) and Okinawa (22 – 39%; 15 - 30%). Seasonally, December solstice maximum was noticed at Ilorin. Semiannual analysis showed that foF2 VR is highest at Ilorin station, followed by Okinawa station and least by Jicamarca station during the nighttime. Diurnal curves of mean foF2 revealed pre-noon and post-noon peaks at all stations, with Jicamarca having highest values for both peaks during December solstice while for the semiannual curves of mean foF2with the exception of Okinawa station, showed almost equal peaks values for Ilorin and Jicamarca stations.

Conclusion: foF2 variability is highest at Ilorin and lowest at Jicamarca while for F2 layer ionization the reverse is the case.

Keywords: foF2 variability, minimum solar activity, critical frequency, F2 layer.

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All co-authors agreed to have their names listed as authors.

1. INTRODUCTION

The ionosphere is that part of the upper atmosphere of the earth where ions and electrons are present in quantities sufficient to affect the propagation of radio waves. The ionosphere can reflect waves of frequencies below about 30 MHz, allowing high frequency (HF) radio communication to distances of many thousands of kilometers across the globe. It is this feature that makes broadcasting around the globe possible [20]. The ionosphere is divided into three layers. These are called D, E and F layers or regions based on level of ionization by solar radiation. The F-layer is the most important part of the ionosphere in terms of high frequency (HF) communication. The F-layer in the presence of sunlight during the daytime, splits into two layers, the F1and F2layers at heights (150–200 km) and (200–1000 km) respectively and combine as a single F2-layer at night. This makes the F_2- layer most prominent of all the Ionospheric regions and also the most important region for radio propagation phenomena. It is also highly influenced by the sun's radiation. At night in low latitudes, the concentration does not fall steadily and may even increase during some periods. The electron density is generally much higher in low latitudes and maximum electron density appears at greater heights. The anomalous behaviour of F2-layer is due to drift motions of ionization in the magnetic field of the earth, driven essentially by electromagnetic (ExB) forces.

The critical frequency of the F2- layer (foF2) is the limiting frequency at which a radio wave is reflected by an ionospheric layer at vertical incidence. It is directly proportional to the amount of F_2- layer ionization. If the transmitted frequency is higher than this value (the plasma frequency)the wave penetrates through the ionosphere F-layer into outer space. Variations in the critical frequency as an important ionospheric parameter provide hints on the happenings within the F2-layer. Observations show that after sunrise foF2 rises, reaches to its maximum value in the early afternoon, and there is a rapid fall shortly after sunset. This layer of the ionosphere is affected by several influences such as solar wind, solar ionizing radiation, neutral atmosphere, geomagnetic activity and electrodynamics effects [27].

Ionospheric variability or deviation from climatological means is a pronounced and permanent feature of the ionosphere [31]. It can occur on hourly, daily, seasonal, and solar cycle scales. There have been a number of recent studies investigating the variability of the F2layer critical frequency of the ionosphere. These studies vary in terms of the specific ionospheric parameter whose variability is being investigated and in the latitudinal and solar cycle spread of the data used and the method used to describe the ionospheric variability for the study. Some of these studies include those of([21]; [16];[27];[22]; [18]; [4];[6];[5]) had investigated ionospheric variability of foF2 at equatorial and low latitude during high, moderate and low solar activity. They reported that equatorial foF2 variability increases with decreasingsolar activity. [1], worked on diurnal, seasonal and annual foF2 variability and response of the F2 layer height over Jicamarca during periods of low, moderate and high solar activities, found that the F2 layer critical frequency pre-noon peak increases by a factor of 2 more than the post noon peak as the solar activity increases i.e. the ionospheric F2 layer height rises to higher level with increasing solar activity. Studies on variability vary from those that analyze specific parameters on a large geographical area, to those that are limited to a few or one station. This work presents a study of the comparison of diurnal, seasonal and semi-annual variation of the variability (VR) of the critical frequency of the F2 layer (foF2) over Ilorin in the African sector and Jicamarca in the American sector and Okinawa in the Asian sector during solar minimum period. After Section 2 where we present the data used in the present study and our methodology, we present discussion of our results in section 3 and section 4 gives the conclusion of the paper.

2. MATERIAL AND METHODS

The data for this study are the F2-layer critical frequency (foF2)hourly values from Ilorin, Nigeria (Lat. 8.47ºN, 4.6ºE, dip 4.1ºS) in the African sector, Jicamarca, Peru (lat. 11.9ºE, long. 76.8ºE1ºE dip) in the American sector and Okinawa, Japan (26.3ºN, 127.8ºE, dip 36.8ºN). These stations lie along the equatorial anomaly except Okinawa stations which lies above the crest of equatorial anomaly. The data sets obtained from the Space Physics Interactive Data Resource (SPIDR) website (http://spidr.ngdc.noaa.gov) were routinely scaled with an accuracy of ±0.3 MHz at 95% confidence level. The study is for the year 2010, a period of minimum solar activity (with sunspot number Rz = 16.5. Only six-month data was available at Ilorin station during that period i.e. June to November 2010, hence the used of these six-month comparable data for the analysis in all the stations considered. Diurnal and seasonal effects are investigated by grouping data into seasons and finding the average of the months that fell in a particular season. Each season contains three months defined as follows; **March Equinox** (February, March, and April), **June solstice** (May, June and July), **September equinox** (August, September and October), and **December solstice** (November, December and January). March equinox was not considered for all stations due to lack of available data at Ilorin station for that season.

The relative variability (VR) is obtained by using the monthly mean, μ and the standard deviation, σ at each hour, adopting the paradigm of [16]; [27]; [7] and [1], assuming that the variations represent real changes in electron density and not just a redistribution of the existing plasma. Relative variability (VR) was computed using the relation below

$$VR\ (\%) = \left(\frac{\sigma}{\mu}\right) X\ 100 \qquad (1)$$

[5],[28],[29],[25] and [30] had made use of similar variability coefficient in studying ionospheric variability at some other ionospheric stations.

VR given by equation 1 has advantage over the one obtained from the quotient of interquartile range and median used by [32] and [13], though the latter is easier to interprete in terms of probability but it has the disadvantage of using only 50% of the data while the formal (equation1 used in this work) uses the whole data set. Relative variability is often expressed as a percentage. A lower percentage indicates that the data set is less varied; a higher percentage indicates the data set is more varied.

3. RESULTS AND DISCUSSION

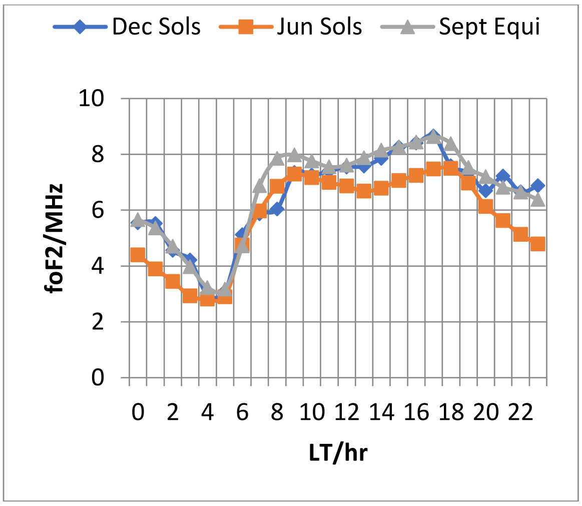

Figure 1: Diurnal variation of mean foF2 for all season during a year of minimum solar activity (2010) at Ilorin.

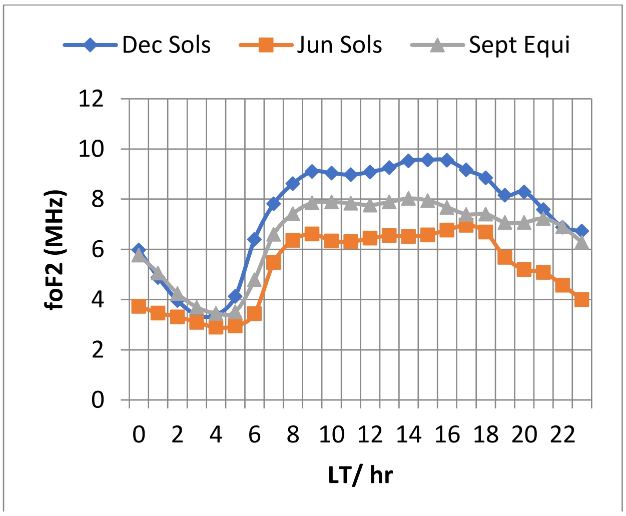

Figure 2: Diurnal variation of mean foF2 for all season during a year of minimum solar activity (2010) a Jicamarca.

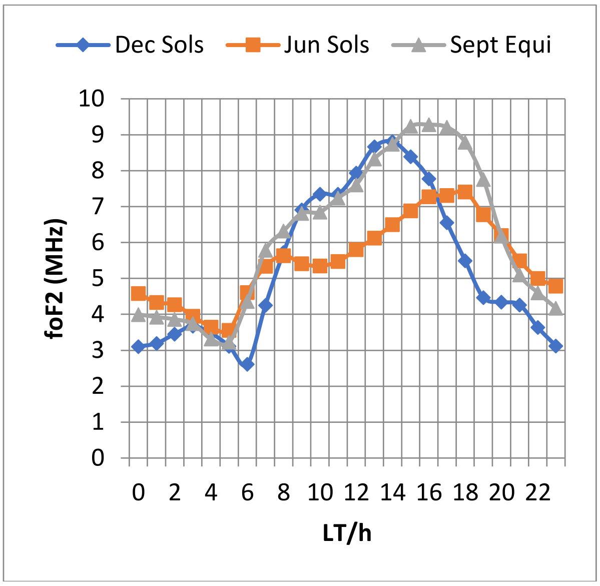

Figure 3: Diurnal variation of mean foF2 for a season during a year of minimum solar activit (2010) at Okinawa.

3.1 Diurnal and Seasonal Pattern in mean foF2 Variation

Figure 1, 2 and 3 revealed the diurnal plots of mean values of foF2 on seasonal scales against local time (LT) over Ilorin, Jicamarca and Okinawa F2 layer respectively during minimum solar activity year. On the average, the diurnal variations follow the same pattern during the entire three seasons covered by the data period used. All the plots are characterized by the same diurnal features, that is high mean values of foF2 during the daytime (0600 - 1800), with a typical maximum around noon (except at Okinawa where the maximum was observed after noon) and low mean values during the nighttime (1800 -0500 LT). Observations reveal two typical peaks (pre-sunrise peak and post- sunset peak). From Figure 1, 2 and 3, mean foF2 values increases from sunrise around 0500 LT and reaches its first peak (pre-noon peak) before 1200 LT around 0800 - 1000 LT for all seasons. The highest pre-noon peak magnitude of 8.0 MHz, was observed during September equinox while the least magnitude of 7.0 MHz was observed in June solstice (winter) at Ilorin while at Jicamaca and Okinawa, the highest pre-noon peak magnitude of 9.0 MHz and 7.0 MHz respectively were observed during December solstice and the least magnitude of 6.0 MHz in June solstice at both stations. Thereafter, there is a general daytime reduction in foF2, reaching a minimum between 1030 and 1200 LT. The highest reduction was yet again in June solstice, while the least was during the equinox (September equinox) and followed by December solstice (summer). Observations have shown that foF2 increases after sunrise; the increase being more prominent at lower and equatorial latitudes. Maximum is reached in the early afternoon and there is a rapid decrease shortly after sunset. This is due to variations of vertical **E** × **B** plasma drifts at the equatorial anomaly region [16]; [14]; [3]. Around local noon, the F2 ionosphere had reached a dynamic stability with respect to losses by recombination and production by solar radiation.

A second peak (the post-noon peak) was observed between 1400 and 1700 LT for the three stations with that of Okinawa being more pronounced. The magnitude of the post - noon peak was least during June solstice about 7.0 MHz for all the stations. It is highest during December solstice (9.0 MHz) and September equinox (9.0 MHz) respectively for Ilorin and Okinawa stations, and highest during December solstice (10.0 MHz) for Jicamarca station. For the nighttime variation of foF2 (1800 - 0600 LT), a general sharp drop is observed immediately after sunset. This sharp drop was around 1800 - 1900 LT. This decay is incessant during the entire season until around 0600 LT, 0500 LT and 0400 LT respectively for Okinawa, Ilorin and Jicamarca, at which time a pre-sunrise minimum occurs. For this nighttime happening, the critical frequency is lowest in June solstice (winter) and highest during the December solstice and September equinox for Ilorin and Jicamarca stations, but that of Jicamarca is more distinct. [23] reported that the F2 layer critical frequency during nighttime is lowest in June solstice and highest during the equinoctial months. Okinawa station shows a contrary observation during this nighttime i.e. it was lowest in December solstice and highest during June solstice. The reason for this is that Okinawa is geographically located above the northern crest of the equatorial anomaly ([8]; [9]).

[11] reported that the foF2 maximum is controlled by enhanced eastward electric fields (EEF) and neutral winds, and this may be supported by diffusion of super fountain plasma from the equator towards Okinawa (a little above the crest of equatorial anomaly). This diffusion according to [10] may be so strong through wind systems to bring out fountain effects, to the extent of transporting ionization over the anomaly crests off-equatorial locations, as in the case of Okinawa.

Both the observed pre-noon and afternoon foF2 peaks in the F2-layer and the variability are due to variations of vertical **E** × **B** plasma drifts ([14]; [16]; [3]). For this minimum solar activity period, (Figures 1, 2 and 3), the post-noon peak otherwise known as the afternoon peak is slightly greater than the pre-noon peak for the three stations, though that of Jicamarca seems nearly equal in appearance. [26] reported similar observation for Ouagadougou (12.4°N, 1.5°E; dip 5.9°) an equatorial station, during a low solar activity year.

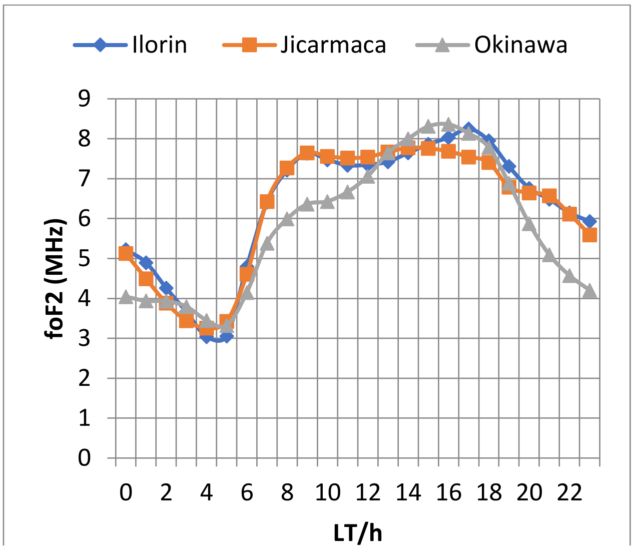

Figure 4: Diurnal variation of mean foF2 values derived from semiannual mean of foF2 values for all seasons during a year of minimum solar activity (2010) at Ilorin, Jicamarca and Okinawa

3.2 Semiannual Variation of Mean foF2

Presented in Figure 4 is the diurnal variation of mean foF2 derived from the semi-annual average values for all the seasons during the year under consideration. The plots show the same diurnal features observed in Figure 1, 2 and 3 though with very little difference among the stations. High mean values of foF2 during the daytime, with typical maximum around noon and low mean values during nighttime. Observation from Figure 4 also depicted two characteristics peaks (pre-noon and post-noon peaks). For Ilorin and Okinawa stations, the post-noon peak recorded an average magnitude of 8.0MHz for both stations. This is higher than the pre-noon peak of magnitude 7.3MHz and 6.0 MHz respectively at these stations. Meanwhile at Jicamarca station, both the pre-noon and post-noon peaks recorded an approximate average value of 8.0MHz.These results for low solar activity period (2010) are closely in agreement with the results reported by Adebesin et al., 2014 using average values for low solar activity years of 2009 and 2010. For all four plots (Fig. 1, 2, 3 and 4), we observed the noon bite-out profile characterized by the presence of the strength counter electrojet (SCE), a phenomenon associated with the magnetic equatorial region [15]; [12]. The noon bite-out feature occurred at the three stations after 1200 LT and the lowest minimum 7.0 MHz, 6.3 MHz and 7.0 MHz at Ilorin, Jicamarca and Okinawa respectively were observed during June solstice.

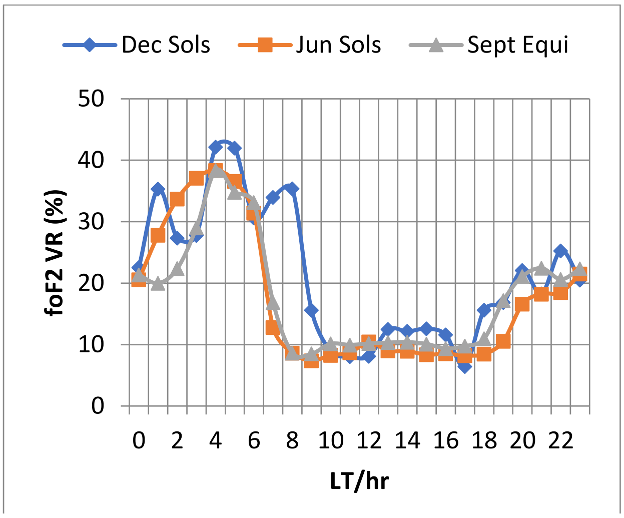

Figure 5: Diurnal variation of foF2 VR for all season durin a year of minimum solar activity (2010) at Ilorin.

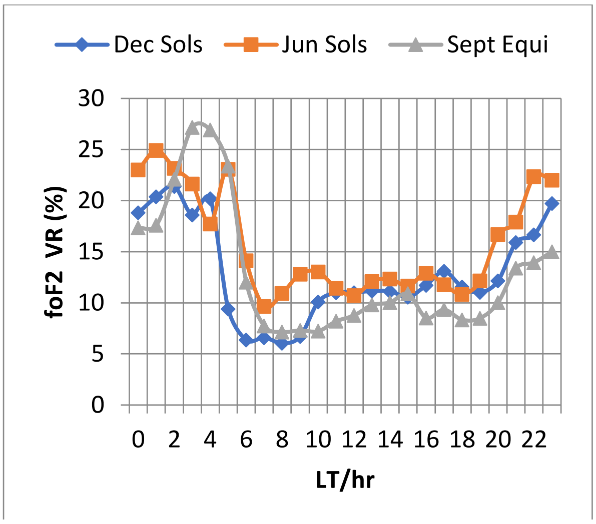

Figure 6: Diurnal variation of foF2 VR for all season du a year of minimum solar activity (2010) at Jicamarca.

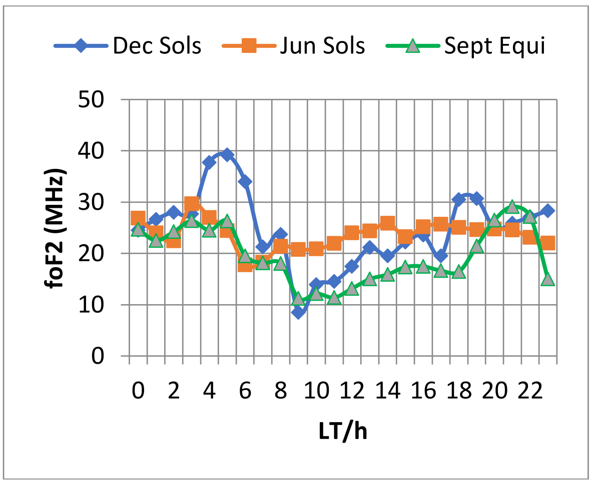

Figure 7: Diurnal variation of foF2 VR for all season during a year of minimum solar activity (2010) at Okinawa.

3.3 Variability Pattern in foF2 (Diurnal and Seasonal Variation)

Figure 5, 6 and 7 revealed the diurnal and seasonal variation of the variability of F2 layer critical frequency (foF2 VR) obtained from equation 1 and plotted against local time (LT) over Ilorin, Jicamarca and Okinawa respectively. On a general consideration, all the plots in Figures 5, 6 and 7 reveal the same diurnal features during the entire three seasons. foF2 VR is observed to be high during nighttime and low during the daytime. However, in Okinawa station, a noticeable difference in foF2 variability pattern was observed on comparison with the patterns observed at Ilorin and Jicamarca stations. During the daytime (0600 – 1800 LT) the variability VR was observed to be lowest about (6 - 16%) for Ilorin, (6 – 13%) for Jicamarca and (8 – 25%) for Okinawa. At nighttime, the variability had increased to about (16- 43%) at Ilorin, (13 - 27%) at Jicamarca and about (25 – 39%) at Okinawa. The plots are characterized by two peaks, the Pre-sunrise peak with a magnitude of about (20 - 43%), (17 - 27%) and (22 – 39%) respectively at Ilorin, Jicamarca and Okinawa were observed between 0000 and 0500 LT for all seasons. The second peak (the post-sunset peak) with a value of about (15 - 25%), (15 -22%) and (20 - 31%) were observed between 1800 and 2300 LT at Ilorin, Jicamarca and Okinawa respectively for all seasons. For the pre-sunrise peak, the highest value of 43% was observed during December solstice (summer) followed by June solstice 38% and September equinox (38%) at Ilorin station while at Jicamarca the highest value of 27% was observed during September equinox, then June solstice (25%) and least in December solstice (21%) and at Okinawa, the highest value of 39% was observed during December solstice (summer) followed by June solstice (30%) and then September equinox (29%). For the post-sunset peak at Ilorin, the highest value of 25% was recorded in December solstice; this is followed by September equinox (20%) and least by June solstice (21%). At Jicamarca, the highest value of the post-sunset peak was noticed in June solstice (22%), then December solstice (20%) and least by September equinox (15%) while at Okinawa, the highest value of 31% was observed during December solstice, followed by September equinox (29%) and lowest by June solstice (25%).In all the seasons, post-sunset peak is lower than pre-sunrise peak. The cause of these two foF2 variability peaks observed are attributed to sudden 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 ([11]; [6]; [2]), In addition the vertical **E** × **B** plasma drift is also responsible for these observed peaks. [11] explained the observed increase in the foF2 VR with decreasing solar activity in terms of low reference value and ion loss. That at night the ionospheric density was largely dependent on the recombination rate of ions, which could be affected by the gas composition and the magnetic meridional winds.

The daytime minimum foF2 VR of between 6 and 16% observed during this minimum solar activity period is consistent with the result of [7] who recorded a value range of 5 -15% over two African equatorial stations of Ouagadougou and Korhogo (Lat. 9.3◦N, long. 5.4◦W, dip 0.67◦S); as well as the results of [24] who recorded 3 -10% for the same daytime period while investigating another equatorial station in the African region, during low solar activity periods.

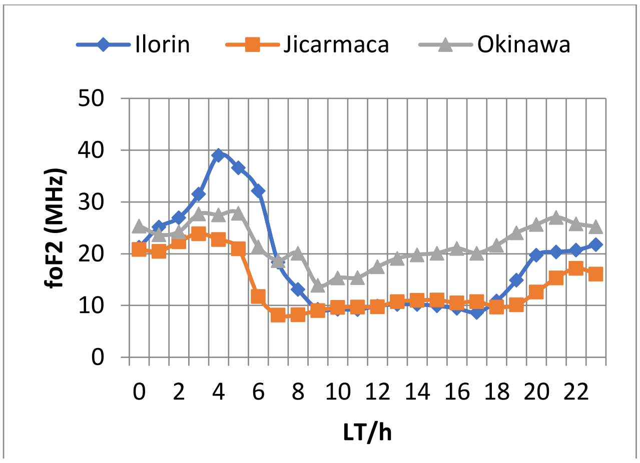

Figure 8: Diurnal variation of mean foF2 VR derived fro semi-annual mean of foF2 values for all seasons during year of minimum solar activity (2010) at Ilorin, Jicamarc and Okinawa.

3.4 Semi-annual Variation of foF2 VR

Presented in Figure 8 is the diurnal plot of foF2 VR derived from semi-annual means for Ilorin, Jicamarca and Okinawa stations during minimum solar activity. From Figure 8, we observed that the variability is higher in the nighttime (13 - 39%) than the daytime (8 - 13%). This is because at night, the ionospheric electron density is dependent on the recombination rate, which is influenced by the gas compositions [11] and equatorial electric field (EEF). At the equator, EEF causes vertical **E** × **B** plasma drift enhancement to altitude above F2-peak [17]. The EEF is caused by the tidal winds in the E region, which drive ionospheric currents to higher latitudes. This current in turn interacts with the Earth's magnetic field and results in a building of positive and negative changes at the dawn and dusk terminal, respectively. Gravity waves had also been suggested to be another factor that could be responsible for the nighttime ionospheric density gradient enhancement. Hence, the reason for the observed higher variability in foF2 at nighttime rather than during daytime. However, observations from the plots showed that foF2 VR increases clearly as the solar ionization decreases. The daytime foF2 VR for Ilorin and Jicamarca stations recorded approximately the same minimum value of about 9 - 11% between (0900-1800 LT) while that of Okinawa station recorded a minimum value of about 14 – 20% for this period. The highest values of the pre-sunrise peaks from Figure 8 are 39%, 24% and 28% at Ilorin, Jicamarca and Okinawa respectively, while the pre-sunset peaks are respectively 20%, 17% and 27% for Ilorin, Jicamarca and Okinawa. Figure 8 clearly revealed that relative variability foF2 at Ilorin is highest, followed by that at Okinawa and least at Jicamarca. Moreover, the study revealed that Okinawa data are characterized by higher absolute values of foF2 in comparison with data from Ilorin and Jicamarca. It is clear from the study that Okinawa data showed unusual features that required further study. Thus the analysis of a large volume of data from Okinawa station will be necessary to ascertain clearer characteristics of its ionospheric foF2 variability.

4. CONCLUSION

We have carried out investigation on comparison of the diurnal, seasonal and semiannual variation of mean foF2 and foF2 VR over the F2 layer at equatorial stations of Ilorin, Jicamarca and Okinawa in the African, American and Asian sectors respectively during minimum solar activity year 2010, with annual mean sunspot value (Rz) = 16.5. Diurnal curves of mean foF2 revealed pre-noon and post-noon peaks at all three stations, with Jicamarca having highest values for both peaks during December solstice while the semiannual curves of mean foF2 values with the exception of Okinawa station, showed almost equal peaks values for Ilorin and Jicamarca stations. Noon bite - out lowest minimum for the three stations were observed during June solstice around 1200 LT. Diurnal analysis revealed that the critical frequency of the F2 layer is more prone to variability (VR) during the nighttime than the day time at these stations, with two characteristics peaks, post-midnight peak and pre-midnight peak. The peaks at Ilorin (20 - 43%, 16 - 25%) are observed to be highest in values than those at Jicamarca (17 - 27%, 15 - 22%) and Okinawa (22 - 39%,15 - 30%). Seasonally, December solstice maximum was noticed at Ilorin. Semiannual analysis showed that foF2 VR is highest at Ilorin, followed by Okinawa and least by Jicamarca station during the nighttime. Overall, foF2 variability is highest at Ilorin and lowest at Jicamarca while for F2 layer ionization the reverse is the case.

ACKNOWLEDGEMENTS

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

AUTHORS' CONTRIBUTIONS

Eugene Onori designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. All other authors managed the literature searches, read and approved the final manuscript.

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