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Quiet-time foF2 characteristics at an equatorial station in the African sector

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Abstract

A study on the morphology of the critical frequency of the F2 layer (foF2) has been done using data obtained with Ionospheric Prediction Sounder (IPS-42) located at Ouagadougou, Burkina Faso (geo. Lat. 12.4^0N, Long. 358.5^0, magnetic dip latitude 5.9^0N) an equatorial station in the West African sector. Data covering a whole solar cycle period from 1985 – 1995 were used to characterize the quiet time morphology of the F2-layer for that region. Results show that foF2 exhibit diurnal, seasonal and solar activity dependence. Diurnal morphology of foF2 is characterized by two peaks; pre-noon and post-noon peaks with the presence of noon-time "bite-out". While the pre-noon peak is more pronounced during high solar activity periods, the post-noon peak is dominant at low solar activity. Also, while the post noon peaks are more pronounced at equinoctial months during low solar activity, the pre-noon peak is more pronounced at the solstices during high solar activity periods.

Keywords: equatorial ionosphere, critical frequency; solar activity

1. Introduction

The critical frequency of the F2-layer, foF2 is one of the parameters for describing the F2 layer of the ionosphere. Critical frequency is the limiting frequency at which a radio wave is reflected by the ionospheric layer at vertical incidence. As a result, knowledge of mean value of critical frequency and the level of variations is of vital importance to radio propagation. The F2-layer, being the layer richest layer in electron density, is the highest layer for bottom-side radio wave propagation and is subject to spatial-temporal variations.

The equatorial ionosphere, in particular, has also presented interesting features such as equatorial ionization anomaly (such as December/winter anomaly), the fountain effect and equatorial spread F which are not common to other latitudes as a result of the orientation of the geomagnetic field in that region (Olawepo and Adeniyi, 2012; Olawepo *et al.*, 2015).

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For instance it has been observed that the equatorial F-layer displays striking variations in electron density and height, especially before sunrise and around sunset (Rishbeth, 2000). All these point to the fact that high frequency radio propagation around the equatorial and low latitude will be quite challenging.

Efforts have been on to develop models that will describe and predict the features of the equatorial ionosphere, especially in Africa (e.g. Bilitza and Reinnisch, 2008). Various scientists such as Adeniyi *et al.* (2003), Adeniyi *et al*. (2005), Ouattara *et al*. (2009) and Gnabahou *et al*. (2013) have studied the equatorial ionosphere over Ouagadougou with different objectives. The aim of this paper is to examine the characteristic features of foF2 during quiet time of different solar activities. While the focus of Adeniyi *et al.* (2003) was the comparison of the F2-peak parameters with the IRI model, Adeniyi *et al.*, 2005 examined the variability of the critical frequency, foF2 of the F2-layer and the statistical method of describing the observed variability. Ouattara *et al*. (2009) studied the morphology of the various parameters of the F2-layer and Gnabahou *et al*. (2013) studied the secular displacement of foF2 as one moves away from the dip equator. One thing common to all these studies is that none of them used data obtained from Ilorin. This is the first time detailed attention will be given to foF2 characterisation for this particular station, previous work by authors mentioned above have different foci and objectives.

2. Materials and Methods

The data used in this study were obtained from ionogram recorded by Ionospheric Prediction Sounder (IPS - 42) located at Ouagadougou, Burkina Faso, an equatorial station with geographical latitude 12.4^0N, longitude 358.5^0 and dip latitude 5.7^0N. *foF2* values were extracted from the routinely scaled ionograms. Though ionograms were recorded at 15 minutes intervals, only the hourly values selected for each of the months studied. Data used were those of the entire period of solar cycle 22 i.e. from 1985 to 1995. Only data for magnetically quiet days (i.e. $Ap < 26$) were used. The data were subjected to graphical analysis which enabled the investigation of the diurnal, seasonal and solar cycle variations of the parameter.

In order to study the seasonal variations, the twelve months of the year was grouped into four different seasons namely: (i) 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). Table 1 shows the years and their 12 month running mean of the sunspot number (obtained from NASA) and the solar activity groupings. The years are classified into three solar activity periods based on the yearly sunspot number, SSN. Years with SSN > 100 are classified as High Solar Activity periods (LSA), years having 50 ≤ SSN ≤ 100 are Moderate Solar Activity (MSA) and years SSN ≤ 50 are Low Solar Activity (LSA) years. The rate of decay of foF2 is obtained using the relation $Rate\ of\ decay = \frac{\Delta y}{\Delta x}$ where y is foF2 and x is LT.

Table 1: Year and sunspot number.

Year	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
SSN	17.9	13.4	29.4	100.2	157.6	142.6	145.7	94.3	54.6	29.9	17.5
Category	Low	Low	Low	High	High	High	High	Moderate	Moderate	Low	Low

3. Results and Discussion

3.1 Results

a) Diurnal characteristics

Fig. 1 shows typical plots of foF2 during each of the solar activity periods. In each case of LSA, MSA and HSA period, foF2 begins to rise from its pre-sunrise minimum at sunrise hour (0600 LT), attains a pre-noon maximum around 0800 -1000 LT followed by a noon 'bite-out' (drop in foF2) between 1000 LT and 1200 LT. This is then followed by a post noon maximum occurring around 1600-1800 LT. A night-time minimum (around 2000-2200 LT) is also observed to precede night-time maximum (around 2300 and 0100LT). The diurnal features of foF2 show three attributes namely the noon bite-out, the post sunset maximum and the night-time minimum. The intensities of these attributes increase with increase in the SSN. This implies that the diurnal variation is solar cycle dependent.

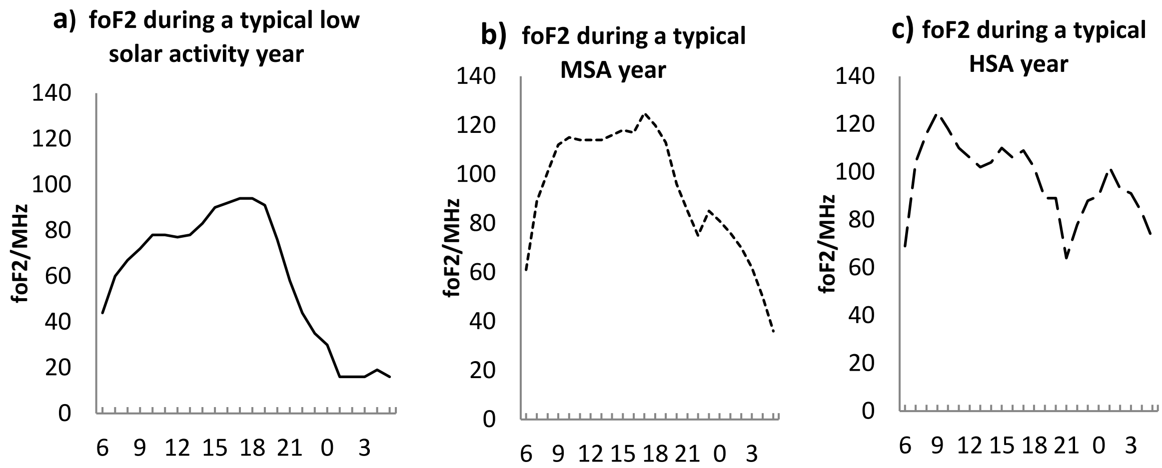

Fig. 1: Plots showing typical diurnal variation in foF2 at different solar activity periods.

b) Seasonal characteristics

Fig.2 shows the seasonal plots of foF2 for the four seasons of year for all the years within the solar cycle 22. The plots further revealed the solar cycle dependence of foF2. The values of foF2 were highest at HSA and lowest during LSA. Bite-outs were prominent in the equinoctial months, with the pre-noon peaks forming between 0800-1000LT (see Fig.2 (a) and (c)). Post sunset minimum and night-time peaks were also more prominent during MSA and HSA periods, occurring between 1800 and 2200 LT at the equinoxes and between 1800 and 2000LT during December solstice. These features were absent during the LSA periods and throughout June solstice (irrespective of the sunspot number). Another observable feature is the rate of decay in foF2 which is observed to be faster during high solar activity periods compared to that of low solar activity period. Fig.3 shows the plots of the comparisons of the seasonal variations in foF2 during the three solar cycle periods. The results revealed that for LSA (Fig.3a), foF2 values were higher during equinoctial months than the solstices. Minimum value of foF2 during sunset (hours after 0600LT) period was prominent only in March equinox while it was completely absent during June solstice. The rate of decay is also observed to be faster in June solstice. At MSA (Fig.3b), foF2 values were highest during March equinox followed by December Solstice. Noontime bite-out and minimum values during the hours after sunset were quite observable during this period. During the period of high solar activity (Fig.3c), December solstice had the highest values during daytime while night-time values were highest during March equinox. June solstice had the lowest values at all the solar activity periods.

Fig. 4 shows the variations of foF2 over the seasons during the three solar activity periods. The characteristics features displayed are summarised in Table 2. From the table, the features that characterize foF2 include pre-noon maximum, noon time bite-out, sunset maximum, post-sunset minimum and night-time maximum values. These features are either present (with varying degrees of intensity) or absent depending on the season/solar activity.

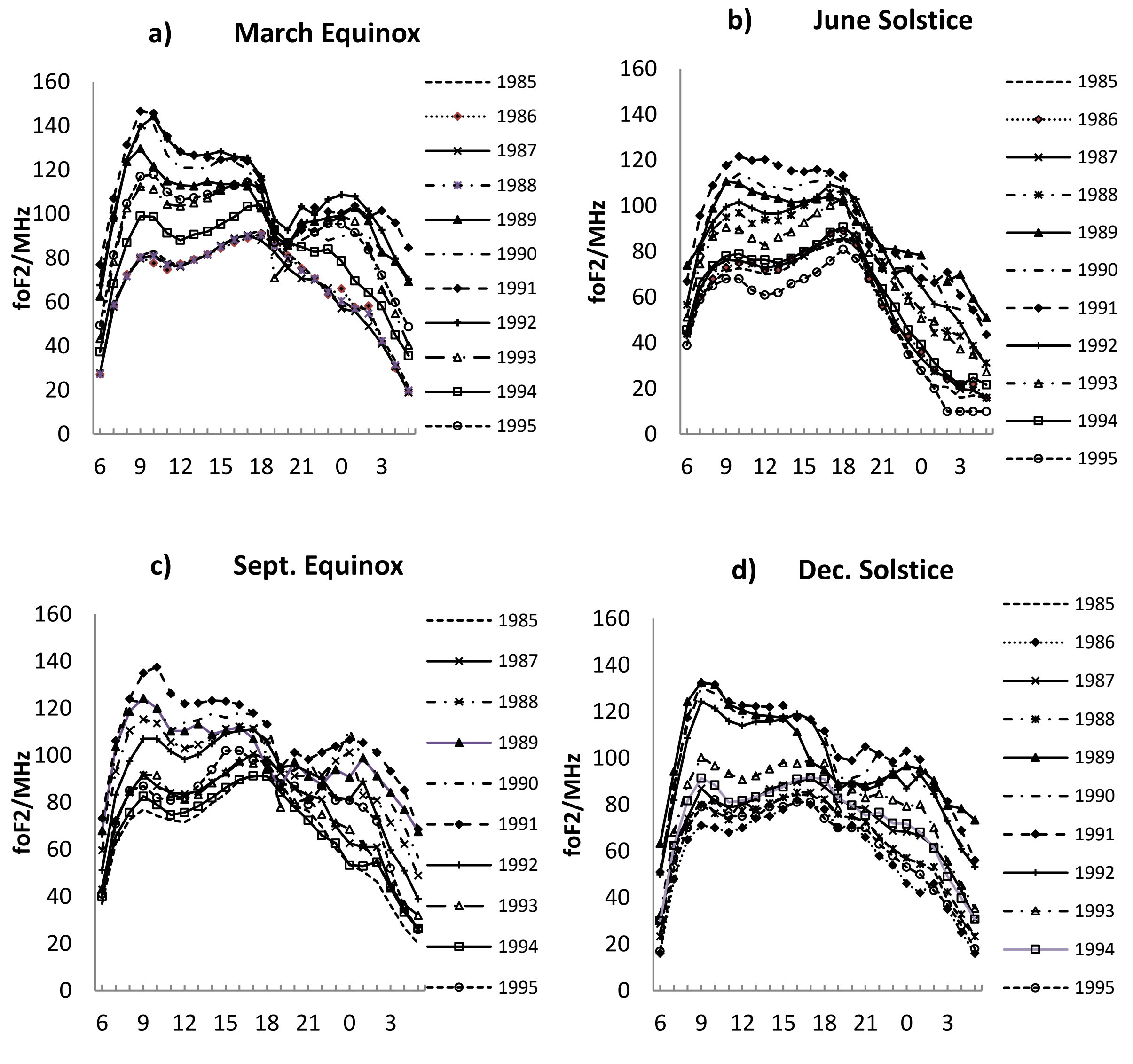

Fig.2: Seasonal variations in foF2 for all the years of the solar cycle (22) showing its solar cycle dependence.

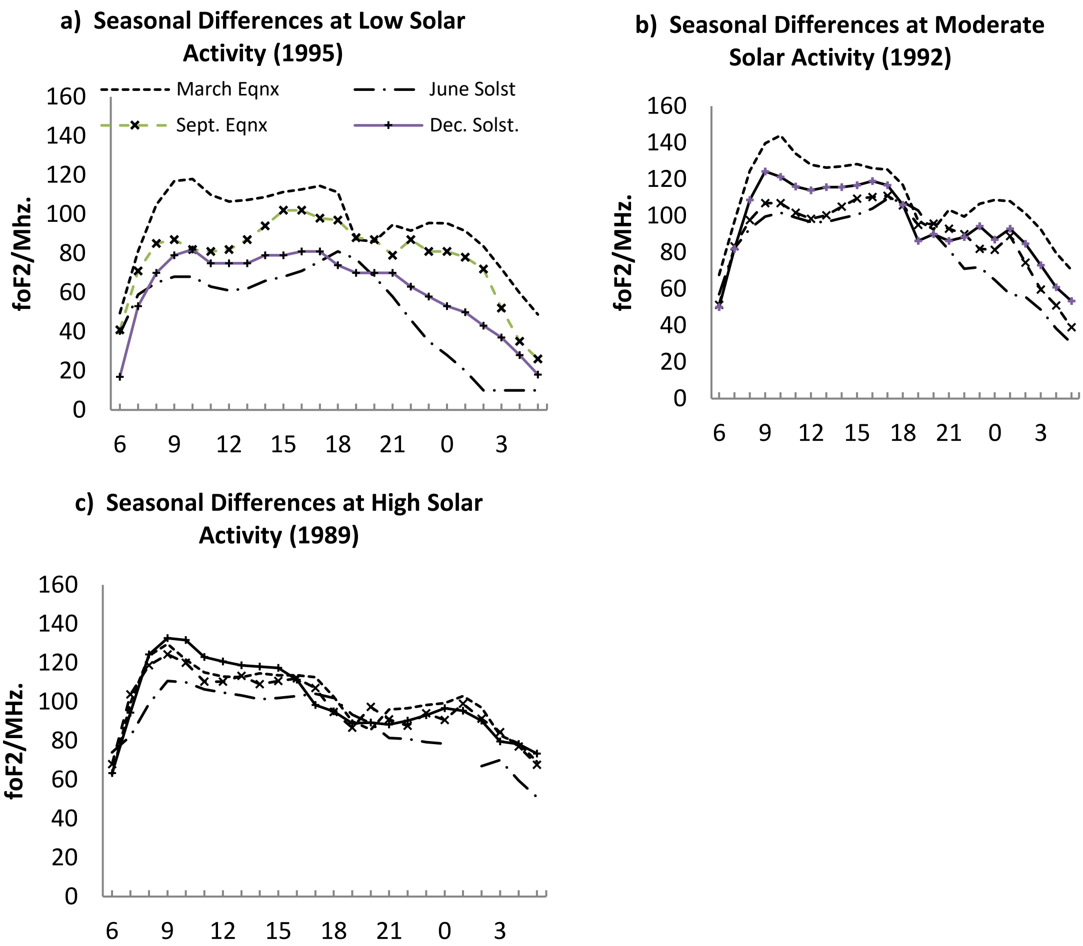

Fig. 3: Seasonal differences in the variation of foF2 at different solar activities.

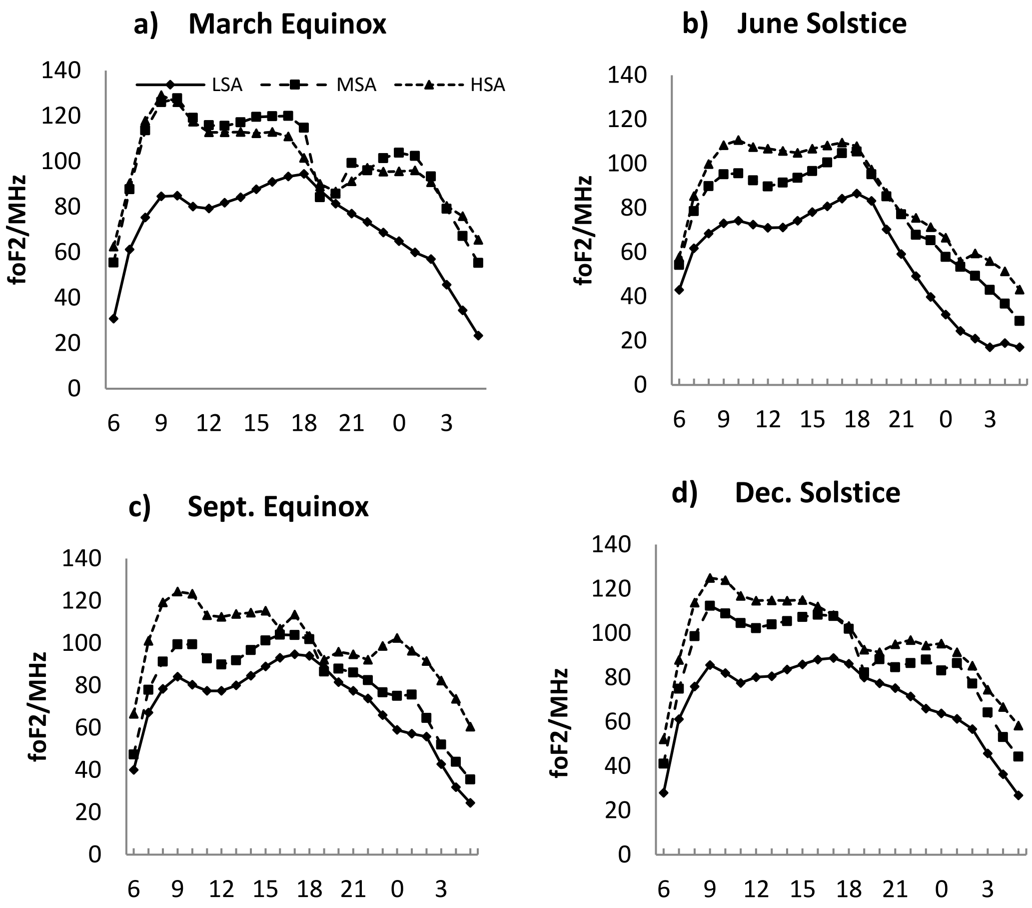

Fig. 4: Features of foF2 at different seasons over the solar activity periods.

c) Annual variation in foF2 and sunspot number.

Fig.5a-5c are plots relating foF2 to solar activity. Fig 5(a) shows that daily variation in foF2 exhibits solar cycle dependence. The dependence of foF2 on solar activity is obvious as shown by three groupings of the annual plots; plots of foF2 during high solar activity years are seen to be having the highest values followed by the years of medium solar activity while foF2 for the years of low solar activity are having the lowest values. Fig.5 (b) shows that variations in foF2 follow the same trend with the 11-year solar cycle. Higher values of foF2 are observed during years of HSA while lowest values of foF2 are observed during low solar activity years. This further confirms the dependence of foF2 on solar activity. Fig.5 (c) shows the correlation of SSN with foF2 with a second order polynomial relationship yielding a correlation coefficient R = 0.836. Although, a linear regression yields approximately the same value, we have used the quadratic fitting based on Huang, 1967. These results show clearly that although the F2-layer in the equatorial region is subject to factors based on the horizontal inclination of the geomagnetic field such as the fountain effect and other transport mechanisms, foF2 still exhibit dependencies on the solar cycle.

Table 2: Summary of characteristic features of foF2 at Ouagadougou.

Feature	Solar Activity	March Equinox	June Solstice	Sept. Equinox	Dec. Solstice
Prenoon peak	LSA	Present but lower than postnoon peak	Present but lower than postnoon peak	Present but lower than postnoon peak	Present, prominent
	MSA	Present, prominent, higher than postnoon peak	Present, prominent, lower than postnoon peak	Present, prominent, lower than postnoon peak	Present, prominent, higher than postnoon peak
	HSA	Present, prominent, higher than postnoon peak	Present, prominent, higher than postnoon peak	Present, prominent, higher than postnoon peak	Present, prominent, higher than postnoon peak
Bite-out	LSA	Present	present, not prominent	present, prominent	present, prominent
	MSA	Present, not prominent	present	Present, not prominent	present
	HSA	Present	Present, not prominent	Present, not prominent	present
Sunset peak	LSA	Present	present, not prominent	present, prominent	present
	MSA	Present, highest	present	present	present
	HSA	Present	present, not prominent	present	present, not prominent
Post sunset minimum	LSA	Absent	Absent	Absent	Absent
	MSA	Present	Absent	present	present
	HSA	Present	Absent	present, not prominent	present
Night-time peak	LSA	Absent	Absent	Absent	Absent
	M	Absent	Absent	Absent	Absent
	HSA	Absent	Absent	Absent	Absent
Others	LSA	Lowest values at all time	Lowest values at all time	Lowest values at all time	Lowest values at all time
	MSA	Post-noon values are higher than HSA			
	HSA				

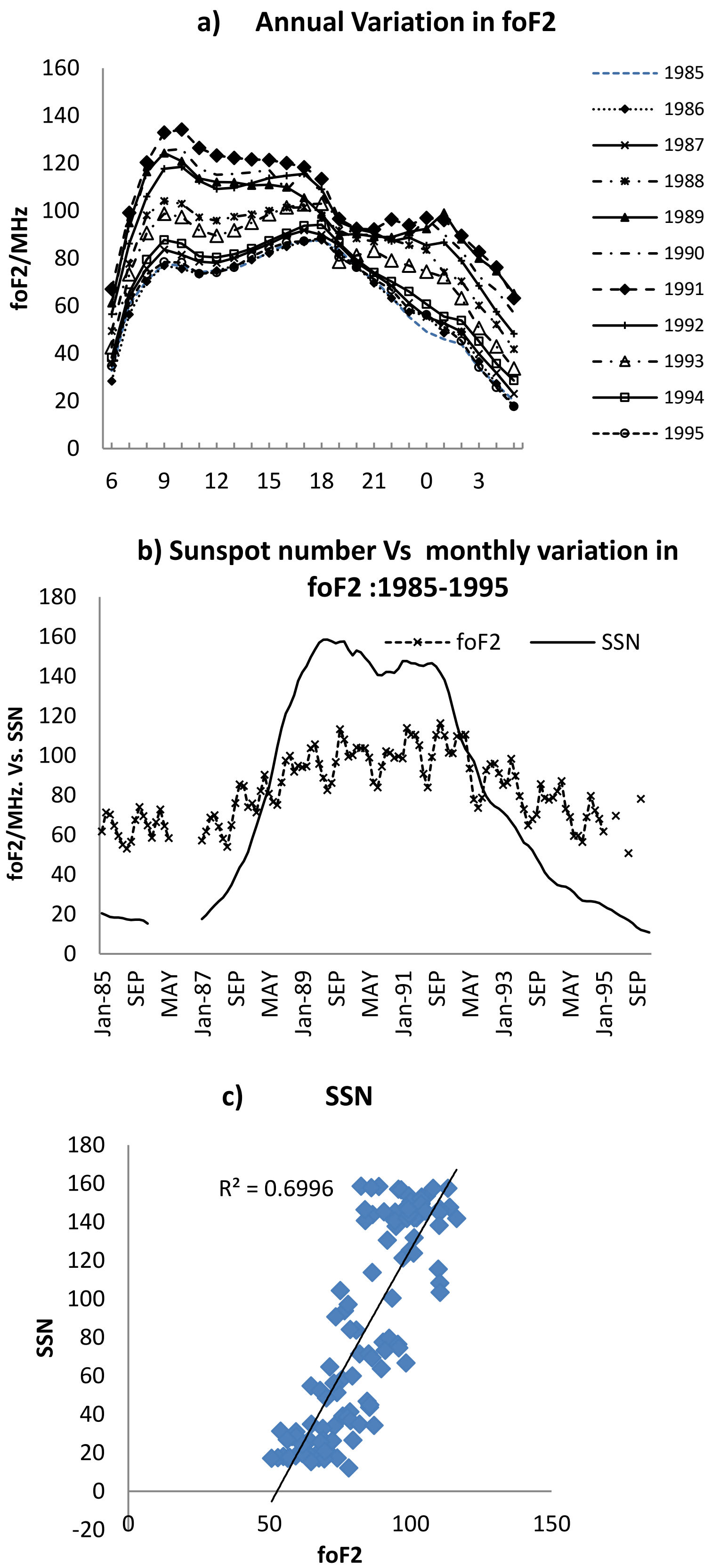

Fig.5: Plots showing (a) Annual variations in foF2 revealing the three solar activity periods (b) comparison of the variation in fo2 with sunspot number and (c) the correlation of variations in foF2 with sunspot number.

3.2. Discussion

It is well known that the ionosphere is solar driven, (Rishbeth, 2000, Olawepo and Adeniyi, 2014) although other factors come into play at the F-region. The diurnal features observed in foF2 in this study is reflective of the daily variation in the intensity of solar radiation, which increases with solar zenith angle with time of day from the sunrise hour to sunset hour. During this time interval also, there is a rise in the height of the F2 layer, showing that electrons are being moved to a region of lower loss rate by recombination. The presence of pre noon peak and noon bite-out or a decrease in foF2 between 1000LT and 1200LT indicates that electrons are moving up and away from the equator and that the depletion of electrons during the daytime around noon is maximum which has been attributed to the symmetrical nature of the meridional wind system (Rishbeth, 2000). This situation generally favours the formation of a maximum foF2 before noon and a minimum around midday. The mechanisms responsible for the bite-out have been adequately treated by Adeniyi and Radicella (1999) and Bolaji *et al.* (2013) and would not be repeated here. Results on the seasonal variations revealed evidence of December/Winter anomaly. The anomaly grows with increase in solar activity; while it is non-existent during LSA, it shows up during MSA period and became prominent at HSA. This results is consistent with Huang (1967), Ana and Garat (1997), Rishbeth (2000), Liu *et al.* (2009) and Ouattara *et al.* (2009). According to Ana and Garat (1997), winter anomalies are directly connected with solar activity. Ouattara *et al.* (2009) (and references therein) attributed it to the Sun – Earth distance. The anomaly, according to Ana and Garat (1997) is always present in the northern hemisphere irrespective of sunspot number, but usually absent in the southern hemisphere during periods of low solar activity. According to Rishbeth (2000), winter is not really a geomagnetic effect. It is thought to be attributed to neutral composition changes in the F region caused by convection of atomic oxygen from summer to winter hemisphere (Ana and Garat, 1997). Annual variation in foF2 generally exhibits solar cycle dependence. This finding corroborates the results obtained by authors such as Ouattarra *et al.* (2009) who working with Ouagadougou data from 1966 to 1998 discovered among other things that foF2 was solar cycle dependent with a correlation coefficient of 0.951. However, the result obtained herein further refines the result obtained by Ouattara *et al.* (2009) in which only yearly averages of foF2 were correlated with sunspot numbers in a linear relationship. According to Huang, 1967, in order to be able to reduce error of prediction, quadratic regression should be preferred.

4. Conclusion

A study of the characteristics features of the critical frequency foF2 have been carried out, using data covering the entire solar cycle 22 obtained from the ionosonde at Ouagadougou, an equatorial station in the African sector. The results obtained can be summarised as follows:

1. The critical frequency of the F2-layer of the equatorial ionosphere exhibits diurnal, seasonal and solar cycle dependence.
2. Diurnal variation in foF2 is characterized by pre-noon peak, occurrence of bite-outs before noon, sunset maximum followed by post sunset minimum and night-time maximum. Night-time peak is prominent at MSA and HSA.
3. Bite-outs are prominent during the equinoxes and December solstice.
4. Bite-outs are not well formed and sunset minimum are absent in June solstice.
5. December/winter anomaly is evident during high solar activity.
6. foF2 values are generally high during March equinox except during HSA when there is the occurrence of December anomaly.
7. Value of foF2 increases with increase in solar activity being lowest at LSA. The rate of decay is also highest during HSA.

It can therefore be concluded from the results obtained in this study that the F2-layer of the equatorial ionosphere is subject to different degrees of variations ranging from day-to-day to 11-year solar cycle. These variations cannot be unconnected with the orientation of the geomagnetic field within the latitudinal range.

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