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foF2 Long Term Trends at Ouagadougou Station

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Author's contribution

Frédéric Ouattara designed the study, performed the statistical analysis and managed the analyses of the study, wrote the protocol and the first draft of the manuscript, and managed the literature searches.

Research Article

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ABSTRACT

A trough station (Ouagadougou station) of African Equatorial Ionization Anomaly sector foF2 long term trends are carried out after the elimination of solar cycle long term variation part. For this part, foF2 is expressed as a third degree polynomial function of Rz. We analyzed diurnal, seasonal and annual foF2 long term trends during 30 years covering the period 1966-1996. Diurnal trend variation showed positive hourly trend at the morning (slope maximum value at 0400 LT: + 1.5 x 10^{-3} per year) and at night (slope maximum value at 2200 LT: + 0.7 x 10^{-3} per year). During night and morning times well correlation is observed between foF2 and Ap. The absolute maximum trend is observed at 1900 LT (+ 2.5 x 10^{-3} per year). Seasonal variation at 1900 LT exhibited for each season positive trend except during summer where negative trend was observed (-0.0472 per year). At equinoxes, there is no asymmetry and foF2 trend is + 0.0412 per year. Annual investigation showed that from 1966 to 1981 Ap and foF2 present the same sense variation while from 1981 to 1966 it is the reverse. At 0400 LT, between 1966 and 1981 relative foF2 presents positive trend (+5.4 x 10^{-3} per year) and between 1981 and 1996, it shows negative trend (- 5.3 x 10^{-3} per year). At 1900 LT, for the 30 years involved, relative foF2 shows strong negative trend (- 6.5x 10^{-3} per year).

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1. INTRODUCTION

For the interest of climate changes, the investigation of long term variations of atmosphere and ionosphere parameters plays a key role. Therefore, during the last decades, ionosphere parameters long term trends have been intensively study (e.g. Givishvili and Leshchenko, 1994; Danilov, 1998; Risbhbeth, 1997; Bremer, 1998, 2001, 2004; Danilov and Mikhailov, 1999; Danilov and Mikhailov, 2001; Marin et al., 2001; Danilov, 2002, 2003; Lastovicka et al., 2006, 2008; Yue et al., 2006; Jarvis, 2008; Bremer and Peters, 2008; Elias, 2009; Cnossen et al., 2011). Nowadays four possible mechanisms must be used to explain F2 region trends (see Elias, 2011): (1) solar cycle long term variation, (2) geomagnetic activity long term variation, (3) increasing greenhouse gases concentration and (4) secular variation of the Earth's main magnetic field. It can be added to the third mechanism ozone decrease and as Elias (2009) asserted the interaction between the all mechanisms involved must be considered. Therefore, the authors who work in ionosphere long term investigation can be separated into three worked groups. It is important to note that whatever the group solar cycle long term variation trend part is always removed in the whole trend before analyzing ionosphere long term trend. The following first group of authors lies the trends to geomagnetic activity long term variation (Mikhailov and Marin, 2000, 2001; Danilov and Mikhailov, 2001; Martin et al., 2001; Danilov, 2002, 2003; Xu et al., 2004; Yue et al., 2006); the following second group links ionosphere trends to the increasing greenhouse gases concentration and ozone decrease (e.g. Upadhyay and Mahajan, 1988; Roble and Dickinson, 1989; Rishbeth, 1990; Rishbeth and Roble, 1992; Bremer, 1992; Ulich and Turunen, 1997; Jarvis, 1998; Akmaev and Fomichev, 2000; Bremer and Berger, 2002; Hall and Cannon, 2002; Akmael et al.; 2006; Bremer, 2008; Bremer and Peters, 2008) and the last third group expresses the trends by the secular variation of Earth's magnetic field (Foppiano et al., 1999; Elias and Adler, 2006; Cnossen and Richmond, 2008; Yue et al., 2008; Elias, 2009; Cnossen et al., 2011; Elias, 2011).

For removing solar cycle long term variation from foF2 long term variation several expressions of the dependence between foF2 and sunspot number (Rz) are used: (1) Elias and Adler (2006) and Elias (2009, 2011) used linear dependence between foF2 and sunspot number (Rz); (2) Bremer (2001) and Bremer (2004) used second degree polynomial function of Rz and (3) third degree polynomial function of Rz is also utilized (e.g. Danilov and Mikhailov, 1998, 1999, 2001; Mikhailov and Marin, 2000, 2001; Danilov and Mikhailov, 2001; Martin et al., 2001). Instead of Rz Danilov (2000, 2003) used the activity index E81 closely related to solar UV radiation. For removing both solar cycle and geomagnetic long term variations (1) Bremer and Peters (2008) used double linear dependence of ionosphere parameters (foE, hmF2) with Rz and geomagnetic activity index Ap; (2) Mikhailov and Marin (2000, 2001) utilized ionosphere parameters as a third degree polynomial function of Rz and sometime combining with linear or 12 monthly running expression of Ap and (3) Danilov and Mikhailov (1999, 2001) and Martin et al. (2001) used ionosphere parameters as a third degree polynomial function F10.7 (solar radio noise at λ=10.7 cm) or E10.7 (extreme ultraviolet solar irradiance index) and sometime combining with linear or 12 monthly running expression of Ap. As it has been pointed out by Xu et al. (2004), Bremer et al. (2004) and Lastovicka et al. (2006) for eliminating solar cycle long term variation instead of using Rz, one must used F10.7 or E10.7 because Bremer (2001) after investigating 100 ionosonde stations data showed that the derived trends are note greatly influence by the choice of the index.

Among the several papers devoted to ionosphere long term trends the majority concerns high and mid-latitude and few of them are devoted to equatorial sector. A lack of long term study in Equatorial Ionization Anomaly (EIA) sector of Africa must be noted. To contribute to the investigation of ionosphere parameters long term trends study, we present for the first time foF2 long term trends variation for a station of Africa equatorial ionization anomaly (EIA) sector and particularly for West Africa region. The aim of the present paper is to analyse Ouagadougou ionosonde station (lat: 12.4°N; long: 358.5°W; dip: +1.5) foF2 diurnal, annual and seasonal trends. The outline of the work is as followed: Method and data are shown in section 2 and in section 3 we present our results and their discussion. The section 4 constitutes the conclusion of the paper.

2. MATERIALS AND METHODS

For the present study, we consider foF2 parameter of Ouagadougou station that operated from 1966 to 1998. This period corresponds to the increasing period of geomagnetic activity (after 1965: Mikhailov and Marin, 2000) and is an advantage for avoiding the influence of merging failing and rising geomagnetic activity as suggested by Marin et al. (2001). For eliminating solar cycle long term variation in the trend, we used foF2 as third degree polynomial function of Rz because our data investigation revealed a better correlation coefficient with third degree polynomial expression than linear one even though these two expressions give higher correlation coefficient. One must note that the third degree polynomial function of Rz that has been proposed by Danilov and Mikhailov (1998) has been used by several authors (e.g. Danilov, 2002; Danilov and Mikhailov, 2001; Mikhailov and Marin, 2001). To determine foF2 trends, we follow Mikhailov and Marin (2000) by using the observed foF2 values relative deviation expression. It is important to note that, the relative deviation expression has been proposed by Danilov and Mikailov (1998, 1999) and used in many publications by more authors.

In the present paper, geomagnetic activity long term variation is not eliminated (i.e. our foF2 expression depends only on Rz) because on one hand Mikhailov and Marin (2000) showed that the used of Ap does not remove the geomagnetic dependence and on the other hand the method for removing this dependence proposed by Danilov (2003) needed at least (30 + 5) years of permanent observations (our data interval (1966-1998) covers 32 years with only six months data for the year 1966 and two months data for year 1998). The determination of the trend without trying to eliminate geomagnetic activity long term variation is made by several authors (see Bremer, 2001; Danilov and Mikhailov, 2001; Elias and Adler, 2006; Lastovicka et al., 2006; Elias, 2009, 2011). An important point must be underlined here Mikhailov and Marin (2001) asserted that any kind of Ap (monthly or annual mean values) or inclusion of Ap to regression cannot remove geomagnetic activity even though they noted that the regression expression of Ap removes only partly this effect without changing the result. So, they concluded that geomagnetic effect is an inalienable part of the revealed trend.

Our foF2 trend is determined by using:

(1) ¢$foF2 = \frac{fof\,2_{obs} - foF2_{theo}}{foF2_{theo}}$ with $foF2_{theo} = aR_z^3 + bR_z^2 + cR_z + d$ and $foF2_{obs}$ the observed values. a, b, c and d are real coefficients determined by using least squares method. In the present paper, δfoF2 are averaged over the entire 30 years involved for particular hours LT and months for daily and seasonal variations, respectively. For yearly variation, δfoF2 are averaged over the year for particular hour LT. To appreciate parameters (Ap, δfoF2, δfoF2 slope) variability, error bars are indicated in parameter time plots. Errors are evaluated by applying $\pm = \sqrt{\Delta}$, with the variance defined by $\frac{1}{N}\sum_{i=1}^{N}\left(x_i - \bar{x}\right)^2$ with $\bar{x}$ parameter mean value).

(2) ¢$foF2 = \sim Time +$ With α and β real coefficients obtained by least squares method. The significance of the slope or the linear trend parameter α, is obtained by using Fisher's F criterion given by pollard (1977): $F = (n-2)\frac{r^2}{1-r^2}$ with r the correlation coefficient between time mean δfoF2 and time and n is the number of time involved in the study.

For diurnal trend determination, we considered on one hand all years from 1966 to 1996 and on the other hand together solar minimum and maximum years involved in the 30 years considered. The determination of solar cycle phase is made under the following consideration (Gnabahou and Ouattara, 2012; Ouattara, 2012: submitted to special issue (IRI over Africa) of Adv. Space, Res.; Ouattara et al., 2012; Zerbo et al., 2012): (1) minimum phase: Rz < 20, where Rz is the yearly average Zürich Sunspot number; (2) ascending phase: 20 ≤ Rz ≤ 100 and Rz greater than the previous year's value; (3) maximum phase: Rz >100 [for small solar cycles (solar cycles with sunspot number maximum (Rz max) less than 100) the maximum phase is obtained by considering Rz > 0.8*Rz max] and (4) descending phase: 100 ≥ Rz ≥ 20 and Rz less than the previous year's value. Table 1 gives the years of the different solar cycle phases and particularly solar cycle minimum and maximum years (in bold) involved in the study.

Table 1. Years of solar cycle phases for solar cycles 20, 21 and 22

Solar cycles	**Solar cycle phases**			
	Minimum	**Increasing**	**Maximum**	**Decreasing**
20	1964-1965	1966-1967	**1968-1970**	1971-1974
21	**1975-1976**	1977-1978	**1979-1982**	1983-1984
22	**1985-1986**	1987	**1988-1991**	1992-1994

For seasonal analysis, the following seasons are considered: spring (March, April and May); summer (June, July, and August); autumn (September, October and November) and winter (December, January and February).

3. RESULTS AND DISCUSSION

3.1 Diurnal Variation of foF2 Trends

Fig. 1 gives diurnal variation of δfoF2 long term trend slope. It must be underlined that δfoF2 are averaged over 30 years involved for each particular hour LT. Each hourly slope is significant at more than 90%. Red curve corresponds to all years and blue curve to solar minimum (m) and solar maximum (M) together. Errors are indicated as vertical bars. Two cases have been considered here because we expected to have significant effect by using (m+M) years as obtained by Danilov and Mikhailov (1998, 1999) during their works. It can be seen the degreasing trend during daytime but there is no systematic effect by considering (m+M) years. Therefore, in the other investigations such as annual and seasonal analysis we will only use the data of all years. It can be seen two absolute maximum slopes for all years graph (1.5x 10^{-3} per year at 0400 LT and 2.5 x 10^{-3} per year at 1900 LT). The higher trend amplitude observed at night than daytime is conformed to that observed in Brazilian EIA sector by Yue et al. (2008) at all seasons.

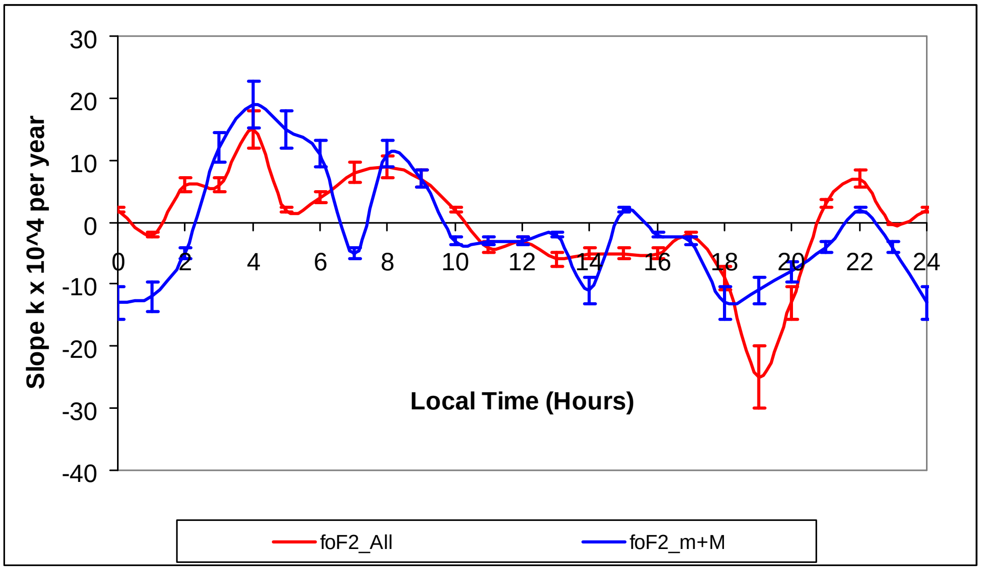

Fig. 1. Diurnal variation of annual mean ¢foF2 slope

For annual long term trends investigations, we will focus our attention to those hour data (0400 LT and 1900 LT) but for seasonal long term trends study, we will only consider the data of 1900 LT which express the higher absolute maximum slope.

Fig. 1 shows positive hourly slope from 2100 LT to 1000 LT and negative hourly slope for the other LT moments with diurnal pronounced slope variation.

A pronounced slope variation is conformed to the observation of Danilov and Mikhailov (1999) who pointed out that the slope variation observed at all latitudes increases from high to low latitude. The slope sign variation observed here (for the period after 1965) is similar to that obtained by Elias and Adler (2006) in the southern crest of EIA. This kind of slope variation is not only observed in equatorial latitude. It can be observed at high latitude (see results of Mikhailov and Marin (2000) at Salekhard station: their left top panel in Fig. 6). Our results, by respecting slope sign, are different from those of Mikhailov and Marin (2001) observed at middle and lower latitudes. On the other hand, the same slope sign is observed by these authors at high altitude: positive trend from post midnight to morning LT (all year graphs: red curve) and negative trend during a day.

For determining δfoF2 variability with respect to that of geomagnetic activity, the correlation coefficient between δfoF2 and Ap is given in Fig. 2. It can be retained that δfoF2 are averaged over the 30 years involved for each particular hour LT. Fig. 2 shows positive correlation except around 1700 LT-~ 2100 LT where negative correlation is observed. Therefore, between 1700 LT-~ 2100 LT δfoF2 is anti-correlated with Ap and for the other LT moments, both parameters are correlated. As according to Danilov (2003) when the correlation coefficient is above 0.4 there is a strong correlation between AP and foF2, we can assert that Ap and foF2 are well correlated between ~ 0100 LT - ~ 0500 LT and between ~2100 LT- ~2300 LT.

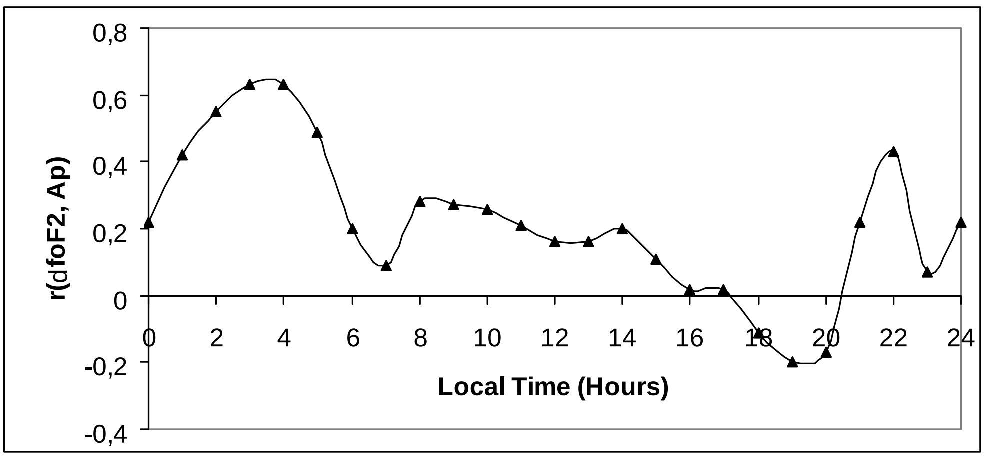

Fig. 2. Diurnal variation of the correlation coefficient between yearly mean ¢foF2 and Ap

3.2 Yearly Variation of foF2 trends

Fig. 3 presents the long term variation of annual mean Ap and δfoF2 during 30 years corresponding to three solar cycles 20, 21 and 22 at Ouagadougou station. Red vertical bars show the limit of each solar cycle. Cycle 20 begins at 1964 and ends at 1976, cycle 21 goes from 1976 to 1986 and cycle 22 corresponds to years between 1986 and 1996. Black curve corresponds to 5th degree polynomials obtained by least squares method. Black stars give annual mean Ap (panel a) and annual mean δfoF2 (panel b). Errors are indicated as black star vertical bars. In this figure δfoF2 is annual mean value.

One can see that from 1966 to 1981 (all cycle 20 and half cycle 21) δfoF2 increases with Ap and it is the reverse from 1981 to 1996 (half solar cycle 21 and all solar cycle 22). foF2 trend variation during the first half time (1966-1981) is different from that of Mikhailov and Marin (2000) at Slough. In fact, during the same period, they showed opposite variation of δfoF2 trend with respect to Ap.

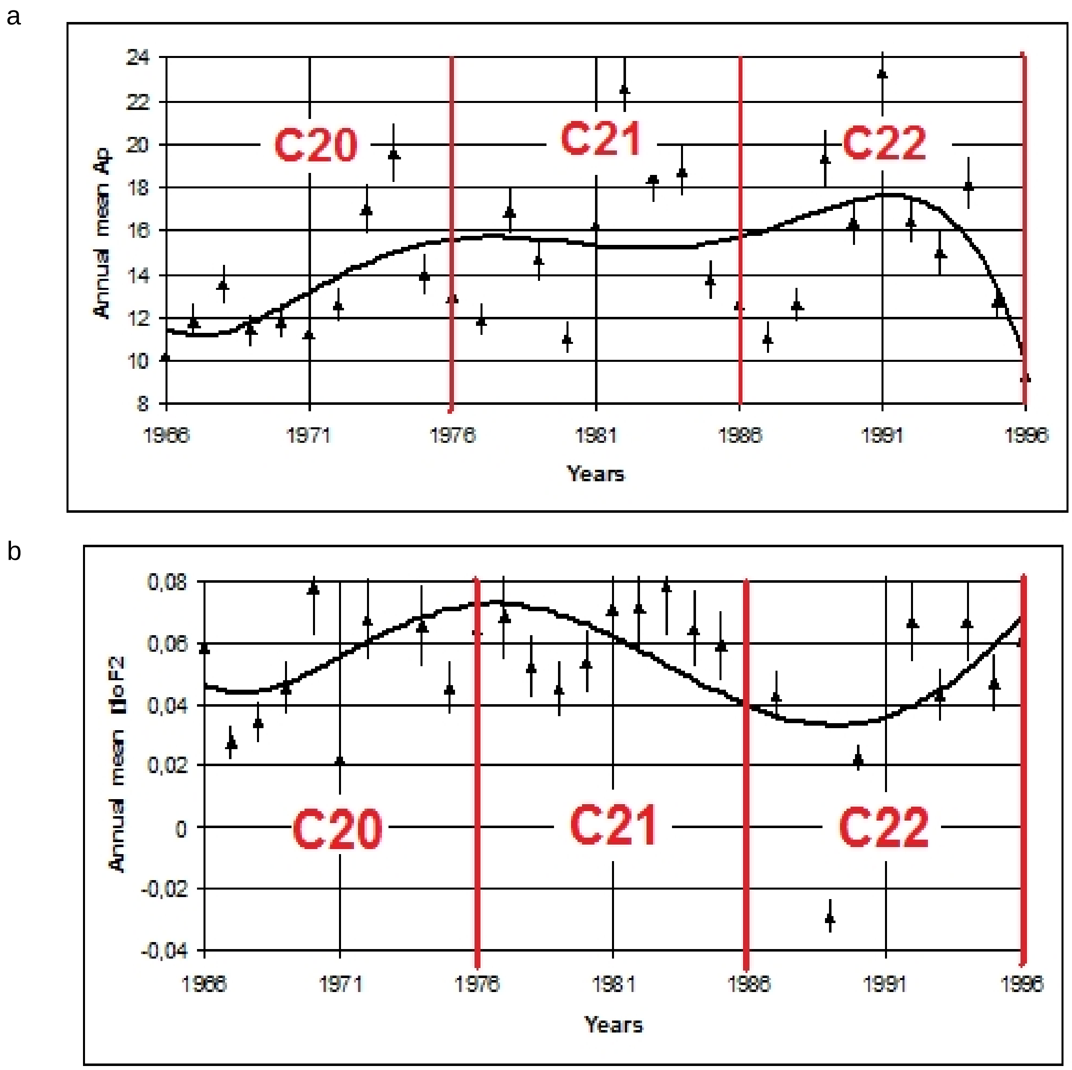

Fig. 3. Annual mean Ap and ¢foF2 long term variation during solar cycles (20-22)

Fig. 4 is showing δfoF2 yearly variation from 1966 to 1996. δfoF2 are averaged over the year for each hour LT. Panel a corresponds to 0400 LT and panel b to 1900 LT. For all panels a and b, from left to right, yearly δfoF2 are plotted for 1966-1996 (left panels), 1966-1981 (middle panels) and 1981-1996 (right panels). Black triangles correspond to δfoF2 and solid line indicated its trend. All mean slopes are significant at more than 85% except that of 1900 LT for the period 1966-1981 where the significance level is less than 85%. For the all 30 years and for this Africa EIA sector station one must note negative trend shown by linear curves slope values (k= + 1.5×10^{-3} per year for left panel a and k= – 2.5×10^{-3} per year for left panel b). It can be noted that these slopes are the same as those given in Fig. 1 for the same LT moments.

a

b

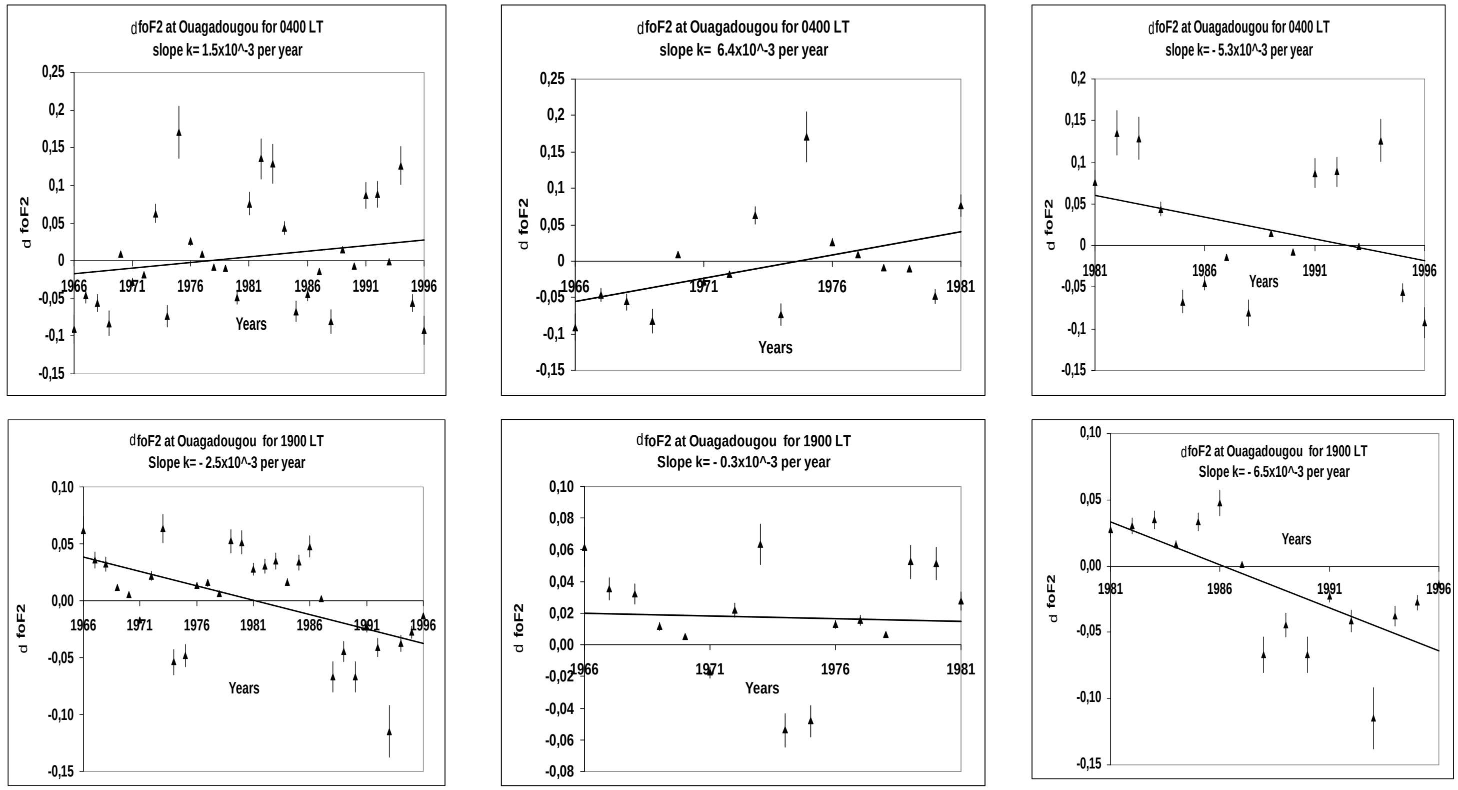

Fig. 4. Annual variation of ¢foF2 at Ouagadougou for 0400 LT (panel a) and for 1900 LT (panel b). Errors are indicated as vertical bars. For each panel, from left to right ¢foF2 plots are given for the periods 1966-1996, 1966- 1981 and 1981-1996, respectively. Except middle panel b where mean slope significance is less than 85%, the other mean slopes are more than 90% significant.

As previously indicated (Fig. 3b), there are two types of trend: in middle and right panels a it is clearly seen positive trend (slope: + 5.4×10^{-3} per year) and negative trend (slope: - 5.3×10^{-3} per year), respectively. In panel b, fairly negative trend is observed in middle (slope: – 0.3×10^{-3} per year) and pronounced negative trend in right (slope: – 6.5×10^{-3} per year). By applying a significance level more than 90%, it can be retained that, at 0400 LT foF2 presents positive trend from 1966 to 1981 and negative trend from 1981 to 1996 while at 1900 LT, foF2 shows negative trends for the whole period involved.

Fig. 5 gives annual variation of δfoF2. δfoF2 is averaged over the year for monthly mean value at 1900 LT. Panel a concerns the period 1966-1996, panel b the period 1966-1981 and panel c the period 1981-1996. Except the slope of the period 1966-1981 which is significant at less than 85%, the other slopes are significant at more than 90%.The comparison of Figs. 4 and 5 linear slopes at 1900 LT shows that the slope observed in Fig. 1 for the period 1966-1996 is also observed in the left panel b of Fig. 4 during the same time interval but is seen in the panel c of Fig. 5 during 1986-1996. The different results obtained from these two different procedures underline the necessity to define clearly the method used for slope determination. It can be noted here that the same method has been used to obtain slope values in Fig. 1 and Fig. 4.

Based on the high magnitude of foF2 trend we can conclude that our trend is not due to greenhouse effect (see Mikhailov and Marin, 2000). On the other hand, we can assert that the strong negative trend shown here may be due to Earth's magnetic field variation because our station is located in the regions where foF2 trends are under the strongest influence of Earth's magnetic variation. In fact, Elias (2009) by investigating the influence of Earth's magnetic field variation in foF2 trends showed that the regions submitted to the strongest influence of Earth's magnetic variation is located between 10°N and 30°S in latitude and between 20°E and 80°W in longitude. Moreover, our foF2 trend sign is the same as that obtained by Yue et al. (2008) in Brazilian EIA sector for the period 1900-2005 when they analyzed the influence of dip angle in foF2 trend. For the influence of dip angle in foF2 trend see Elias and Alder (2006) and Foppiano et al. (1999).

3.3 Seasonal Variation of foF2 Trends

Fig. 6 expresses monthly mean δfoF2 slope for seasonal variation at 1900 LT. The slope significance is more than 90%. Each monthly mean δfoF2 is averaged over the 30 years involved. δfoF2 slope is always negative at all seasons like that observed at all latitudes (see Elias and Adler, 2006; Danilov and Mikailov, 1999, 2001). One can see that δfoF2 slope remains negative over the year with strong seasonal variations. The absolute maximum values of seasonal slope are seen in January, April, August and September. The maximum absolute slopes are observed in equinoctial months with higher peak during September (3.8×10^{-3} per year).

a

b

c

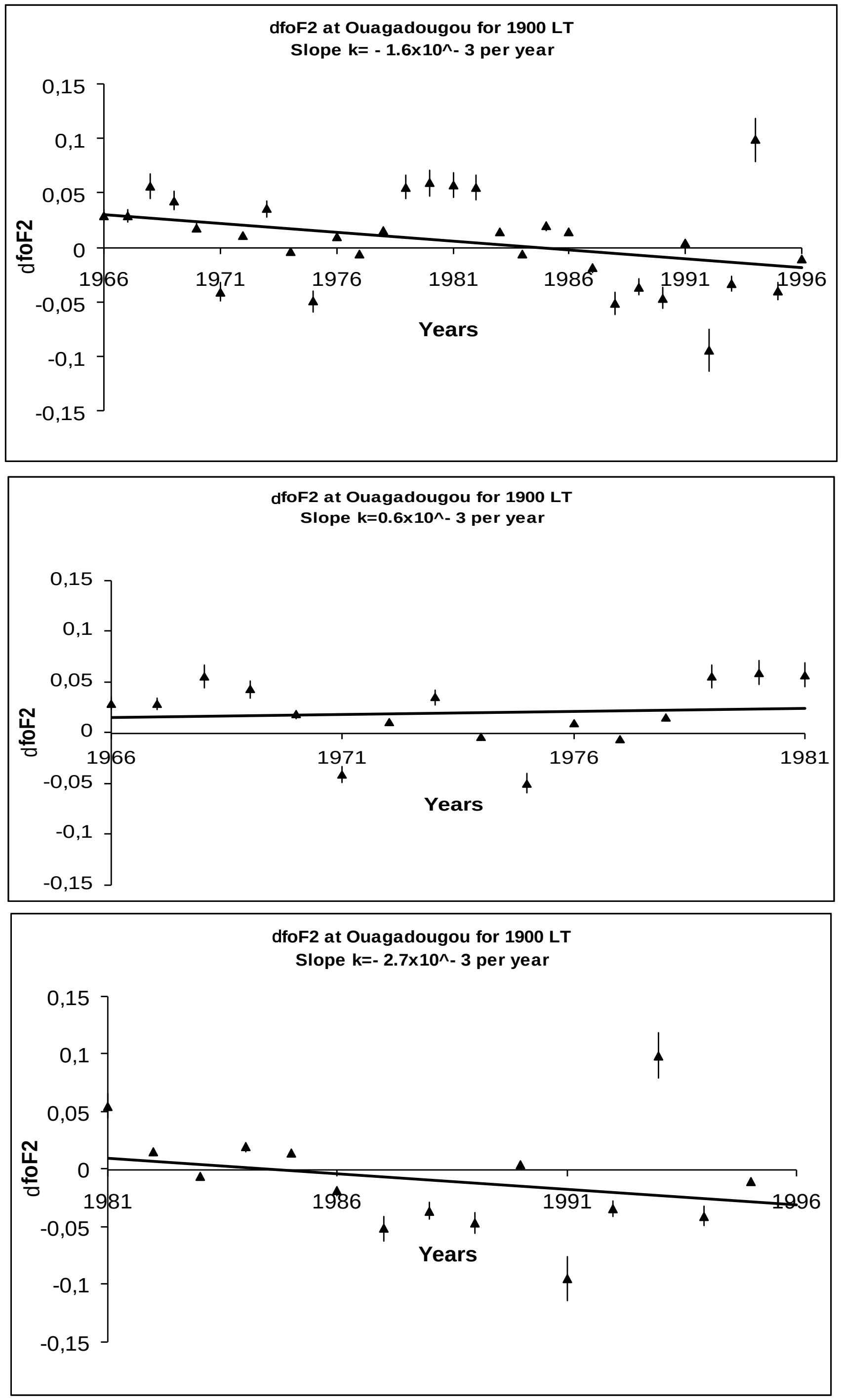

Fig. 5. Annual variations of ¢foF2 at Ouagadougou for 1900LT. Errors are indicated as vertical bars. Panel a corresponds to the period 1966-1996, panel b to the period 1966-1981 and panel c to the period 1981-1996.

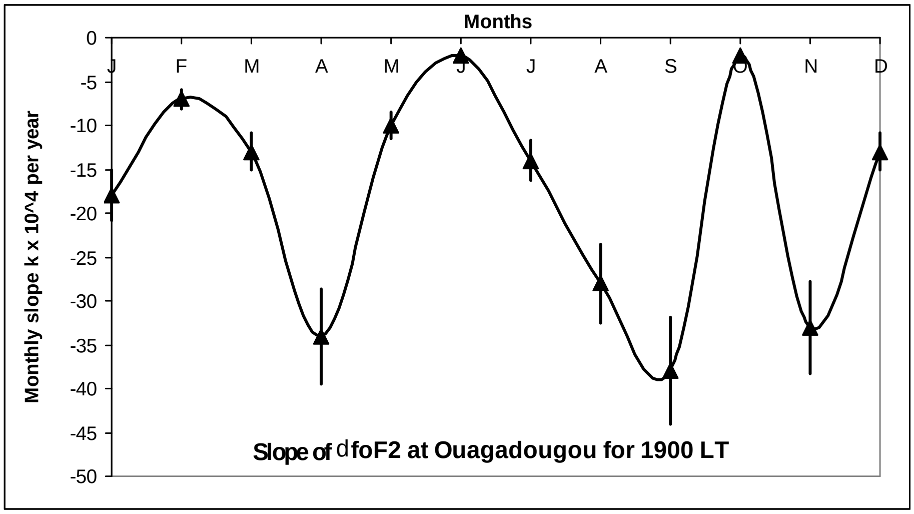

Fig. 6. Seasonal variation of 1900 LT monthly ¢foF2 slope

This result shows the equinoctial asymmetry of slope magnitude. Moreover, it can be noted that absolute slopes are higher in summer than in winter. This result has been also observed by Danilov and Mikhailov (1999). The analysis of seasonal variation by Cnossen and Richmond (2008) showed that magnetic field variation cannot explain seasonal variation observed in foF2 trends. Therefore, Danilov and Mikhailov (1999) suggested ionospheric storm as a probable reason of trend seasonal variation. May be the multiple reasons of foF2 trends variation explained its non consistent patterns observed at different stations (Marin et al., 2001; Yue et al., 2006) even though Yue et al. (2006) attributed the multiple patterns to data and methods used during the seasonal trend investigation.

4. CONCLUSION

The present study shows annual decreasing mean trends of foF2 at Ouagadougou station. Diurnal investigation showed hourly negative trends during daytime and positive hourly trends from night to 1000 LT. Trend amplitude is higher at night than at daytime. foF2 is well correlated to geomagnetic early in the morning and early at night. foF2 trend is correlated to geomagnetic activity except between 1700 LT-2000 LT where both parameters are anti-correlated. Seasonal trends remain negative over the season. Trend amplitude is higher in summer than in winter. At 0400 LT, annual trend shows positive trend from 1966 to 1981 and negative trend from 1981 to 1996. At 1900 LT, negative trend is observed from 1966 to 1996. It can be retained from this work that foF2 trend depends (1) on geomagnetic effect regarding to its well pronounced variability and its well correlation with Ap index and (2) on Earth's magnetic variation due to station geographical location.

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COMPETING INTERESTS

Author has declared that no competing interests exist.

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