Original Research Article

Variability of f_oE in relation to the solar indices (R_z and $F_{10.7}$) at the equatorial ionosphere (Ouagadougou station)

ABSTRACT

The correlation coefficients between the critical frequency of the ionosphere E-layer and the solar indices have not been formally evaluated at the Ouagadougou station. The objective of this paper is to conduct a study on the variability of the critical frequency of ionosphere E-layer with the solar radio flux ($F_{10.7}$) and sunspot number (R_z) at the Ouagadougou station. The Ouagadougou station is located at the equatorial ionosphere whose coordinates are: lat: 12.5°N; long: 358.5°E; dip 1.5. Moreover, the local time is equal to the universal time (LT=UT). We worked on the solar cycles 21 and 22 (SC21 and SC22) considering their different phases (minimum, increasing, maximum, and decreasing). The results show a good correlation between f_oE and R_z, and between f_oE and $F_{10.7}$. Thus, the correlation coefficient evaluated between f_oE and R_z is 0.96 at SC21 and 0.93 at SC22, and between f_oE and $F_{10.7}$ is 0.95 at SC21 and 0.93 at SC22. We subsequently compared f_oE of the two solar cycles for the same phase. The calculated deviation between the minimum of SC21 and SC22 is 4.46%. We then find a very small variation of f_oE from a solar cycle to another at the minimum phase, and this is also verified at the other phases.

Keywords: critical frequency (f_oE); correlation; solar radio flux ($F_{10.7}$); solar cycle (SC); sunspot number (R_z).

1. INTRODUCTION

The particularity of the ionosphere is its interaction with radio waves in the field of telecommunication. In this area of the Earth's atmosphere, neutral particles such as oxygen (O_2) and nitrogen (N_2) are ionized by UV and EUV radiation from the sun or radiation from stars. The sun follows a cycle of 11 years on average with respect to the number of sunspots and a cycle of 22 years with respect to the inversion of its magnetic field. In a solar cycle there are four phases that are classified according to the sunspot number R_z [1]. Indeed, a solar cycle starts with a minimum phase, reaches its maximum through its increasing phase, and then completes its cycle with a decreasing phase to make way for a new cycle. At the maximum phase of a solar cycle, the sun is in full activity and propels more energetic particles in its environment. The solar radio flux of 10.7 cm, or $F_{10.7}$ is also one of the most widely used indices of solar activity by Earth ionosphere physicists. The measurement of the 10.7 cm solar flux is a determination of the power of the solar radio emission in a 100 MHz band, centered on 2800 MHz (a wavelength of 10.7 cm), averaged over one hour (1h). It is expressed in solar flux units (sfu), where 1 sfu = 10^{-22} W m^{-2} Hz^{-1}. It comprises a time-varying mixture of more than three main emission mechanisms that may be differently distributed over the solar disk and may vary independently with time [2]. It contains free thermal emission from the chromosphere and corona, and from plasma concentrations include in the chromosphere and corona from active magnetic field regions [2]. Tapping et al [3] described the equipment and procedures used for the $F_{10.7}$measurements and also addressed some of the most asked questions about the data. The dependence of the ionosphere on solar radiation is obvious. Indeed, the effects of solar flares on the ionosphere have been the subject of several investigations: e.g [4, 5, 6, 7, 8, 9, 10]. The response of the ionosphere to solar activities is more or less well known [11], and should be an ongoing quest. In this work, we will estimate the dependence of f_oE on sunspot number and solar radio flux at the Ouagadougou station.

2. METHODOLOGY

The Ouagadougou station, our study site, is located in the equatorial ionosphere. There is less work done on the E layer in this station. It is marked by the following geographical coordinates: latitude: 12.5°N; longitude: 358.5°E, dip: 1.5. The parameter used is the critical frequency of the E layer measured by the ionosonde from 1966 to 1998 of the British Telecommunications Agency. The solar cycles considered are: solar cycle 21 and solar cycle 22. We selected the values of f_oE at noon local time (1200LT), which represents the time when foE is maximum at the Ouagadougou station [12]. We then calculated foE for each phase of the solar cycles according to equation (1).

$$f_O E = \frac{1}{k}\frac{1}{n}\sum_{j=1}^{k}\sum_{i=1}^{n} f_O E_{i,j} \quad (1)$$

Where *n* is the number of days in month *d* and k the number of months in the year.

The correlation coefficients between $f_O E$ and $F_{10.7}$; $f_O E$ and R_z are calculated according to equations (2) and (3).

$$r(f_O E, F_{10.7}) = \frac{\mathrm{Cov}(f_O E,\ F_{10.7})}{\sigma_{f_O E}\,\sigma_{F_{10.7}}} \quad (2)$$

$$\mathrm{Cov}(f_O E,\ F_{10.7}) = \frac{1}{\mathrm{N}}\sum_{\mathrm{i}=1}^{\mathrm{N}}(f_O E_{\mathrm{i}} - \overline{f_O E})(F_{10.7_{\mathrm{i}}} - \overline{F_{10.7}}) \quad (3)$$

Finally, we estimated the foE difference between the two solar cycles by equation (4).

$$\sigma\mathrm{foE}(\%) = \frac{\mathrm{foE}_{\mathrm{min/SC21}} - \mathrm{foE}_{\mathrm{min/SC22}}}{\mathrm{foE}_{\mathrm{min/SC22}}} \times 100 \quad (4)$$

$\mathrm{foE}_{\mathrm{min/SC21}}$ denotes the critical frequency of the E-layer at the minimum phase of solar cycle 21. The values of R_z and $F_{10.7}$ are taken from https://omniweb.gsfc.nasa.gov/form/dx1.html. The selected study dates are recorded in Table1.

Table 1: R_z and $F_{10.7}$ of each phase of the two solar cycles

		minimum	**increasing**	**maximum**	**decreasing**
SC21	year	1976	1978	1979	1984
	R_z	18	131	220	60
	$F_{10.7}$	73,4	143,5	191,6	100,9
SC22	year	1985	1987	1990	1993
	R_z	21	34	192	76
	$F_{10.7}$	74	85,3	189,9	109,6

3. RESULTS AND DISCUSSION

3.1 Variability of $f_o E$ in relation to R_z

Fig. 1 shows the variation of $f_o E$ and R_z as a function of the phases of the two solar cycles 21 and 22. We have the evolution of R_z on the main axis and $f_o E$ on the secondary axis.

The lowest value of f_oE estimated at 3.5MHz is measured at the minimum phase. This value corresponds to a sunspot number equal to 18. At maximum phase, foE is 4.2 MHz, for R_z equal to 220. The value of the critical frequency of the E-layer at the equatorial ionosphere is then higher at the maximum phase of SC21 than at the minimum phase. This has been demonstrated by Abe et al. [13] and Gédéon et al [12]. The correlation coefficient between f_oE and R_z at SC21 calculated is 0.96, at the Ouagadougou station. The variation of the two curves shows the close dependence of f_oE on the sunspot number. The value of f_oE during the increasing and decreasing phases remains higher than the minimum phase and lower than the maximum phase.

Fig. 2 compares the variation of f_oE and R_z at solar cycle 22 as a function of the four phases. When R_z increases, f_oE also increases. Thus, f_oE grows from the minimum phase to the maximum phase and decreases from the maximum to the decreasing phase of SC22. The largest value reached by f_oE at the maximum phase is 4.12 MHz. The lowest value of f_oE estimated at about 3.6 MHz is measured at minimum phase. This correlation between f_oE and R_z was also goodlighted by Wongcharoen et al. [14], when they conducted the seasonal study on the dependence of f_oE on sunspot number at Chumphon station (Thailand) which is located almost at the magnetic equator (lat. 10.72° long. 99.37° dip. 3°). At SC22, the correlation coefficient between f_oE and R_z is 0.93 at the Ouagadougou station. This correlation coefficient is slightly lower than the one calculated at SC2, nevertheless, these coefficients show that there is a very good correlation between the critical layer frequency and the sunspot number at the Ouagadougou station.

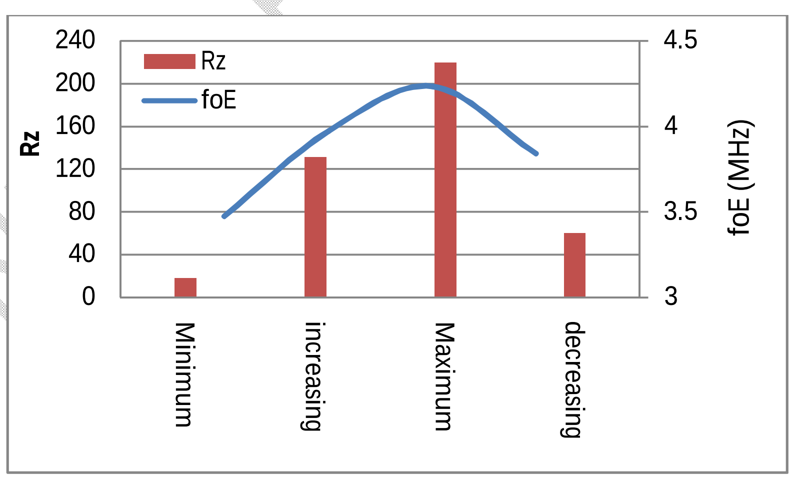

Fig.1. Variation of R_z and foE as a function of the phases of SC21

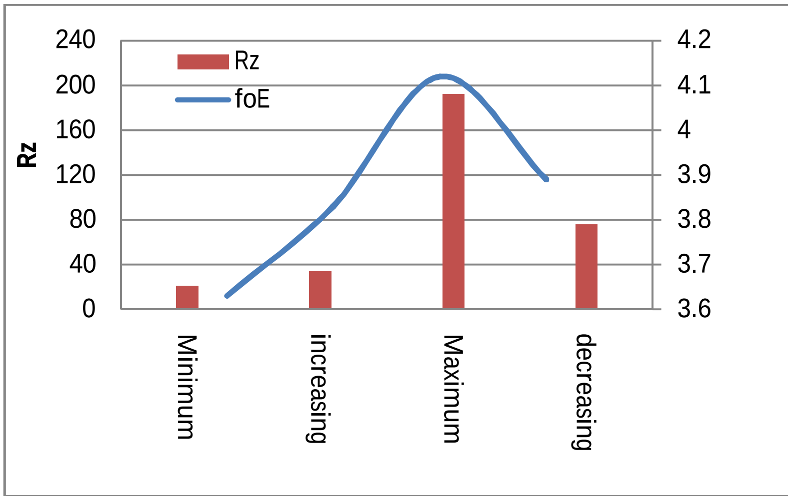

Fig.2. Variation of R_z and f_oE as a function of the phases of SC22

3.2 Variability of f_oE in relation to $F_{10.7}$

Fig. 3 shows on the main axis the variation of the solar radio flux and on the secondary axis the variation of f_oE as a function of the four phases of SC21. At the minimum phase of SC21, f_oE is 3.47 MHz, corresponding to $F_{10.7}$=73.4sfu. At the maximum phase, f_oE is 4.23 MHz, corresponding to $F_{10.7}$=192sfu. We note that f_oE increases when $F_{10.7}$ increases and decreases when $F_{10.7}$ decreases. Thus, we find a good correlation between the two parameters. At the Ouagadougou station, the correlation coefficient calculated between f_oE and $F_{10.7}$ at SC21 is 0.95.

Fig. 4 compares the variation of f_oE with the variation of R_z as a function of the four phases of CS22. In this Figure, the variation of f_oE follows that of $F_{10.7}$. At the maximum phase, f_oE is 4.12 MHz for $F_{10.7}$= 190 sfu. The correlation coefficient between f_oE and $F_{10.7}$ at SC22 is estimated at 0.93. It is this good correlation between f_oE and $F_{10.7}$ that allowed the developers of ionospheric models to include it in the empirical equations. This is the case of Yue et al [15] who developed the Chinese Reference Ionosphere (CRI) model. In their model, they evaluate f_oE according to equation (5).

$$f_oE = m\,(n + F_{10.7})^{0.25}\,(\cos\chi_{noon})^{P}\,\left(\cos(\chi + \delta_{\chi})\right)^{B} \quad (5)$$

In equation (5), $F_{10.7}$ is the solar activity index (solar radio flux), $\cos\chi_{noon}$ is the cosine of the local solar zenith angle at noon, and χ is the solar zenith angle. m and n are the coefficients used to determine the relationship between f_oE and $F_{10.7}$. $\delta\chi$ is the adjustment to χ that are needed to properly describe the dependence of f_oE on the solar zenith angle. We note that in this equation, f_oE depends goodly on the solar index $F_{10.7}$. The IRI model is based on a photochemical approximation, which describes the E region fairly well under calm geomagnetic conditions. Thus, f_oE is estimated on the basis of the studies of Kouris and Muggleton [16, 17] of the model they developed for the CCIR. Based on a large database of ionosonde measurements of f_oE as described by Muggleton [18], four factors (A, B, C, and D) are used to calculate the f_oE values (equation 6).

$$f_oE^4 = A.B.C.D \qquad (6)$$

In equation (6) the parameter A depends on the solar index ($F_{10.7}$) with:

$$A = 1 + 0{,}0094\left(F_{10.7_{12}} - 66\right) \text{ MHz} \qquad (7)$$

In the models developed to investigate the ionosphere, the solar indices are crucial, especially $F_{10.7}$. This good correlation between f_oE and $F_{10.7}$ (especially at 1200LT) was found by Danilov et al [19], when they studied the diurnal and seasonal variations of the E-layer critical frequency trends in three stations in the European region (Juliusruh, Slough, and Rome). This good correlation between $F_{10.7}$ and f_oE or R_z and f_oE is a step towards the development of an ionospheric model of the African equatorial zone.

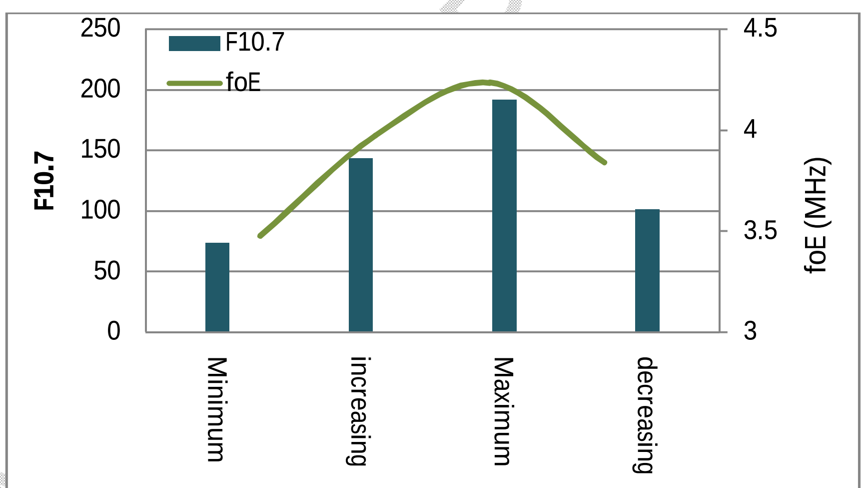

Fig.3. Variation of $F_{10.7}$ and f_oE according to the phases of SC21

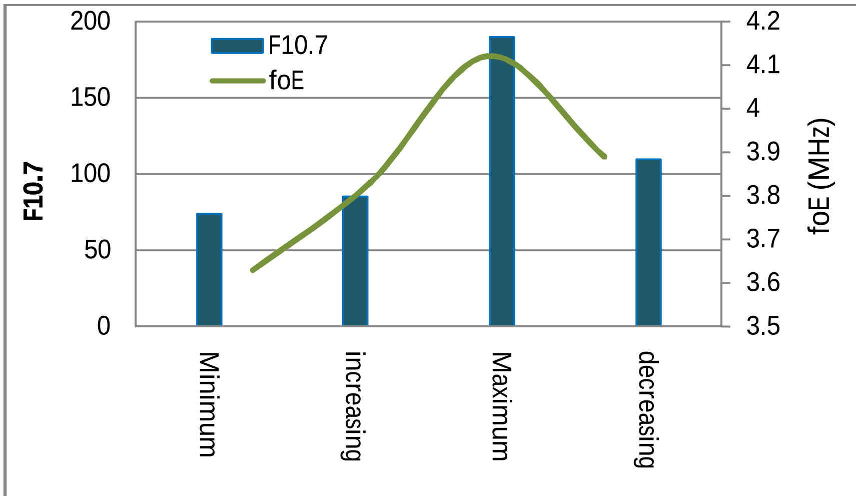

Fig.4. Variation of $F_{10.7}$ and f_oE according to the phases of SC22

3.2 Variation of f_oE between two identical phases from SC21 to SC22.

In this part of our study, we seek to determine the gap that exists between f_oE from SC21 to SC22. This comparison is based on the calculation of percentage deviation (σf_oE (%)) given by equation (4). The assessment of the gap will be based on the following hypothesis:

if -10%<σf_oE (%)<+10% then the gap is negligible, otherwise the gap is non-negligible [20].

Fig.5a shows the variation of f_oE as a function of the phases of solar cycles 21 and 22. Fig.5b shows the deviation between f_oE at the minimum phase of SC21 and SC22, at the increasing phase of SC21 and SC22, at the maximum phase of SC21 and SC22, and at the decreasing phase of SC21 and SC22. Indeed, the deviations between the minimum phase of SC21 and SC22, between the decreasing phase of SC21 and SC22, between the maximum phase of SC21 and SC22 and between the decreasing phase of SC21 and SC22 are +4.46%; -3.58%; -2.71% and +1.3%, respectively. According to the hypothesis made above, the values of the deviations are in an interval that allows us to neglect the gap that exists between f_oE from SC21 to SC22.

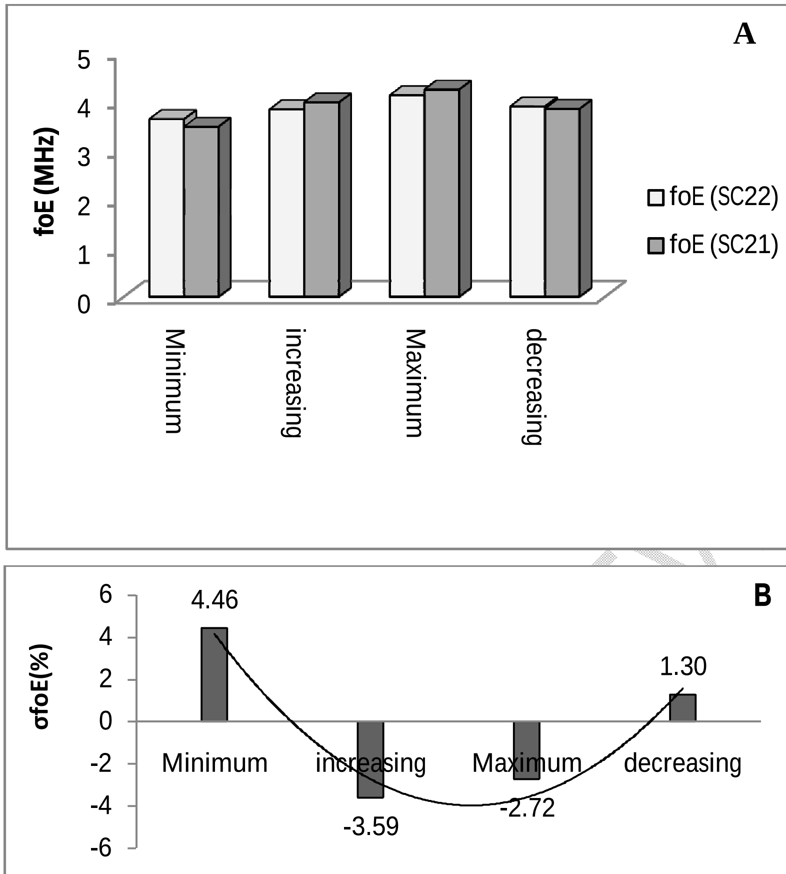

Fig.5. (A) Comparison of f_oE for each phase of SC21 and SC22 / (B) deviation of f_oE for each phase of SC21 and SC22.

4. CONCLUSION

The dependence of f_oE on solar indices such as sunspot number and solar radio flux has been proven by several researchers in different measuring stations. This has led to the development of several ionospheric models, mainly based on solar indices and solar zenith angle. In this paper, we proved that there is a good correlation between the E-layer critical frequency and the solar indices. We used the f_oE data of the four (4) phases of the solar cycles 21 and 22 measured at the Ouagadougou station.

- The comparative study between f_oE and R_z shows a high dependence of f_oE on sunspot number with correlation coefficients of 0.96 and 0.93 at SC21 and SC22 respectively.

- The comparative study between f_oE and $F_{10.7}$ also shows that there is a high dependence between the two parameters. The correlation coefficients between f_oE and $F_{10.7}$ are respectively 0.95 and 0.93 at SC21 and SC22.
- The difference between f_oE of a phase, from one solar cycle to another is negligible (for solar cycles 21 and 22).

This study leads us to the design of an ionospheric model of the African equatorial zone.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

f_oE: E-layer critical frequency

SC21: Solar cycle 21

SC22: Solar cycle 22