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(f_oE) and the solar radio fluxhave 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 values of foE taken into account are those measured at 12:00 TL. 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 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 [1]. In a solar cycle there are four phases that are classified according to the sunspot number R_z[2]. The different phases of a solar cycle are: minimum phase, maximum phase, increasing phase, and decreasing phase. At maximumphase of a solar cycle, the sun is in full activity and propels more energetic particles into its environment. The 10.7 cm solar radio flux, or $F_{10.7}$, is also one of the most widely used indices of solar activity in ionospheric models. The measurement of the 10.7 cm solar flux is a characterization of the power of the solar radio emission in a frequency of 2800 MHz (a wavelength of 10.7 cm). It is expressed in solar flux units (sfu), where 1 sfu = 10^{-22} W m^{-2} Hz^{-1}. It contains free thermal emission from the chromosphere and corona, active regions of the solar magnetic field [3]. Tapping *et al* [4] described the equipment and procedures used for measurements of $F_{10.7}$. The effects of solar flares on the ionosphere and the response of the ionosphere to solar activities have been the subject of several investigations [5, 6, 7, 8, 9, 10, 11, 12]. Ouattara *et al* [13] studied the correlations between different ionosphere parameters and sunspot number at the Ouagadougou station. According to their results, the correlation coefficients between f_oE and R_z are 0.726; 0.169 and 0.560 respectively at SC20, SC21 and SC22. In this work, we determine the correlations between f_oE and two solar indices ($R_z$and $F_{10.7}$) at the Ouagadougou station with a new approach, considering only the f_oE values at 12:00 LT.

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 (12:00LT), which represents the time when foE is maximum at the Ouagadougou station [14]. Equation (1) allows calculatingf_oE average of each phase of the solar cycles 21 and 22.

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

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

Equations (2) and (3) allow to calculatethe correlation coefficients between $f_o E$and $F_{10.7}$, and$f_o E$ and R_z.

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

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

Equation (4)allowscalculatingthe gape of $f_o E$ between the two solar cycles.

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

$\mathrm{foE}_{\mathrm{min/SC21}}$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 fromhttps://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_oE in relation to R_z

Fig. 1 shows the variation of $f_oE$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 $f_oE$on the secondary axis. The lowest value of f_oE estimated at 3.47MHz 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 maximumphase of SC21 than at the minimum phase. This has been demonstrated by Abe et al[15] and Gédéon et al [14]. 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[16], 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 0.93at the Ouagadougou station. This correlation coefficient is slightly lower than the one calculated at SC22, nevertheless, these coefficients show a good correlation between the critical layer frequency and the sunspot number at the Ouagadougou stationat 12:00 LT.

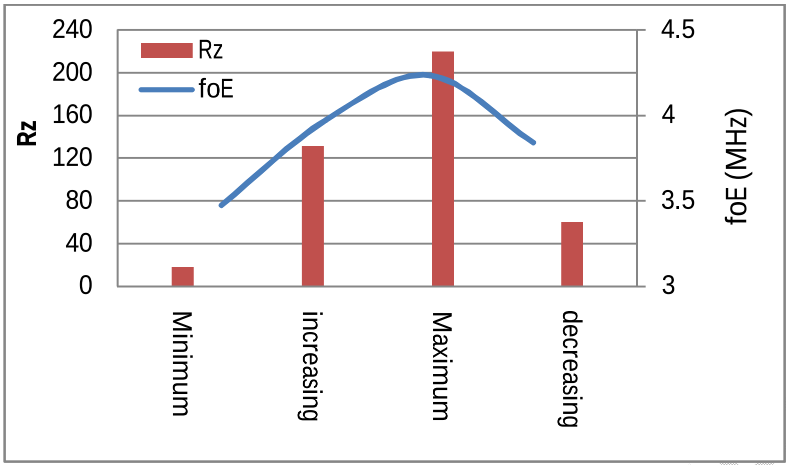

Fig.1. Variation of R_z and foE as a function of the phases of SC21

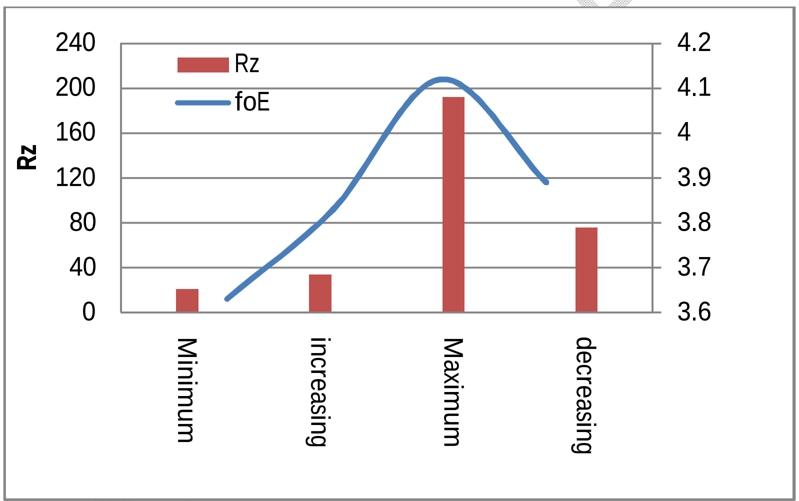

Fig.2. Variation of R_z **and f_oE as a function of the phases of SC22**

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 SC22. 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 [17] 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 $F_{10.7}$. δχ 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 highly 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 [18, 19] of the model they developed for the International Radio Consultative Committee(CCIR). Based on a large database of ionosonde measurements of f_oE as described by Muggleton [20], four factors (A, B, C, and D) are used to calculate the f_oE values (equation 6).

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

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

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

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 12:00LT) was found by Danilov et al [21], 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).

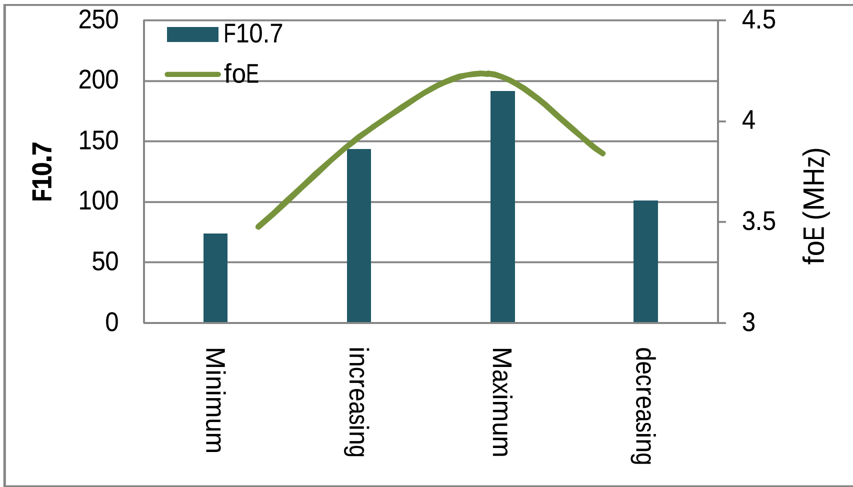

Fig.3. Variation of $F_{10.7}$and f_oE according to the phases of SC21

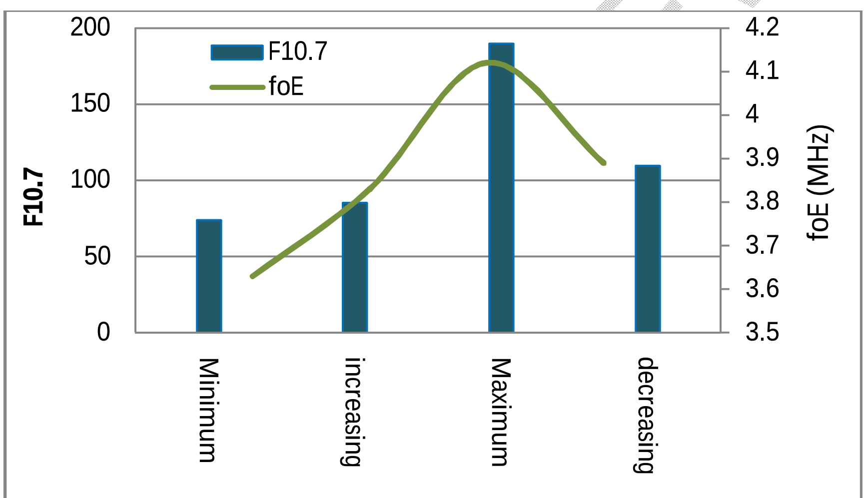

Fig.4. Variation of $F_{10.7}$and f_oE according to the phases of SC22

3.2Variation 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 [22].

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 $f_o E$from SC21 to SC22.

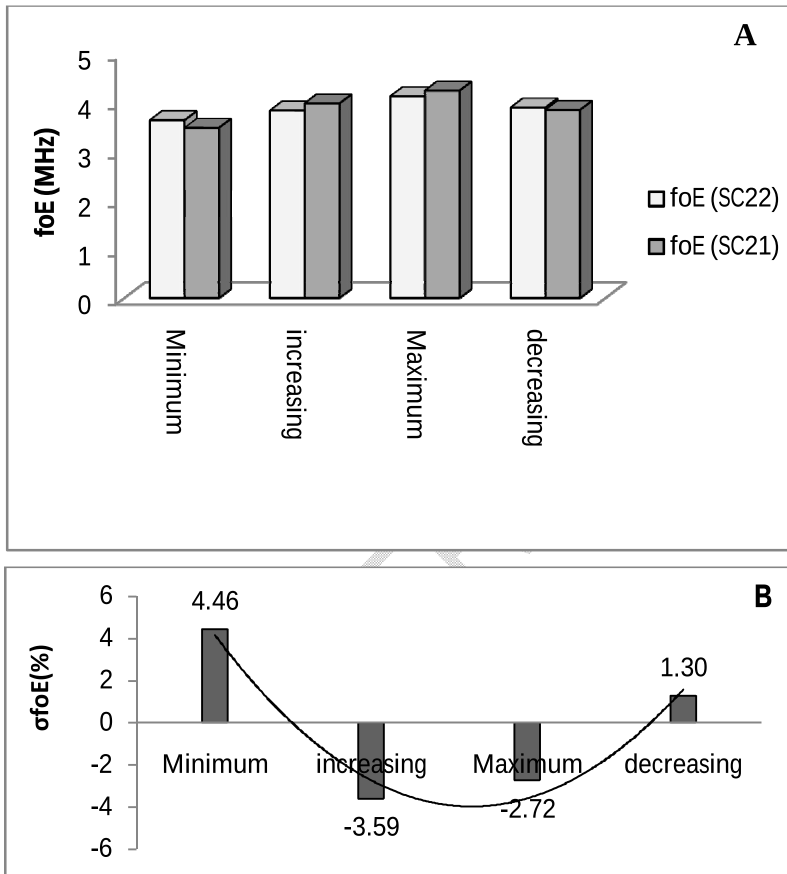

Fig.5. (A) Comparison of $f_o E$ for each phase of SC21 and SC22 / (B) deviation of $f_o E$ for each phase of SC21 and SC22.

4. CONCLUSION

The dependence of $f_o E$ 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 at 12:00 LT.

- 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 showed a good correlation between the critical frequency of the E layer of the ionosphere, and two solar indices such as sunspot number and solar radio flux, at the Ouagadougou station at 12:00 LT.

REFERENCES

1. G. Maris., Adrian Oncica andM. D.Popescu. The 22-Year Solar Magnetic Cycle. I. Sunspot and Radio Activity.*Romanian Astronomical Journal*, 2001, 11, 13-25

2. Clette, F., Svalgaard, L., Vaquero, J.M. and Cliver, E.W. Revisiting the Sunspot Number. A 400-Year Perspective on the Solar Cycle. *Space Science Reviews*.2014, **186**,35-103. https://doi.org/10.1007/s11214-014-0074-2

3. Kruger, A. Introduction to solar radio astronomy and radio physics, *Geophys. andAstrophys.* 1979, *16*.
4. Tapping, K. F. The 10.7 cm solar radio flux ($F_{10.7}$). Space weather. 2013, 11, 394-406. doi:10.1002/swe.2006.

5. Afraimovich, E. L. Ionospheric effects of the solar flares of September 23, 1998 and July 29, 1999 as deduced from global GPS network data. J. Atmos. Sol. Terr. Phys. 2000, 63, 1841-1849.

6. Le, H., Liu, L., Ren, Z., Chen, Y., Zhang, H. and Wan, W. A modeling study of global ionospheric and thermospheric responses to extreme solar flare. J. Geophys. Res. Space Physics.2016, 121, 832-840. doi:10.1002/2015JA021930.

7. Leonovich, L. A., Afraimovich, E. L., Romanova, E. B. and Taschilin, A. V. Estimating the contribution from different ionospheric regions to the TEC response to the solar flares using data from the international GPS network. Ann. Geophys. 2002, 20, 1935-1941.

8. Liu, J. Y., Lin, C. H. , Tsai, H. F. and Liou, Y. A. Ionospheric solar flare effects monitored by the ground-based GPS receivers: Theory and observation. J. Geophys. Res.2004, 109,A01307. doi:10.1029/2003JA009931.

9. Nogueira, P. A. B. Modeling the equatorial and low-latitude ionospheric response to an intense X-class solar flare. J. Geophys. Res. Space Physics. 2015, 120, 3021-3032. doi:10.1002/2014JA020823.

10. Tsurutani, B. T. The October 28, 2003 extreme EUV solar flare and resulting extreme ionospheric effects: Comparison to other Halloween events and the Bastille Day event. Geophys. Res. Lett.2005, 32, L03S09. doi:10.1029/2004GL021475.

11. Wan, W., Liu, L., Yuan, H. ,Ning, B. and Zhang, S. The GPS measured SITEC caused by the very intense solar flare on July 14, 2000. Adv. Space Res.2005, 36, 2465-2469.

12. Atulkar, A., Mansoori, A., Khan, P. A. and Purohit, P. K. Solar cycle variation and its impact on critical frequency of F layer. Indian Journal of Radio & Space Physics.2018, 47, 20-29.

13. F. Ouattara, C. Amory-Mazaudier, R. Fleury, P. Lassudrie Duchesne, P. Vila, and M. Petitdidier.West African equatorial ionospheric parameters climatology basedon Ouagadougou ionosonde station data from June 1966 toFebruary 1998**.***Ann. Geophys*. 2009, 27, 2503–2514

14. Gédéon, S., Roger, N., Moustapha, K., & Emmanuel, N. Seasonal Variability of $f_o E$ and Nocturnal Winter Anomaly in E-layer during Solar Cycles 21 and 22 at the

Ouagadougou Station. Physical Science International Journal. 2022, 26(2), 1-10. https://doi.org/10.9734/psij/2022/v26i230307

15. Abe, O.E., Rabiu, A.B., Adeniyi, J.O.Variation of f_oE in theequatorial ionosphere with solar activity. Adv. Space Res.2013, 51, 69-75

16. P. Wongcharoen, P. Kenpankho, K. Sepsirisuk, P. Supnithi, S. Noppanakeepong, S. Lerkvaranyu, T. Tsugawa, T. Nagatsuma. International Conference on Space Science and Communication. 2013, 978-1-4673-5233-8/13/$31.00 ©2013 IEEE

17. Yue, X., W. Wan, W., Liu, L., Ning, B. An empirical model of ionospheric $f_oE$over Wuhan, Earth Planets Space. 2006, 58, 323-330.

18. Kouris, S.S. Muggleton, L.M. Diurnal variation in E-layer ionization. J. Atmos. Terr. Phys.1973a, 35, 133-139.

19. Kouris, S.S., Muggleton, L.M. World morphology of Appleton E-layer seasonal anomaly. J. Atmos. Terr. Phys.1973b, 35, 141-151.

20. Muggleton, L.M. A method of predicting f_oE at any time and place. Telecommunications Journal. 1975, 42, 413-418

21. Danilov. A.D, Konstantinova. A.V. Geomagnetism and Aeronomy. 2018, 58(5), 629-637

22. Karim, G., Zerbo, J-L., M'Bi Kaboré, Ouattara, F. Critical Frequency foF2 Variations at Korhogo Station from 1992 to 2001 Prediction with IRI-2012, International Journal of Geophysics. 2019, Article ID 2792101, 11 pages https://doi.org/10.1155/2019/2792101

DEFINITIONS, ACRONYMS, ABBREVIATIONS

$\boldsymbol{f_oE}$: E-layer critical frequency

SC21: Solar cycle 21

SC22: Solar cycle 22