Original Research Article

Seasonal variability of foE and nocturnal winter anomaly in E-layer during solar cycles 21 and 22 at the Ouagadougou station

ABSTRACT

This paper aims to study the variability of foE during two solar cycles 21 (SC21) and 22 (SC22) at Ouagadougou station (lat = 12.4°N, long = 358.5°E, local time (TL) = universal time (UT)), to give visibility on the behaviour of foE in this station. We used International Reference Ionosphere (IRI) to collect data from five (5) quiet days of each characteristic month of the season. This study reveals that in this station located at the ionospheric equator, the variability of foE follows the evolution of the sun intensity during the day. There is a correlation between foE and the solar cycle phase, the season, and the time of day. During the day [0500 LT-1900LT], the foE profile does not show a winter anomaly, contrary to what is observed in the F_2 layer at maximum phase of solar cycle 22. On the other hand, a nocturnal winter anomaly was observed related to that observed in the F_2 layer in the same periods. The study of foE at the Ouagadougou station will allow ionospheric physicists to have visibility on the seasonal variability of foE in this station.

Keywords: foE variability, season, solar cycle phase, equinoctial asymmetry, winter anomaly.

1. INTRODUCTION

The ionosphere is a part of the Earth's atmosphere that extends from about 50 km to 1000 km. It contains many particles among which we have nitrogen (N_2) and dioxygen (O_2), major particles. The interaction between X-rays and UV rays from the sun and the particles present in the ionospheric layer causes the ionization of these particles. During the day, the ionosphere, in low latitudes, presents a clear stratification (D, E, F_1, and F_2). During the night, F_1 and F_2 combine to form the F layer, the D layer disappears completely while E remains weakly ionized. Several studies have been conducted at different ionosphere stations around the world [1, 2, 3, 4]. The spontaneous, uncontrolled variation of ionospheric parameters influences the propagation of radio waves, the transmission and/or reception of signals by satellites, positioning systems (GPS for example), the monitoring of the planet Earth [5, 6], etc. A concrete example, the determination of ionospheric parameters allows in the context of telecommunications, the determination of the maximum usable frequency (MUF) for an oblique propagation of radio waves [7]. The importance of a thorough study of the ionosphere is obvious, especially in the equatorial zone where several anomalies frequently occur. In the last decades, several scientists have started to investigate the intrinsic characteristics of the equatorial ionosphere [8, 9, 10, 11, 12]. Measurement stations such as Dakar (lat: 14.8°N; long: 342.6°E), Djibouti (lat: 11.5°N; long: 42.8°E); Korhogo (lat: 9.3°N; long: 356.10°E), Ouagadougou (latitude: 12.5°N; longitude: 358.5°) etc., have been privileged targets. These studies have allowed us to understand the behaviour of the ionosphere in the face of solar irradiation, to determine phenomena such as equinoctial asymmetry and the absence or presence of winter anomalies [13, 14, 15]. These studies are international in scope, as they provide more information about the ionosphere in the equatorial zone and enrich the databases of mathematical model developers. Our study on the variability of the critical frequency of the E layer during geomagnetic quiet days in solar cycles 21 and 22, at the Ouagadougou station (latitude: 12.5°N; longitude: 358.5°) is part of this logic. It will give visibility to the seasonal behaviour of foE at this station, as studies on foE are rare at the Ouagadougou station.

2. METHODOLOGY

The International Reference Ionosphere (IRI) is the most widely used model in the scientific community for the determination of ionospheric parameters [16]. IRI is a semi-empirical model, developed and updated every four years (on average) by a team of researchers, it was initiated by the Committee on Space Research (COSPAR) and the International Union of Radiosciences (URSI) in the late 1960s [17]. The purpose of this work is to establish an international network standard for the specification of ionospheric parameters based on all available global data [18]. The IRI model is based on a photochemical approximation, which describes the E-region fairly well under quiet geomagnetic conditions. Thus, NmE (or foE) is estimated based on studies by Kouris and Muggleton [19, 20] of the model they developed for the CCIR (1973). Based on a large database of ion-probe foE measurements as described by [21], four factors (A, B, C, and D) are used to calculate the foE values (Equation 1).

$$\mathrm{foE}^4 = \mathrm{A.B.C.D} \qquad (1)$$

In this equation, A is a solar activity factor, B is a seasonal variation factor, C is a main latitude factor, D is a time-of-day factor.

$$A = 1 + 0{,}0094\ (\mathrm{COV}_{12} - 66)\ \ \mathrm{MHz} \quad (2)$$

$$B = \cos^{m}\chi_{noon} \quad (3)$$

$$m = \begin{cases} -1{,}93 + 1{,}92\ \cos\varphi \text{ pour } |\varphi| < 32° \\ \ 0{,}11 - 0{,}49\ \cos\varphi \text{ pour } |\varphi| \geq 32° \end{cases} \quad (4)$$

$$C = \begin{cases} 23 + 116\ \cos\varphi \text{ pour } |\varphi| < 32° \\ \ 92 + 35\ \cos\varphi \text{ pour } |\varphi| \geq 32° \end{cases} \quad (5)$$

$$D = \cos^{n}\chi_{a} \quad (6)$$

$$n = \begin{cases} 1{,}2\ \text{ pour } |\varphi| > 12° \\ 1{,}31\ \text{ pour } |\varphi \leq 12° \end{cases} \quad (7)$$

$$\chi_a = \chi - 3\ln\left(1 + e^{\frac{\chi - 89{,}98}{3}}\right) \quad (8)$$

χ_{noon} the solar zenith angle at noon in each season, φ is the geographical latitude and χ_a the zenith angle, COV_{12} is the monthly average of the solar radio noise flux over 10.7 cm, expressed in 10^{-22} Wm^{-2} Hz^{-1} units. The minimum value of foE is given by [22] according to equation 9.

$$foE_{min} = 0{,}121 + 0{,}0015\ (\mathrm{COV}_{12} - 66)\ \mathrm{MHz} \quad (9)$$

These data are collected in measuring stations as well as satellite observations. The Ouagadougou station, located in West Africa, has the following characteristics: lat = 12.5°N, long = 358.5°E. Our choice was the minimum and maximum phase of solar cycles 21 and 22. The quiet days in this work are defined by Aa ≥20nT according to the classification of Jean-Louis Zerbo [23]. The characteristic months of the seasons are December for winter, March for spring, June for summer, and September for autumn. The methodology for determining the critical frequency is based on the calculation of the monthly hourly average of the parameter foE on the five quietest days of each characteristic month. Thus, equation (10) defines the critical frequency as follows:

$$foE_h = \frac{\sum_{j=1}^{5} foE_{h,j}}{5} \quad (10)$$

In Equation10, foE_h denotes the critical frequency of E-layer at time *h* for the characteristic month under consideration, $foE_{h,j}$ is the value of the critical frequency at time *h* for day *d*. Thus, *h* ∈ [0000LT-2400LT], and *d* ∈ [1, 5].

The IRI model allows the extraction of the different $foE_{h,j}$ values. It then becomes possible to determine the value of the critical frequency at time *h* (foE_h) by calculating the average value of the $foE_{h,j}$ parameters over the five quietest days for each characteristic month.

3. RESULTS AND DISCUSSION

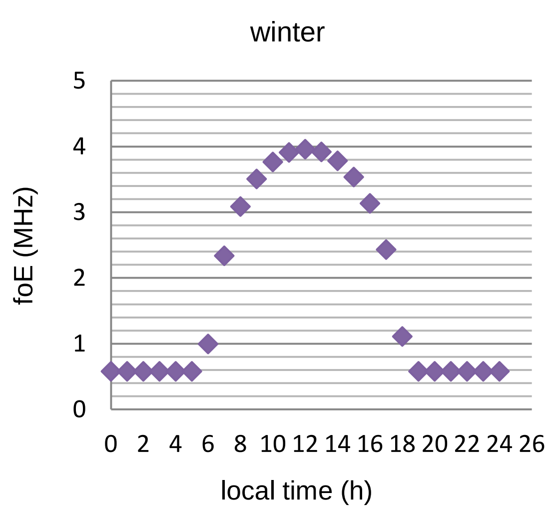
3.1 seasonal variability of foE

For seasonal variability, we use the maximum phase data from solar cycle 22 with Rz=142.6. Solar cycle 22 started in 1985 and ended in 1996. This cycle had duration of eleven (11) years. The selection of the quiet days, according to the pixel diagram is presented in the table1. The treatment of the data according to equation (10) allows us to have the curves.

Table1: Selection of the quietest days at the maximum phase of the solar cycle 22

Phase	Season	Winter	Spring	Summer	Autumn
maximum of the solar cycle 22	Month	December	March	June	September
	Quiet days	10,11,19,21, 29	4,10,16,17,31	16,17,20,21, 30	2,3,27,29,30

The figures below show the variability of the E-layer critical frequency (foE) peak during the four seasons at maximum phase of solar cycle 22. We first isolated each season (the first four figures), to see the foE evolution of each. Then, we confounded the foE variability of the four months (December, March, June, and September) that characterize the four seasons, to highlight the seasonal dependence of foE (Fig. 5). Finally, to highlight the existence or not of winter anomaly phenomena or equinoctial asymmetry, we compared the variability of foE of December and June (fig.6a) and the variability of foE of March and September (fig.6b), respectively.



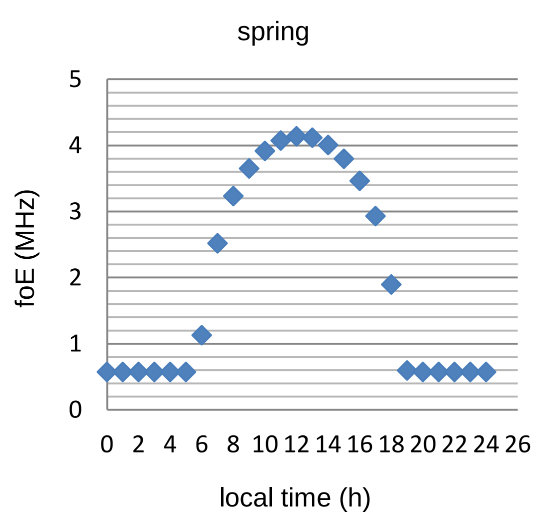
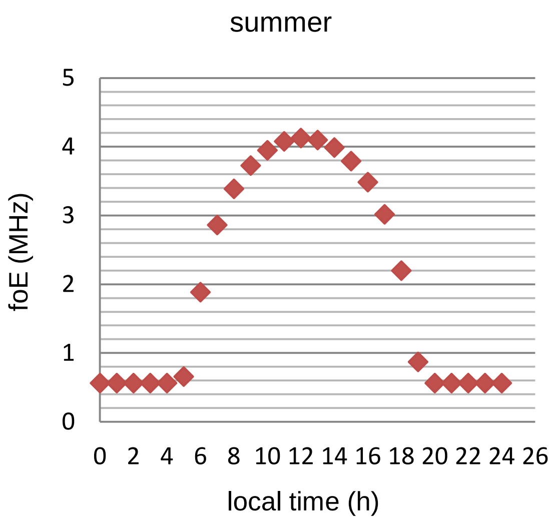


Fig.1. FoE profile in winter 1990

Fig.2. foE profile in spring 1990



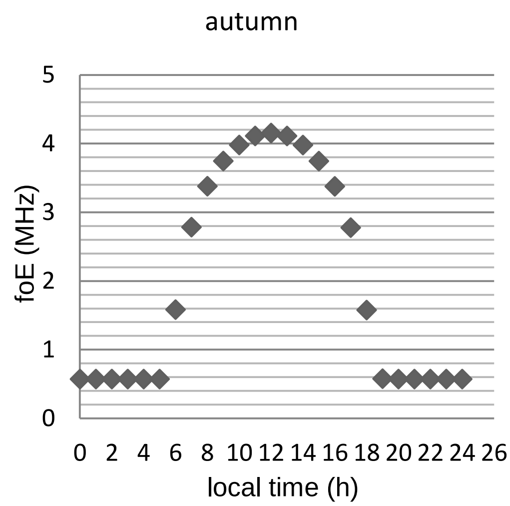


Fig.3. foE profile in summer 1990

Fig.4. Profile of foE in autumn 1990

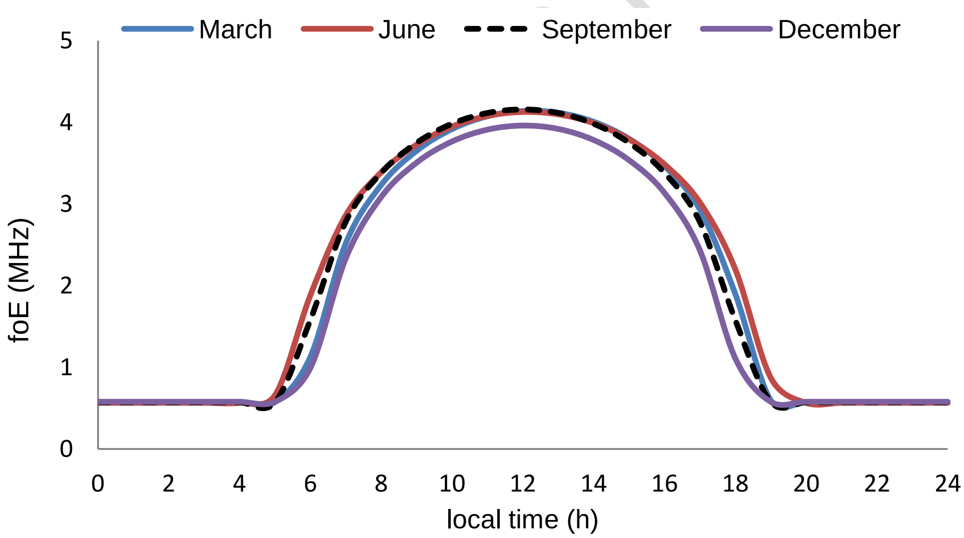


Fig.5. Variability of foE by season during maximum phase of CS22

The seasonal variability of E-layer critical frequency during the maximum phase of SC22 is depicted in fig. 1, 2, 3, and 4.

All profiles show the same pattern with three main phases: constant, increasing, and decreasing. In fig.1, we can observe the variation of foE in winter, which evolves differently over three-time intervals. The period between [00:00h-05:00h] and [19:00h-24:00h] shows a constant evolution of foE. Although low, the E layer during this period remains ionized. This low value of foE reflects a total absence of solar radiation in this area since the ionization of the E layer depends mainly on the X- and UV-rays of the sun. The nocturnal ionization of the E layer according to D. F. Strobel, is related to five main factors: collisions between particles in their motion within the ionospheric plasma; Starlight (this source of ionization varies by a factor of 2±4 with latitude and time of year, with a maximum under the southern Milky Way and Orion regions, it is independent of solar activity); the radiation of the hydrogen and helium lines of the solar energy, scattered by resonance through the Earth's atmosphere on the night side; the solar radiation received at night by resonant scattering of the interplanetary gas and recombination in the F region (the photons produced by the recombination of the ionization of the F region can give an appreciable production at low latitudes, for heights near 150 km). The last three sources of nocturnal ionization vary with solar activity and produce most of the ionization at heights above 140 km [24, 25, 26]. The value of foE in the time interval between [0500LT-1200LT] increases progressively until reaching its maximum value at 1200LT, this is the increasing phase. We note that in this time interval, at the Ouagadougou station, the intensity of solar radiation increases, which induces an increase in the intensity of X-rays and UV, the main factors of ionization of the E layer. In this period, the E layer becomes an obstacle to the propagation of radio waves in a certain frequency range. The decreasing phase is that part of the curve included in the interval [1200LT-1900LT]. The critical frequency of the E layer during these moments undergoes a decrease. This decrease in foE is due to a progressive decrease in solar radiation intensity at the Ouagadougou station.

Fig.2, 3, and 4**,** dealing with the variability of foE in spring, summer, and autumn respectively, have similar interpretations as the previous one. The difference is in the time intervals that constitute each phase in summer. Indeed the constant, increasing and decreasing phase are observed respectively in the time intervals [0000LT-0400LT] and [2000LT-2400LT], [0400LT-1200LT] and [1200LT-2000LT]. These time intervals show that in summer, foE appears earlier (at 0400 LT) and disappears (partially) later (2000 LT) than in other seasons. These results are more or less expected because foE has a dependence on the solar zenith angle (equation 8). If we observe globally (over the four seasons) the variability of foE at the maximum phase of solar cycle 22, we retain that the E layer exists formally between 0500LT and 1900LT and its highest value is recorded at 1200TL which is about 4MHz.

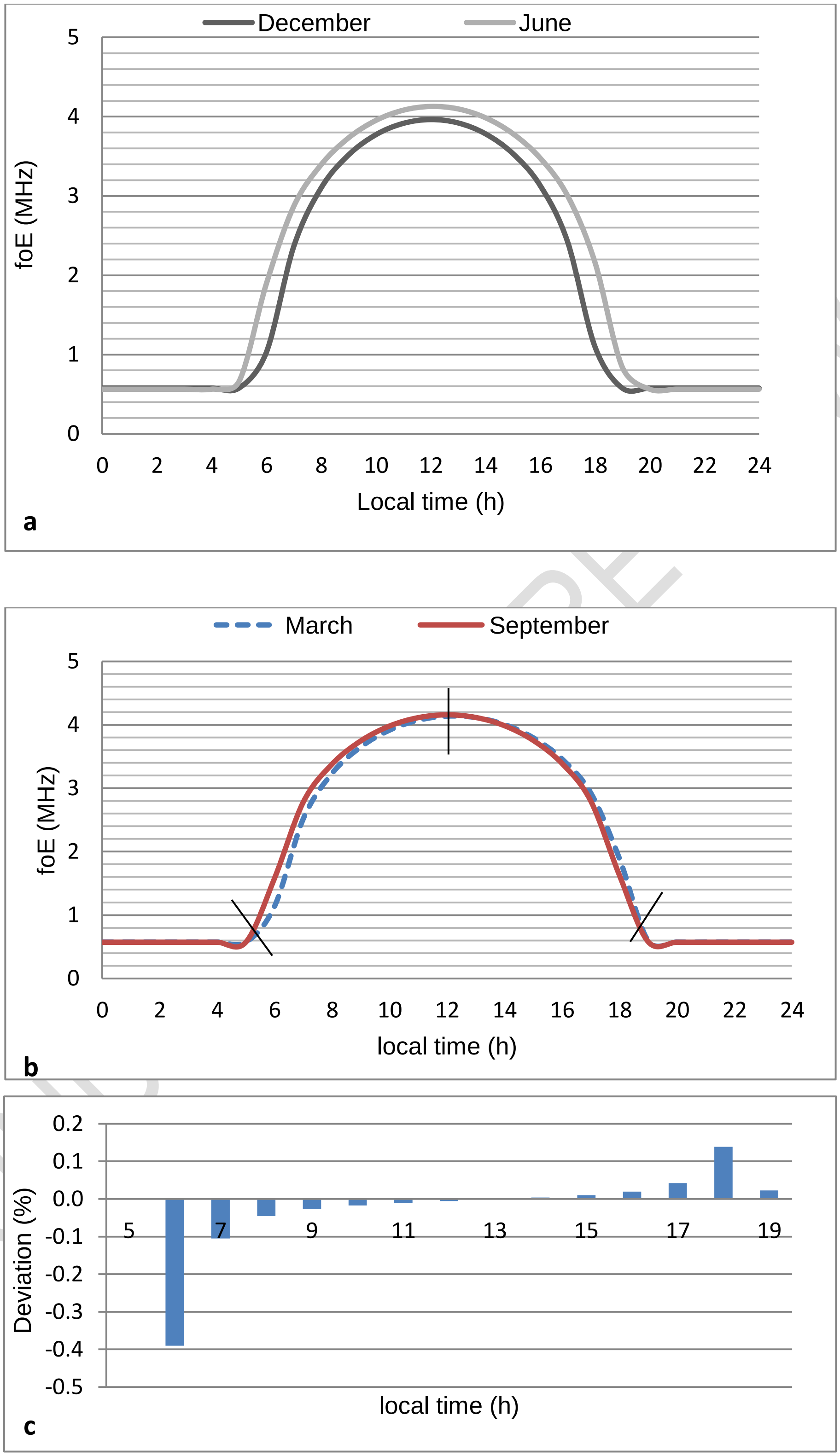


Figure: 6a) variability of foE in December and June; b) variability of foE in

March and September; c) deviation between foE March/September

Fig.5 compares the variability of foE in the four seasons. The variability of foE in winter represented in purple is lower than that in summer represented in red. This difference shows us that foE is highly dependent on the season. Looking at fig.6a, in the time interval between [0500LT-1900LT] the winter anomaly phenomenon, observed at the maximum phase of SC22 in foF_2 study, is not observed in this study. Note that a winter anomaly is observed when the critical frequency values in winter are higher than those in summer. foE profiles for March (spring equinox) and September (summer equinox) do not overlap perfectly over the entire time interval of the day. For example, from 0500LT to 1000LT, foE values in September are higher than those in March; however, from 1600 LT to 1900LT, foE in March is higher than foE in September (fig. 6b). This morphological difference, although visible, does not allow us to show the existence of an equinoctial asymmetry at the maximum phase of SC22 in the E-layer. This can be seen in fig.6c, which depicts low values of deviations between foE March and September.

3.2 Night-time winter anomaly in the E layer

It will be a question of presenting in this part of our work, the highlighting of a winter anomaly on NmE night at the ionospheric equator. We speak of a winter anomaly when the electron density is higher in winter than in summer. This phenomenon has already been observed in the F_2 layer during maximum phase of SC22 at Ouagadougou station and E-layer during the night in the auroral zones [27, 28].

The figures below show the peak electron density variability of the F_2 layer (NmF_2) and the variability of the electron density of the E layer (NmE). In fig.7a, 8a, and 9a, the discontinuous curve in red shows the variability of NmF_2 in December, and the continuous curve in blue shows the variability of NmF_2 in June, which reflects the winter and summer seasons respectively. We note that in winter, NmF_2 is higher than in summer over almost the entire time interval of the day.

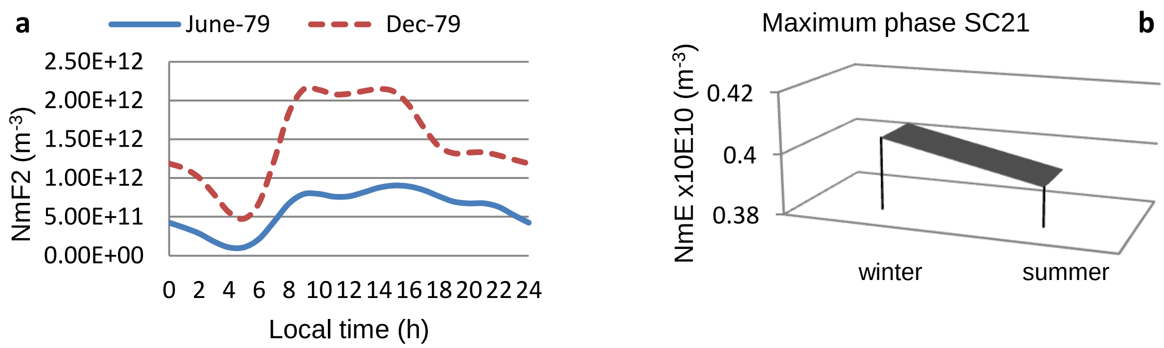


Figure 8: a) Variability of NmF_2, b) variability of NmE: maximum phase of SC21

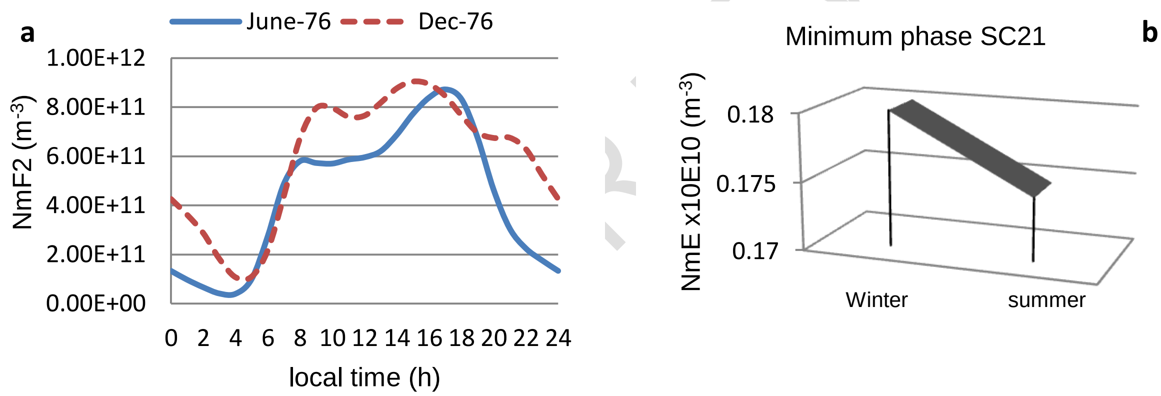


Figure 7: a) Variability of NmF_2, b) variability of NmE: minimum phase of SC21

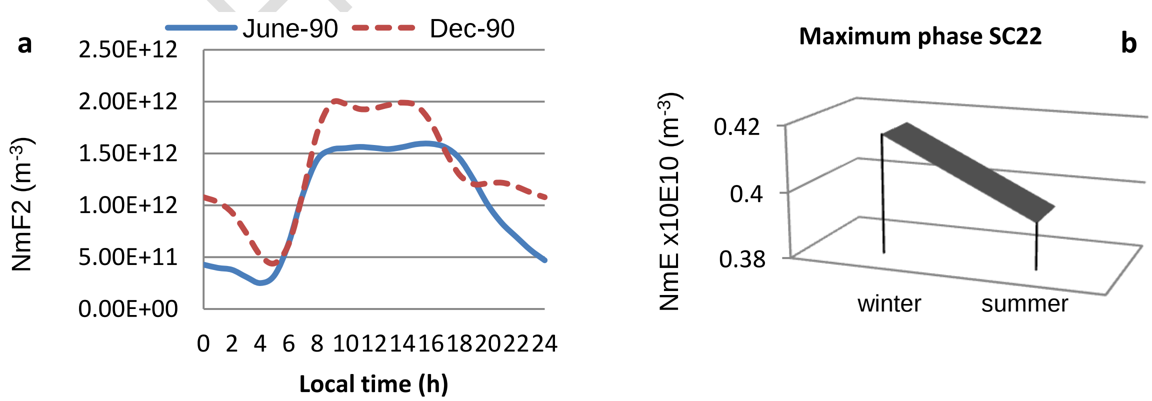


Figure 9: a) Variability of NmF_2, b) variability of NmE: maximum phase of SC22

From fig. 7b, 8b, and 9b**,** from top to bottom, we can observe the night-time variability of NmE at the minimum and maximum phase of SC21 and at maximum phase of SC22. For each of the three variabilities, the electron density is higher in winter than in summer. This observation is made for the NmF_2 variability during the same periods. The values used are those included in the period between [0000LT-0400LT] and [2000LT-2400LT]. In these time intervals, the variability of NmE drops too low values. The fact that the value of NmE is higher in winter than in summer reflects the phenomenon of winter night anomaly in E-layer at the Ouagadougou station. It is important to note that this phenomenon is not observed during the day. A winter anomaly in the F_2 layer leads to a nocturnal winter anomaly in E-layer (fig. 7a, 8a, and 9a). We can thus link the nocturnal ionization of the E-layer to the recombination phenomenon in the F layer [26]. The sunspot number (Rz), the main indicator of solar activity, is a very important factor in the ionization process. Its increase induces a consequent ionization in the different layers of the ionosphere.
The observed winter night anomaly is due to the fact that during these periods, the sunspot number, the main indicator of solar activity, is higher in winter than in summer (data available at https://omniweb.gsfc.nasa.gov), since among the five main factors of the night ionization of the E-layer, three are directly related to solar activity. These results show that the nocturnal E-layer ionization is more related to solar activity and particle motion in the ionosphere than to the season.

4. CONCLUSION

This study presents the variability of the critical frequency of the ionosphere E-layer during two solar cycles 21 (SC21) and 22 (SC22) at the Ouagadougou station, located in the low latitudes (equatorial zone). The profiles of the seasonal variability of the critical frequency have been presented. They show that during the night, the values of the critical frequency are low, reflecting the existence of a residual ionization whose origin is not related to X-rays and UV rays coming directly from the sun but rather to collisions between particles in their movement within the ionospheric plasma, as well as some phenomena related to the activity of the sun. The disappearance of the E-layer during the night is highlighted in this study with the help of almost zero values of the critical frequency. This study also highlights the absence of a winter anomaly and an equinoctial asymmetry, during maximum phase of solar cycle 22, in the period between [0500LT-1900LT], the period during which the E layer is strongly present. However, NmE in winter is higher than NmE in summer during the night at minimum and maximum phase of solar cycle 21 and at maximum phase of solar cycle 22, this highlights a winter anomaly at night in the E layer related to the recombination process of the F layer.

REFERENCES

1. L. Qian, A. G. Burns, P. C. Chamberlin and S. C. Solomon. Flare location on the solar disk: Modeling the thermosphere and ionosphere response. Journal of Geophysical Research. 2010. 115, A09311.

2. H. Rishbeth and I. C. F. Muller- Wodarg. Why is there more ionosphere in January than in July? The annual asymmetry in the F2-layer. Annales Geophysicae. 2006, 24: 3293-3311.

3. E. Nanéma, I. Ouédraogo, C. Zoundi and F. Ouattara. Electron Bulk Surface Density Effect on Critical Frequency in the F2-Layer. International Journal of Geosciences. 2018, 9:572-578.

4. E. Nanéma, M. Konaté and F. Ouattara. Peak of Electron Density in F2-Layer Parameters variability at Quiet Days on Solar Minimum. J. Mod. Phys. 2019, 10: 302-309.

5. Daniel N. Baker. How to Cope with Space Weather. Science. 2002, 297:1486

6. John M. Goodman. Operational communication systems and relationships to the ionosphere and space weather. Advances in Space Research. 2003, 36:2241-2252.

7. P. Wongcharoen, P. Kenpankho, P. Supnithi, M. Ishii, T. Tsugawa. Comparison of E layer critical frequency over the Thai station Chumphon with IRI. Advances in Space Research. 2015, 55: 2131-2138.

8. Wafaa Zaki, Rwziah Mahmood Mohammed, Jawdet Hidayat. The Effect of Sunspots Number on the Total Electron Content (TEC) of the Ionospheric Layer E Over Kirkuk Station for Solar Cycle 24. Kirkuk University Journal/Scientific Studies (KUJSS). 2020.

9. P. S. Brahmanandam, Y.-H. Chu, K.-H. Wu, H.-P. Hsia, C.-L. Su, and G. Uma. Vertical and longitudinal electron density structures of equatorial E- and F-regions. Ann. Geophys. 2011, 29:81-89.

10. F. Ouattara and C. Amory-mazaudier. Statistical study of the equatorial F layer critical frequency at Ouagadougou during solar cycles 20, 21 and 22, using Legrand and Simon's classification of geomagnetic activity. EDP Sci. (2012). DOI: 10.1051/swsc/2012019.

11. E. Nanéma and Frédéric Ouattara. HMF2 quiet time variations at Ouagadougou and comparison with IRI-2012 and TIEGCM predictions during solar minimum and maximum. Archives of Applied Science Research. 1013, 5:55-61.

12. Aristide Marie Frédéric Gyébré, Doua Allain Gnabahou, Frédéric Ouattara. The Geomagnetic Effects of Solar Activity as Measured at Ouagadougou Station. International Journal of Astronomy and Astrophysics. 2018, 8:178-190.

13. Sibri Alphonse Sandwidi, Doua Allain Gnabahou, and Frédéric Ouattara. foF2 Seasonal Asymmetry Diurnal Variation Study during Very Quiet Geomagnetic Activity at Dakar Station. International Journal of Geophysics. 2020. Article ID 8896188.

14. E. Nanéma and F. Ouattara. HmF2 quiet time variations at Ouagadougou and comparison with IRI-2012 and TIEGCM predictions during solar minimum and maximum. Arch. Appl. Sci. Res. 2013, 5:55-61.

15. D. A. Gnabahou, F. Ouattara, E. Nanéma and F. Zougmoré, "foF2 diurnal variability at African equatorial stations: Dip equator secular displacement effect. Int. J. Geosci. 2013. 4 (1145).

16. Inez S. Batista, M.A. Abdu. Ionospheric variability at Brazilian low and equatorial latitudes: comparison between observations and IRI model. Advances in Space Research. 2004, 34:1894-1900.

17. Bilitza, D., Reinisch, B.W. International reference ionosphere 2007: improvements and new parameters. Adv. Space Res. 2008, 42:599-609.

18. Dieter Bilitza, David Altadill, Yongliang Zhang, Chris Mertens, Vladimir Truhlik, Phil Richards, Lee-Anne McKinnell, and Bodo Reinisch. The International Reference Ionosphere 2012 - a model of international collaboration. J. Space Weather Space Clim. 2014, (4) A07.

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

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

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

22. Bilitza, D. International Reference Ionosphere: IRI-90. Greenbelt, Maryland, National Space Science Data Center. 1990, 59-60.

23. Zerbo J-L, Ouattara F, Zoundi C, and Gyebre A. Solar cycle 23 and geomagnetic activity since 1868. Rev. CAMES-Series A. 2012, 12 (2):255-262.

24. Strobel, D.F., Young, T.R., Meier, R.R., Coffey, T.P., Ali, A.W. The night-time ionosphere: E-region and lower F-region. Journal of Geophysical Research. 1974, 79:3171-3178.

25. Strobel, D.F., Opal, C.B., Meier, R.R. Photoionization rates in the night-time E and F-region ionosphere. Planetary and Space Science. 1980, 28:1027-1033.

26. J.E. Titheridge. Modelling the peak of the ionospheric E-layer. Journal of Atmospheric and Solar-Terrestrial Physics. 2000, 62:93-114.

27. M. G. Deminov and G. F. Deminova. Winter Anomaly of the E-Layer Critical Frequency in the Nighttime Auroral Zone. Geomagnetism and Aeronomy. 2017, 57 (5): 584-590.

28. M. G. Deminov and G. F. Deminova, W. inter Anomaly in the Critical Frequency of the Nighttime Polar Ionosphere's E Layer. Cosmic Research. 2019, 57 (1):29-35.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

foE: E-layer critical frequency

foF_2: F_2-layer critical frequency

NmE: E-layer electron density

NmF_2: F_2-layer electron density

SC21: Solar cycle 21

SC22: Solar cycle 22

IRI: International Reference Ionosphere