



RESEARCH ARTICLE

MONTHLY/SEASONAL STATISTICAL STUDY ON THE CONVERGENCE OF foE AT THE OUAGADOUGOU STATION DURING THE SOLAR CYCLE 22

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Abstract

In this paper we studied the variability of the peak of the critical frequency of the ionospheric E layer (foE) during the minimum and maximum phase of solar cycle 22 (SC22) at Ouagadougou station whose geographical coordinates are: 12.4°N and 358.5°E. We made a statistical study with the aim of highlighting the month which would have the value of foE which best converges towards the average of its corresponding season. We prove that the median months of each season have their critical frequencies (foE) that best converge to the average foE values of each season. Thus, for the winter, spring, summer and autumn seasons, the months best suited for a seasonal study of foE are January, April, July and October respectively at solar minimum and maximum. This study also revealed that foE varies according to the time of day, the season and the phase of the solar cycle at Ouagadougou station.

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Introduction:-

The critical frequency of an ionosphere layer is the frequency below which a radio wave is reflected by this layer. The determination of this parameter allows, in the context of telecommunications, the determination of the maximum usable frequency (MUF) for oblique propagation of radio waves. Several researchers have therefore been interested in investigating this layer (Ouattara et al., 2011a, 2011b, 2012a, 2009a, 2013, 2008, 2009b, 2014, 2011c, 2009c, 2015a, 2017; Boutiouta et al., 2006; Xu et al., 2003; Gnabahou et al., 2012, 2013; Wang et al., 2004; Liu et al., 2010; Gnabahou; Richmond et al., 1992; Zhao et al., 2012; Nanéma et al., 2018a, 2013, 2019; Burns et al., 2014; Thiam et al., 2012; Qian et al., 2011; Rishbeth et al., 2000, 2006, 1969). At the Ouagadougou station, the study of the F layer of the ionosphere was carried out by several researchers. The variability of the critical frequency of the F-layer depends on three (3) main factors: the season (spring, summer, autumn and winter), the phase of the sunspot cycle (minimum, ascending, maximum and descending) and the geomagnetic activity (Ouattara et al., 2012b). The foF2 profile differs from station to station (Ouattara et al., 2015b). The variability of the peak of the critical frequency of the F2 layer (foF2) shows a winter anomaly at phase minimum and maximum (Nanéma et al., 2018b). Chen and al tried to highlight the relationship between F10.7 and EUV ticked foF2, but their study proved that F10.7 is not an ideal indicator of foF2 (Chen et al., 2011). As for the E-layer, several works have shown that foE directly affects wave propagation (Wongcharoen et al., 2015). The E-layer does not disappear completely at night, but remains weakly ionised (Zolesi et al 2014). The nocturnal ionisation of the E layer can be largely explained by a

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combination of transport due to the downward phase progression of tidal/planetary waves and meteoric influx (Zhou et al., 1999). foE increases progressively as the intensity of solar irradiation increases (Abe et al., 2013) and reaches its maximum value at local noontime, a value that varies according to the seasons of the year (Mostafa et al., 2018). The NmE electron density is maximum at the equator and decreases with increasing latitude (Chu et al., 2009), it also depends on the season, the solar flux and the local weather (J.E. Titheridge, 2000). In the following we will give our data acquisition method, present the methodology of our work, display our results followed by discussions and make a conclusion.

Data and Methodology:-

The data we use are those of the critical frequency of the E layer (foE) measured at the Ouagadougou station (12.4°N, 358.5°E) at the minimum and maximum phase of solar cycle 22 (Zerbo et al., 2011). We then considered the four seasons of the year which are: winter (December, January and February), spring (March, April and May), summer (June, July and August) and autumn (September, October and November) (Diabaté et al., 2018). Our methodology is based on the calculation of the variability of foE by month, season and standard deviation of foE between a month and a season (%DS). Equation (1) is used to evaluate the monthly variability of foE according to the hours of the day. Equation (2) calculates foE for a season. Equation (3) calculates the standard deviation of foE between a month and a season.

$$foE_{mois} = \frac{\sum_{j=1}^n foE_j}{n} \quad (1)$$

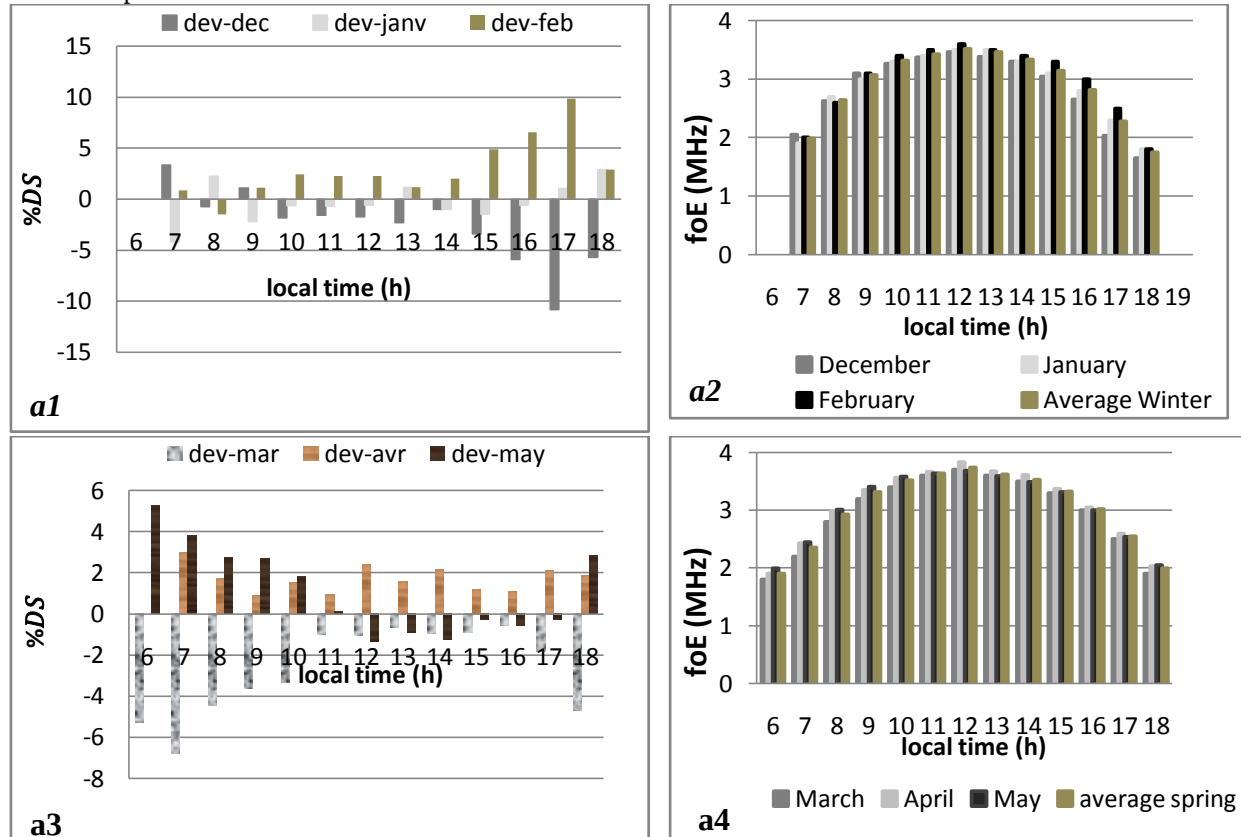
$$foE_{saison} = \frac{\sum_{j=1}^3 foE_{mois j}}{3} \quad (2)$$

$$\%DS = \frac{foE_{mois} - foE_{saison}}{foE_{saison}} \times 100 \quad (3)$$

In these relationships n denotes the number of days in a month. The convergence of foE will be assessed by %DS.

Results and Discussions:-

Minimum phase of SC22



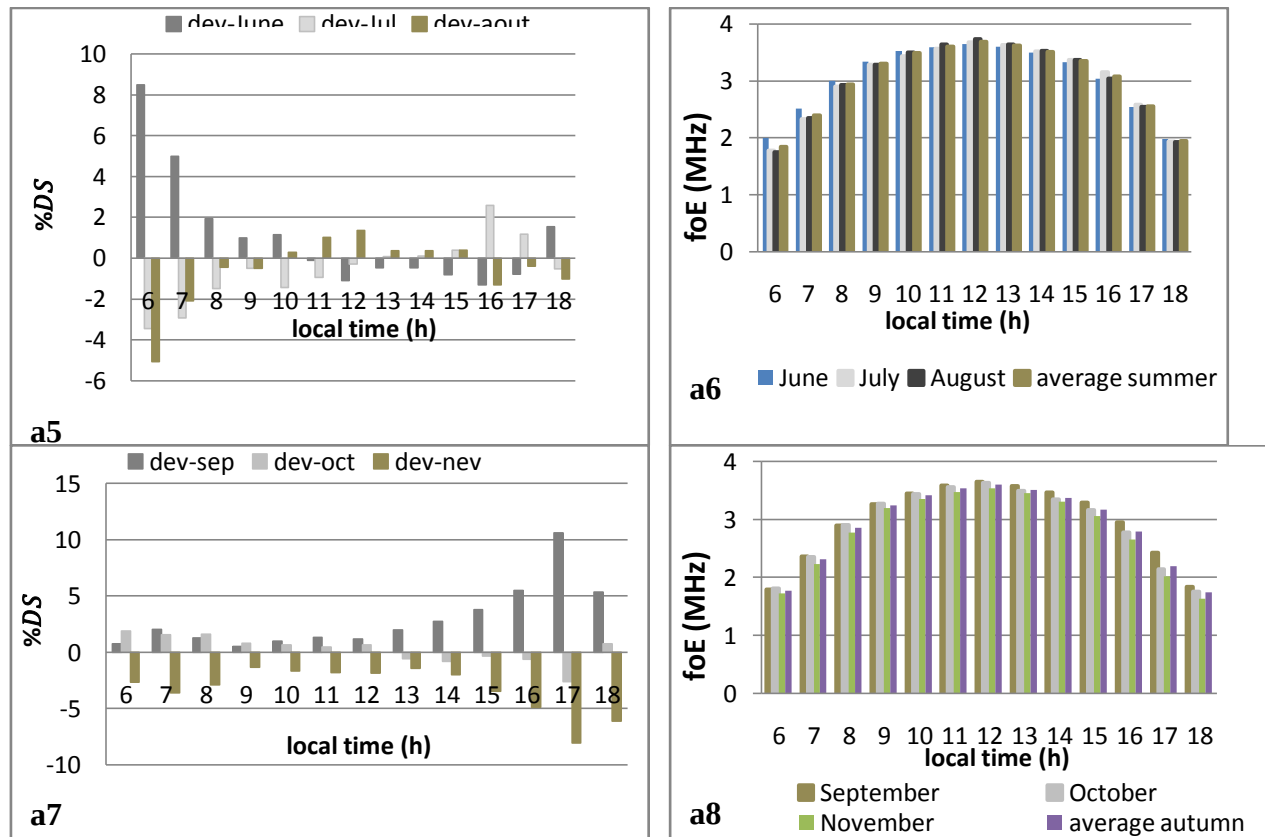
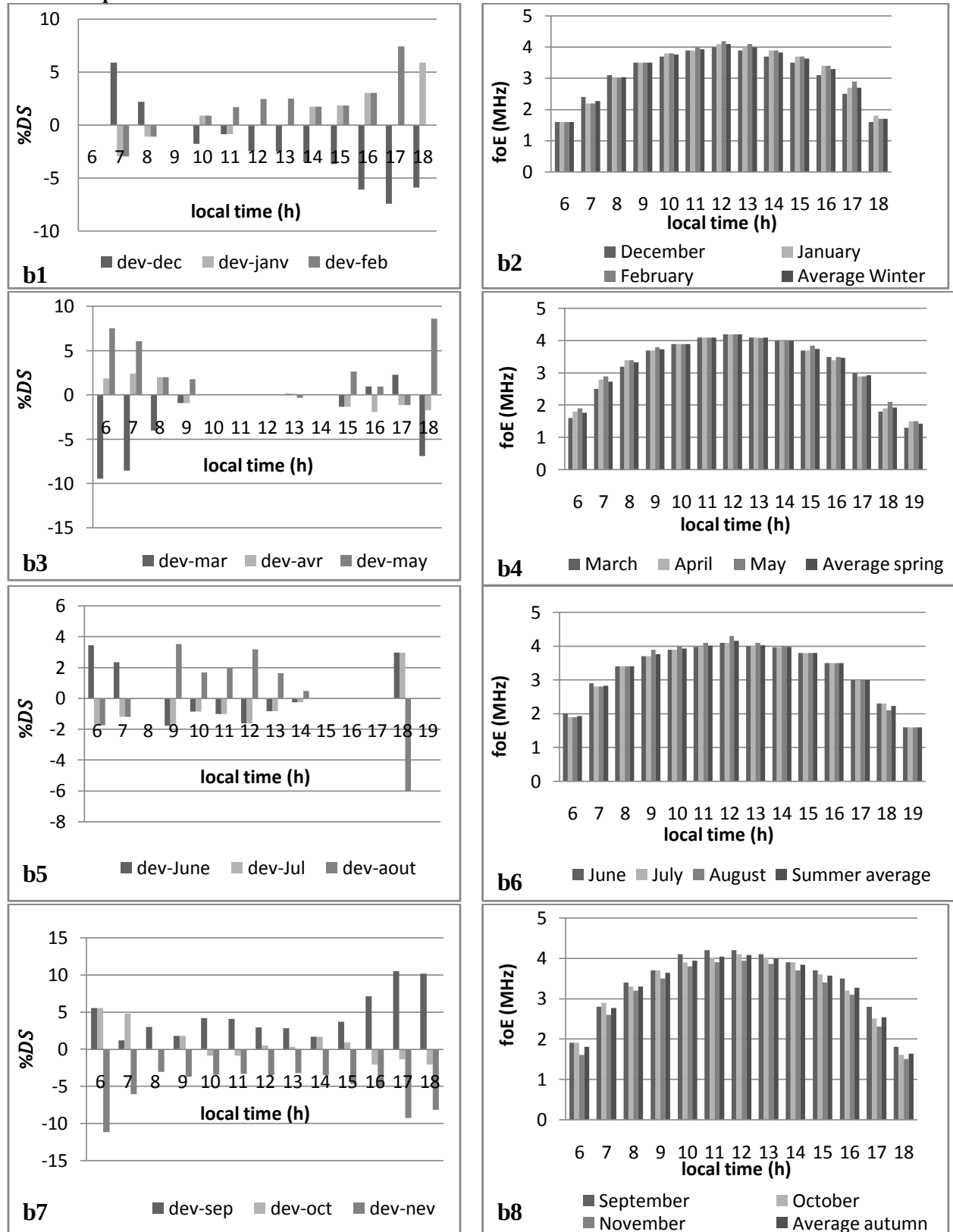


Figure 1:- Monthly/seasonal foE Variabilities and %DS of the four seasons at the phase minimum of SC22

foE variabilities of minimum solar are given in Figure 1.a1 and 1.a8. From Figure 1.a2 and 1.a1, from right to left, we have respectively the monthly/seasonal variability in winter (December, January and February, and the average giving the seasonal variability), the value of %DS of foE in December, January and February. The maximum foE value is reached at 1200 TL with an average value of 3.52 MHz. This diurnal variability of foE in winter is observed from 0700 TL to 1800 TL. The highest deviations occur in the months of December and February, of about 11% and 10% respectively. January, on the other hand, has the lowest values of %DS values, which explains its perfect overlap with the average winter foE profile. We therefore find that it will be the month to which we could refer when conducting a seasonal study of foE. Figures 1.a4 and 1.a3, from right to left, show us the monthly and seasonal evolution of the diurnal variability of foE in spring, as well as the deviations of foE for each month from the mean value in spring. The evolution from 0700 TL to 1800 TL is then observed, with its maximum value of 3.74 MHz being reached at 1200 TL. April has the lowest %DS. However, the highest deviations are observed in March and May (7% and 5.26% respectively). Thus, April being the median month of spring is better suited for a seasonal study of foE in spring because of the low deviations of foE it registers from the average spring value. From right to left in figure 1.a6 and 1.a5, we have respectively the monthly/seasonal variability of foE in relation to the hours of the day, and the percentage deviations that illustrate the difference in value that exists between the different months and the average foE value of the three months considered as summer foE. As for the variability of foE, it is observed from 0600 to 1800 TL with a maximum value at 1200 TL, estimated at 3.69 MHz. As for the deviations, the highest values are 8.5% in June, 3.4% in July and 5% in August. Using the July foE variability for the summer season would therefore be less error-prone. From Figure 1.a7 to 1.a8, the monthly/seasonal variability of foE as a function of local weather and the deviations of foE (month/season) in percent are discussed. Furthermore, the deviations in September and November are the highest (maximum value, $\approx 11\%$ and 8% respectively). The month of October shows low deviations on average. Thus, for a seasonal study, fewer errors would be made by using the October data in autumn.

Maximum phase of SC22**Figure 2:-** Monthly/seasonal foE Variabilities and $\%DS$ of the four seasons at the phase maximum of SC22

foE Variabilities at solar maximum are given in Figures 2.b1- 2.b8. From figure 2.b1 and 2.b2, from right to left, we have respectively the monthly/seasonal variability in winter (December, January and February, and the average giving the seasonal variability), the percentage deviation of foE from December, January and February. The maximum value of foE is reached at 1200 TL with an average value of 4.1 MHz. This diurnal variability of foE in winter is observed from 0600 to 1800 TL. The months of December and February show on average the highest deviations. Statistically we can see a deviation of about 8% at 1700 TL for both months. January, on the other hand, has the smallest deviations, which explains its perfect overlap with the average winter foE profile. We therefore find that it will be the month to which we could refer when doing a seasonal study of foE. If we look at figures 2.b3 and 2.b4, we can see the monthly and seasonal evolution of the diurnal variability of foE in spring, as well as the deviations of foE for each month in relation to the average value in spring. We then observe an evolution from 0600 to 1900 TL, with its maximum value of 4.2 MHz being reached at 1200 TL. April has the smallest deviations of foE from the spring average foE value, so a perfect superposition of the two profiles can be seen in Figure 2.b4. However, the highest deviations are observed in March and May (10% and 9% respectively). These observations lead us to consider the month of April as the most suitable for a seasonal study of foE in spring at solar maximum. From figures 2.b6 and 2.b5 we have respectively the monthly/seasonal variability of foE in relation to the hours of the day, and the percentage deviations that illustrate the difference in value that exists between the different months and the average value of foE of the three months, considered as summer foE. As for the variability of foE, it is observed from 0600 to 1900 TL with a maximum value at 1200 TL, estimated at 4.17 MHz. As for the deviations, the highest values are 3.5% in June, 3% in July and 6% in August. Less error would therefore be made by using the July foE variability for the summer season. From Figure 2.b7 and 2.b8, we can see the monthly/seasonal variability of foE during the autumn season as a function of local time (LT) and the deviations of foE (month/season) in percent (%). Furthermore, the deviations in September and November are the highest (maximum value, $\approx 11\%$ for both months). October shows low deviations on average. Its profile overlaps perfectly with that of the average. Thus, for a seasonal study, fewer errors would be made by using the October data to represent the season.

Conclusion:-

In this work, a statistical study of the variability of the peak of the critical frequency of the E-layer per month/season at the maximum and minimum phase of the solar cycle 22 was carried out. The seasons considered for each phase are: winter (December, January and February), spring (March, April and May), summer (June, July and August) and autumn (September, October and November). It was found that the middle months of each season, i.e. January (winter), April (spring), July (summer) and October (autumn) are the most representative for a seasonal study of foE. This is because the foE profiles of these median months overlap better with those of the mean values we have considered to be that of the respective seasons and their %DS values on average are the lowest. It will therefore make sense for a foE study to use data from January, April, July and October to represent winter, spring, summer and autumn respectively.

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References:-

1. F.Ouattara, and F.Rolland .(2011).“Variability of CODG TEC and IRI 2001 Total Electron Content (TEC) during IHY Campaign Period (21 March to 16 April 2008)at Niamey under Different Geomagnetic Activity Conditions”, *Scientific Research and Essays*, Vol.6pp. 3609-3622.<https://doi.org/10.5897/SRE10.1050>
2. S. Boutiouta, A. H.Belbachir, and H.Dekkiche. (2006). “Contrôle de l’activité ionosphérique à partir des données GPS”, *Téledétection*, Vol. 5, n°4, pp. 325-338.
3. R. Ma, J. Xu, and H. Liao. (2003). “The features and a possible mechanism of semi-annual variation in the peak electron density of the low latitude F2 layer”, *Journal of Atmospheric and Solar- Terrestrial Physics*, vol. 65, no. 1, pp. 47–57.
- 4.F. Ouattara and E.Nanéma. (2011).“hmF2 Quiet Time Variations at Ouagadougou and Comparison with IRI-2012 and TIEGCM Predictions during Solar Minimum and Maximum”, *Archives of Applied Science Research*, 5, 55-61.
- 5.FOuattara and C. A. Mazaudier. (2012).“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*.

6. D. A. Gnabahou and F.Ouattara. (2012).“Ionosphere variability from 1957 to 1981 at Djibouti station”,*Eur. J.Sci. Res.* 73, 382–390.
- 7.W. Wang, M.Wiltberger, A.G. Burns, S. C.Solomon, T. L.Killeen, N. Maruyama, and J.G. Lyon. (2004).“Initial Results from the Coupled Magnetosphere-Ionosphere Thermosphere Model: Thermosphere-Ionosphere Responses”,*Journal of Atmospheric and Solar-Terrestrial Physics*, 66/1516,1425.
<https://doi.org/10.1016/j.jastp.2004.04.008>
- 8.L. Liu, M. He, X. Yue, B. Ning, and W. Wan. (2010) “Ionosphere around equinoxes during low solar activity,” *Journal of Geophysical Research*, vol. 115, no. A9, article A09307.
9. D.A.Gnabahou, F. Ouattara, E. Nanéma, and F. Zougmore. (2013).“foF2 diurnal variability at African equatorial stations: Dip equator secular displacement effect”,*Int. J. Geosci.* 4, 1145.
- 10.A. D. Richmond, E. C. Ridley, andR.G. Roble.(1992).“A Thermosphere/IonosphereGeneral Circulation Model with Coupled Electrodynamics”,*Geophysics Research Letter*, 19, 60.<https://doi.org/10.1029/92GL00401>
11. H. Zhao and Q. G. Zong. (2012). “Seasonal and diurnal variation ofgeomagnetic activity: Russell-McPherron effect during different IMF polarity and/or extreme solar wind conditions,” *Journal of geophysical research*, vol. 117, no. A11, article A11222.
12. E.Nanema, D. A. Gnabahou, C. Zoundi,F. and Ouattara.(2018).“Modeling the Ionosphere during Quiet Time Variation at Ouagadougou in West Africa”,*Int. J. Astron. Astrophys*, 8, 163.
13. E. Nanéma, and F. Ouattara. (2013). “HmF2 quiet time variations at Ouagadougou and comparison with IRI-2012 and TIEGCM predictions during solar minimum and maximum”, *Arch. Appl. Sci. Res.* 5, 55–61.
- 14.E. Nanéma, M. Konaté, and F. Ouattara.(2019).“Peak of Electron Density in F2-Layer Parameters Variability at Quiet Days on Solar Minimum”, *J. Mod. Phys.* 10, 302–309.
- 15.F. Ouattara. (2009). “Relationship between geomagnetic classes’ activity phases and their occurrence during the sunspot cycle”, *Ann. Geophys*, 52, 107–116.
16. F. Ouattara .(2013).“IRI-2007 foF2 predictions at Ouagadougou station during quiet time periods from 1985 to 1995”, *Arch. Phys. Res*, 4, 12–18.
- 17.F. Ouattara, and C. A. Mazaudier. (2008).“Solar–geomagnetic activity and Aa indices toward a Standard”, *Journal of Atmospheric and Solar-Terrestrial Physics* 1736– 1748.
- 18.F. Ouattara, and C. A. Mazaudier. (2009). “Solar–geomagnetic activity and Aa indices toward a standard classification”,*J. Atmospheric Sol.-Terr. Phys*, 71, 1736–1748.
19. F. Ouattara andE.Nanéma. (2014).“Quiet Time foF2 Variation at Ouagadougou Station and Comparison with TIEGCM and IRI-2012 Predictions for 1985 and 1990”, *Phys. Sci. Int. J.* 892–902.
- 20.F. Ouattara, and J. L. Zerbo .(2011).“Ouagadougou station F2 layer parameters, yearly and seasonal variations during severe geomagnetic storms generated by coronal mass ejections (CMEs) and fluctuating wind streams”, *Int. J. Phys. Sci*, 6, 4854–4860.
21. A. G. Burns, W. Wang, L. Qian. (2014). “On the solar cycle variation of the winter anomaly,” *Journal of Geophysical Research: Space Physics*, vol. 119, no. 6, pp. 4938–4949.
- 22.F. Ouattara, C. A. Mazaudier, M. Menvielle, P. Simon, and J. P. Legrand.(2009).“On the long term change in the geomagnetic activity during the 20th century”.
23. F. Ouattara, S. Kaboré, A.M.F. Gyébré, and J-L.Zerbo.(2015).“CMEs’ Shock Occurrences from Solar Cycle 11 to solar Cycle 23”,*European Journal of Scientific Research* 130, 153–159.
24. F. Ouattara, J-L.Zerbo, M. Kaboré, and R. Fleury. (2017). “Investigation on equinoctial asymmetry observed in Niamey Station Center for Orbit Determination in Europe Total Electron Content (CODG TEC) variation during~ solar cycle 23”,*Int. J. Phys. Sci.* 12, 308–321.
- 25.N. Thiam, F. Ouattara, A. Gnabahou, C. A. Mazaudier, R. Fleury, and P. L. Duchesne. (2012). “Variation de la Fréquence Critique de la Couche F2 (foF2) de la Station de Dakar avec le Cycle Solaire”,*J. Sci.* 11, 16–20
- 26.L. Qian,A. G. Burns, P. C. Chamberlin and S. C. Solomon. (2011).“Flare location on the solar disk: Modeling the thermosphere and ionosphere response”, *Journal of Geophysical Research*, 115, A09311,doi:10.1029/2009JA015225.
- 27.H. Rishbeth,I. C. F. Muller-Wodarg, L. Zou, T. J. Fuller-Rowell, G. H.Millward, R. J. Moffett, D. W.Idenden, and A. D. Aylward. (2000).“Annual and semiannual variations in the ionospheric F2-layer: II. Physical discussion”, *AnnalesGeophysicae*, 18(8), 945–956.
- 28.H. Rishbeth, and I. C. F. Muller-Wodarg. (2006).“Why is there more ionosphere in January than in July? The annual asymmetry in the F2-layer”, *AnnalesGeophysicae*, 24, 3293–3311.
- 29.H. Rishbeth, O. Gariott. (1969).“Introduction to ionospheric physics”, *International Geophysics Series*, pp. 160-189. Academic Press, New York.

30. F. Ouattara and C. A. Mazaudier. (2012). "Statistical study of the equatorial F2 layer critical frequency at Ouagadougou during solar cycles 20, 21 and 22, using Legrand and Simon's classification of geomagnetic activity", *J. Space Weather Space Clim.* 2, A19.
doi: 10.1051/swsc/2012019
31. F. Ouattara , A. Mahamat Nour, F. Zougmore.(2015). "A comparative study of seasonal and quiettime foF2 diurnal variation at Dakar and Ouagadougou stations during solar minimum and maximum for solar cycles 21-22", *European Scientific Journal August*, edition vol.11, No.24 ISSN: 1857 - 7881 (Print) e - ISSN 1857- 7431.
32. E. Nanéma, I. Ouédraogo, C. Zoundi, F. Ouattara.(2018). "Electron Bulk Surface Density Effect on Critical Frequency in the F2-Layer", *International Journal of Geosciences*, (9) 572-578, <https://doi.org/10.4236/ijg.2018.99033>
33. Y. Chen, L. Liu, and W. Wan. (2011). "Does the F10.7 index correctly describe solar EUV flux during the deep solar minimum of 2007-2009?", *Journal of Geophysical Research*, vol. 116, a04304, doi:10.1029/2010JA016301
34. P. Wongcharoen, P. Kenpankho, P. Supnithi, M. Ishii, T. Tsugawa.(2015). "Comparison of E layer critical frequency over the Thai station Chumphon with IRI", *Advances in Space Research* 55 2131-2138, <http://dx.doi.org/10.1016/j.asr.2015.01.031>
35. B. Zolesi and L. R. Cander. (2014). "Current and Future Trends in Ionospheric Prediction and Forecasting", *Springer Geophysics*, DOI: 10.1007/978-3-642-38430-1_10.
36. Q. H. Zhou .(1999). "Incoherent scatter radar study of the impact of the meteoric influx on nocturnal E-region ionization", *Geophysical Research Letters*, vol. 26, no. 13, pages 1833-1836.
37. O.E. Abe, A.B. Rabiou and J.O Adeniyi.(2013). "Variability of foE in the equatorial ionosphere with solar activity", *Advances in Space Research* 51 69-75, doi.org/10.1016/j.asr.2012.08.010
38. M. G. Mostafa, H. Haralambous, and C. Oikonomou. (2018). "Statistical Ionospheric E Layer Properties Measured with the Cyprus Digisonde and Comparisons with IRI Predictions", *Advances in Space Research* 61(1):337-47, doi.org/10.1016/j.asr.2017.10.029.
39. Y-H. Chu, K-H. Wu and C-L. Su.(2009). "A new aspect of ionospheric E region electron density morphology E region", *journal of geophysical research*, vol. 114, A12314, doi:10.1029/2008JA014022
40. J.E. Titheridge.(2000). "Modelling the peak of the ionospheric E-layer", *Journal of Atmospheric and Solar-Terrestrial Physics* 62 93±114, PII: S13 6 4- 68 2 6(99) 0 01 0 2- 9
41. J-L. Zerbo, F. Ouattara, C. Zoundi, and A. Gyebre.(2011). "Solar cycle 23 and geomagnetic activity since 1868", *Rev. CAMES-Serie A*, 12 (2): 255-262,
42. A. Diabaté, F. Ouattara and J-L. Zerbo. (2018). "Annual and Diurnal Variabilities in the Critical Frequency (foF2) during Geomagnetic Fluctuating Activity over Solar Cycles 21 and 22 at Ouagadougou", *Atmospheric and Climate Sciences*, (8) 435-445, <https://doi.org/10.4236/acs.2018.84029>.