Indian Journal of Radio & Space Physics
Vol 45, March 2016, pp 5-10

Equatorial M(3000)F2 estimation of F2-layer models peak heights during high solar activity

O E Ehinlafa
Physics Department, University of Ilorin, Ilorin, Nigeria
E-mail: emmanolu4u@yahoo.com

Received 28 April 2015; revised 22 February 2016; accepted 26 February 2016

The validation of M(3000)F2 estimation of h_mF2 based on four different formulated models, viz: Shimazaki, Bradley & Dudeney, Dudeney and Bilitza *et al.* at an equatorial station in West Africa are carried out during high solar activity period (1991) to ensure its conformity with observed and International Reference Ionosphere (IRI) model. Fifteen (15)-day local time data during the solstice months (December and June) and equinox months (March and September) are selected and analyzed. The results obtained show that the M(3000)F2 estimation of h_mF2 from the ionosonde measured values [using the Ionospheric Prediction Service (IPS-42) sounder] compared to the observed values (deduced using an algorithm from scaled virtual heights of quiet day ionograms) are highly correlated with Bilitza model. International Reference Ionosphere (IRI-2012) model for the equatorial region also agrees with the formulation developed by Bilitza *et al.* for the four different seasons of the year. Also, h_mF2 is highest (548 km) in summer (June solstice) season and lowest (471 km) in autumn (March equinox) season with daytime peaks occurring at 1300 hrs LT during the solstices and at 1000 hrs LT during the equinoxes, respectively. Also, the post-sunset peaks are highest (596 km) in the winter season (December solstice) and lowest (556 km) in the autumn season (September equinox) both occurring during 1800 – 2100 hrs LT.

Keywords: F2-layer peak height, Peak electron density height, High solar activity, Equatorial M(3000)F2 estimation

PACS Nos: *94.20.dt*; *94.20.dj*; 96.60.Q-

1 Introduction

The morphological study of the equatorial ionosphere is usually based on peak electron density parameters. Majority of studies on electron density profiles in the last few decades in the mid and high latitude has assisted in modeling effort. However, in recent years, the study of topside electron density profiles have been carried out to enhance modeling efforts, particularly in the African continent *viz-a-viz* equatorial region because of the presence of few ionospheric stations. This has imposed a major problem on global ionospheric modeling. In this study, the morphology of M(3000)F2 estimation of peak electron density height profiles of the F2-layer of formulated models from an equatorial station in the African region was investigated. The first of the models which depends mainly on the propagation factor M(3000)F2 developed by Shimazaki[1] was:

$$h_m F2 / Km = \frac{1490}{M(3000)F2} - 176 \qquad \ldots(1)$$

The performance of the above formulation was enhanced by Bradley & Dudeney[2], Dudeney[3] and Bilitza *et al.*[4] in the field by introducing a correction factor ΔM into the equation. Their models do not only depend on the propagation factor but also on the critical frequencies for F2-layer (foF2) and E–layer (foE) introduced into the formulated models to give h_mF2 as:

$$h_mF2/Km = \frac{1490}{M\,(3000)F2+\Delta M} - 176 \qquad \ldots (2)$$

$$\Delta M = \frac{0.18}{\frac{f_0F_2}{f_0E} - 1.4}\,(\text{Bradley \& Dudeney}^2) \qquad \ldots (2.1)$$

$$\Delta M = \frac{0.253 \pm 0.008}{\frac{f_0F_2}{f_0E} - 1.215} - (0.012 \pm 0.009)\ \ (\text{Dudeney}^3) \qquad \ldots (2.2)$$

$$\Delta M = \frac{F_1F_4}{\frac{f_0F_2}{f_0E} - F_2} - F_3 \quad (\text{Bilitza } et\ al.^4) \qquad \ldots (2.3)$$

where, $F_1 = 2.23\times10^{-3} R_z - 0.222 \qquad \ldots (2.3a)$

$$F_2 = 1.2 - 1.16 \times 10^{-2} \exp(2.39 \times 10^{-3} R_z) \quad \dots (2.3b)$$

$$F_3 = 0.00064(R_z - 25) \quad \dots (2.3c)$$

$$F_4 = 1 - \frac{R_z}{150} \exp\left[-\left(\frac{\phi}{40} \right)^2 \right] \quad \dots (2.3d)$$

where, R_z, is the monthly mean sunspot number for each month in question; and ϕ, the latitudinal angle in degrees. The numerical coefficients used by Bradley & Dudeney[2] were derived from the application of magneto-ionic theory to model N(h) profiles; the coefficients developed by Dudeney[3] were derived from a statistical analysis of the data from the Argentine Islands (65°S, 64°W) ionosonde, and those derived by Bilitza *et al.*[4] were from incoherent radar scatter measurements at Millstone Hill, Arecibo and Jicamarca.

Berkey & Stonehocker[6] compared the mean hourly values of electron density profile generated from the Shimazaki[1], Bradley & Dudeney[2], Dudeney[3] and Bilitza *et al.*[4] models. The individual result of h_mF2 obtained was compared with real height values of h_mF2 for a mid-latitude station, Logan in Utah (41.6°N, 111.6°W) with the results showing a high degree of correlation with real height values. It was then concluded that all the models followed the expected morphology but as far as mid-latitude is concerned, Bradley & Dudeney[3] is most suitable for the prediction of the peak height of electron density for the F2-layer.

The result of M(3000)F2 estimation of h_mF2 from the dependent parameters are compared with both the observed and IRI model of the same equatorial station. A good prediction of h_mF2 usually gives a mean value of this parameter taking into consideration the diurnal, seasonal, solar cycle, and the coordinates of the location of the station on the surface of the earth. The M(3000)F2 estimation of h_mF2 with the introduction of the correction factor is expected to increase the capability of the models as compared with both the real heights and IRI model[7].

The International Reference Ionosphere is probably the most mature of the models employed here, having undergone more than two decades of scrutiny and improvement. It is empirical model based on a wide range of ground and space data. The IRI-2000 model, is based on experimental data and has been widely used for predictions[8,9]. Also, the IRI-2007 model, which has incorporated the topside electron density, electron density changes in the lower ionosphere, plasma temperatures, ion composition and spread F have been used by some researchers to make predictions[10]. Finally, the IRI-2012 is the latest version of the model, which has been improved significantly and new parameters have been introduced[5]. This model, which is known as the predicted h_mF2 values, has been used in this study. Although, this model does not have any modification on the electron density height particularly when compared to the IRI-2000 model[8,11].

2 Data and Analysis

Data used is from Ouagadougou, Burkina Faso (geog lat 12.4°N, geo long 1.5°W, magnetic dip 5.9°N) for the year 1991, a period of high solar activity. The hourly, monthly mean values of M(3000)F2, f_oF2 and f_oE are used for estimating peak F2-layer height (h_mF2) for this study. Winter, spring, summer, and autumn seasons are represented by January (December solstice), April (March equinox), July (June solstice), and October (September equinox), respectively. The monthly mean sunspot number Rz for the four seasons under study are: 136.9, 140.0, 173.7 and 144.1, respectively. Fifteen-day records from each of these months were chosen. Days chosen are magnetic quiet days and those with ionograms good enough to be scaled. These were then used to obtain the peak F2–layer height for the four different models. The results covered 24 hours for each of the days chosen.

For the observed values, an inversion program, the Automatic Real Time Ionogram Scaler with True Height (ARTIST) program NHPC (a program for inversion of scaled ionogram traces into electron density profiles), developed by Huang & Reinisch[12], was used to derive the electron density profile from digital ionograms recorded at Ouagadougou. The extracted observed values of the F2-layer height (h_mF2) were obtained from those profiles. The IRI-2012 model values of h_mF2 covering 24 hours for each month under consideration were obtained from the IRI-2012 computer based software program. In the IRI-2012 model, the values of M(3000)F2, f_oF2 and f_oE were taken from experimental values embedded in the program.

3 Results

3.1 Models M(3000)F2 estimation of h_mF2

The results of h_mF2 computed using the four formulated models are presented here. The results of

f_oF2, f_oE, and M(3000)F2 hourly mean values calculated, the h_mF2 results computed for the four different seasons (i.e. winter, spring, summer, and autumn) compared with both the observed and the IRI-2012 model values are presented. Figures 1(a-d) show the h_mF2 plots for the four different seasons. The observed and IRI-2012 model values are also indicated on each of the figures along with the four models.

The morphologies of h_mF2 of all the models for the four different seasons are similar to both the observed and IRI-2012 model value. A slight fall in h_mF2 for all the seasons at sunrise during 0600-0700 hrs LT was observed except there is a gentle rise in h_mF2 for winter (December solstice) season. Thereafter, h_mF2 rises sharply during 0700–1100 hrs LT but the peak occurrence time for equinoxes is at 1000 hrs LT and for solstices, it is at 1300 hrs LT. It has a very small variation during 1100–1400 hrs LT. During this period, h_mF2 has magnitudes varying from 417 to 548 km for all the models in all the season. After this period, h_mF2 begins to decrease and gets to a minimum during 1700–1800 hrs LT. A post-sunset peak occurs during 1800-2100 hrs LT for all models in all seasons. The post-sunset peak is highest (596 km) in the winter season (December solstice) and lowest (556 km) in the autumn season (September equinox). A sharp decrease is observed to occur in all the seasons after this post-sunset peak except in the spring season (March equinox), where h_mF2 was found to rise in a slightly undulating manner. The h_mF2 decreases progressively to attain a minimum value at around 0500 hrs LT. The lowest value of 293 km is noticed in autumn (September equinox) season. A pre-sunrise minimum is observed during 0500–0700 hrs LT with value varying from 277 km to 387 km for all the models in almost all the seasons

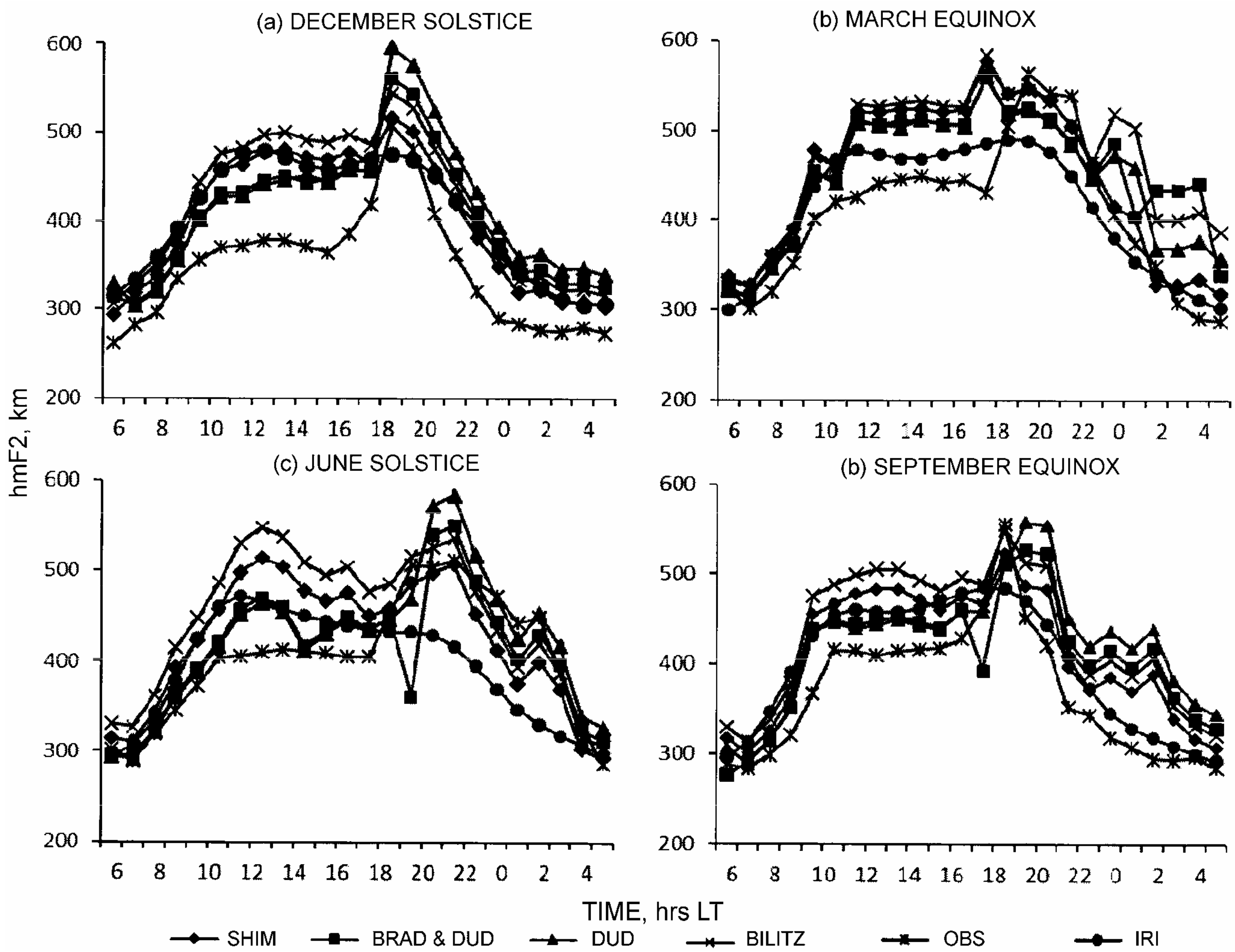

Fig. 1 — Models M(3000)F2 estimation of h_mF2 compared with both the observed and the IRI-2012 model during: (a) December solstice; (b) March equinox; (c) June solstice; and (d) September equinox during high solar activity in 1991

3.2 Comparison of models h_mF2 estimated with observed and IRI model

The degree of similarities and dissimilarities are observed among the models with the observed and the IRI-2012 model morphologies. It is shown from the degree of deviation among the models considering the four different seasons, i.e. both solstices (December and June) and equinoxes (March and September) that the best predicted performance for the equatorial h_mF2 is the Bilitza mode[1].

For the solstices, the best predicted model (Bilitza) compared with the observed deviate more in winter (December solstice) season than in the summer (June solstice) season while the deviation of the predicted model (Bilitza) from the IRI is small in the summer (June solstice) season than in winter (December solstice) season during 0600–1000 hrs LT. The deviation of h_mF2 between the predicted model (Bilitza) and the observed has magnitude in the range of 45 - 71 km as compared with h_mF2 deviation between the predicted model (Bilitza) and the IRI-2012 model, which has magnitude in the range 22 - 35 km. During 1100 – 1600 hrs LT, the deviation of the predicted model (Bilitza) from the observed values is large in summer (June solstice) season with magnitude varying in the range 83 - 138 km when compared to the deviation of the predicted model (Bilitza) from the IRI-2012 model in winter (December solstice) season with magnitude varying in the range 16 - 28 km during the daytime. At nighttime during 2300–0500 hrs LT, a slight deviation of all the four models away from the IRI was observed in December solstice when compared to the large deviation of all the four models away from the observed values. However, a slight deviation of all the four models away from the observed values in June solstice was observed when compared to the large deviation of all the four models away from the IRI model.

During the equinoxes, the deviation of predicted model (Bilitza) from the observed is more in autumn (September equinox) season than in the spring (March equinox) season; while the deviation of Bilitza model from the IRI model is small in the spring (March equinox) season than in autumn (September equinox) season during 0600–1000 hrs LT. The magnitude of h_mF2 deviation between the Bilitza model and the observed one varies from 42 to 109 km; and the magnitude of h_mF2 deviation between the predicted model (Bilitza) and the IRI-2012 model varies from 34 to 60 km. The deviation of the Bilitza model from the observed values is large in spring (March equinox) season with magnitude varying from 38 to 83 km as compared to the deviation of the Bilitza model from the IRI-2012 model in autumn (September equinox) season with magnitude varying from 11 to 48 km during 1100–1600 hrs LT. During nighttime of 2300–0500 hrs LT, a large deviation of all the four models away from the observed values in September equinox was observed as compared to the slight deviation of all the four models away from the IRI model. However, a slight deviation of all the four models away from the IRI was observed in March equinox as compared to the large deviation of all the four models away from the observed values.

4 Discussion

The study on the equatorial ionosphere shows that the general morphology of the h_mF2 is characterized with two peaks, viz. daytime peak and post-sunset peak. Figure 1(a-d) shows the comparison of h_mF2 values of the observed and the IRI-2012 models. The four seasons (equinoxes and solstices) included in this has enabled to observe the differences in them.

The study of equatorial ionosphere shows that h_mF2 have specific values and variation during 1000–1600 hrs LT at high solar activity for the four seasons as in seen in Fig.1(a–d). During daytime, h_mF2 is highest (548 km) in summer (June solstice) season and lowest (471 km) in spring (March equinox) season. The difference between daytime peak values and post–sunset peak values vary from 48 km to 85 km. The daytime peaks are higher during the solstices at 1300 hrs LT than during the equinoxes at 1000 hrs LT. These differences are attributed to the effect of winds and the E × B force on the plasma in the equatorial region[13]. The electric field (E) in the equatorial ionosphere E-region is eastward during the day and westward at night. The electric field E in conjunction with the earth's magnetic field B, which is about horizontal around the equatorial region produces E × B force that causes upward vertical plasma drift when E is eastward (daytime) and downward when E is westward (nighttime)[14]. According to Anderson & Matsushita[15], the vertical E × B drift velocity (observed at Jicarmarca) primarily accounts for the seasonal differences in h_mF2 decrease with the increase in electron density, N occurred as parameters measured in Huancayo at the magnetic equatorial.

The present obtained diurnal and seasonal variations of h_mF2 generally agree with those of Rajaram & Rastogi[16]. Their observation of h_mF2 increase during high solar activity is confirmed in present result. The sharp decrease observed here in h_mF2 was reported in their work also. They ascribed this decrease to the drifting of ionization away from the equator.

A review of drift measurements taken at Jicamarca, an equatorial station, shows diurnal, seasonal and solar cycle variations in vertical drift, particularly during the time interval 0600 – 2100 hrs LT (Ref. 17) follows the same trend as the variations of h_mF2 observed in the present study.

All the h_mF2 models tested portrayed the morphology expected of the electron density peak height for equatorial ionosphere showing seasonal and diurnal variations during 0600 - 2100 hrs LT. At night, when the underlying ionization is negligible (and when the equipment cannot see the E-layer because its frequency is very low), the difference between the values of the models and the reference model (IRI model) is negligible. These observations are in agreement with Ehinlafa & Adeniyi[18], Ouattara & Zerbo[19], Ouattara &Amory-Mazaudier[20], Kouris *et al.*[21] and Ouattara *et al.*[22,23] for the seasonal and diurnal variations of F2 layer peak height based on M(3000)F2 noticed during high solar activity for all the seasons, and also, in a fairly good agreement with Jesus *et al.*[24] during the nighttime in all the seasons.

5 Conclusion

It is inferred that the use of the propagation factor [M(3000)F2] in estimating h_mF2 is highly dependable. All the models are quite good in that as they gave good prediction of the F2-layer peak height following the same pattern with the observed and the IRI for the equatorial ionosphere as observed at Ouagadougou. The post-sunset h_mF2 compared to daytime h_mF2 is more pronounced because h_mF2 around the magnetic equator is determined by the vertical E × B drift. It is possible because the post-sunset upward drift is higher compared to daytime upward drift[16,18] during the period of high solar activity.

Studies have also shown that variability of f_oF2 at high solar activity is greater during most part of the day (0600 – 0800 hrs LT) (Ref. 25). This is true in this work for all seasons except for the March equinox. The variability during the nighttime did not have a consistent pattern except in the September equinox when the variability is higher (at high solar activity). The results obtained here showed a high degree of conformity with these findings about the equatorial ionospheric parameters [Fig. 1(a-d)].

In addition, from the results of this study, a clear picture seems to be emerging for IRI prediction of h_mF2 for equatorial region. The Bilitza model has a very high degree of correlation of h_mF2 at all times of the day during high solar activity as compared with both the observed and the IRI-2012 model. The correction factor ΔM introduced by the best selected model (Bilitza *et al.*[4]) is highly commendable in predicting the h_mF2 value. The conclusion of this study is drawn by noting the following points for h_mF2:

(i) Daytime magnitude is highest during the solstice season.
(ii) A post-sunset peak of h_mF2 is most pronounced during solstices for the period of high solar activity.
(iii) The post-sunset peaks are more pronounced than the daytime peaks during high solar activity.

Acknowledgement

The author is grateful to the Dr Hanbaba, Centre National d'Etudes des Telecommunications (CNET) for making available the data used for this research study from the ionosonde equipment in Ouagadougou. He also thanks NASA and NSSDC for making available IRI-2012 model (online version, http://nssdc.gsfc.nasa.gov/irimodelweb) for scientific use. The author finally thanks the National Geophysical Data Centre (NGDC), NOAA Satellite and Information Service and SPIDR website (http://spidr.ngdc.noaa.gov/spidr) for the R_z indices. Many thanks to reviewers for their useful suggestions, remarks and advice.

References

1 Shimazaki J, World-wide daily variations in the heights of the maximum electron density of the ionospheric F2-layer, *Sci Radio Res Lab (Japan)*, 2 (1955) pp 85-97.
2 Bradley P A & Dudeney J R, Application of magneto-ionic theory to model N(h) profiles, *J Atmos Terr Phys (UK)*, 35 (1973) 2131.
3 Dudeney J R, Statistical analysis of ionosonde data from Argentine Island station, *J Atmos Terr Phys (UK),* 45 (1974) 629.
4 Bilitza D, Shelikin N M & Eyrig R, Peak heights of electron density of F2-layer, *Telecommun J (UK)*, 46 (1979) 549.
5 Bilitza D & Mckinnel, L. A., International Reference Ionosphere – A tool for space weather applications: Recent developments, *Geophys Res Abs (Germany)*, 14 (2012) pp 12927.

6 Berkey F T & Stonehocker G H, A comparison of the height of the maximum electron density of the F2-layer from real height analysis and estimates based M(3000)F2, *J Atmos Terr Phys (UK)*, 51 (1989) pp 873-877.

7 Ehinlafa O E & Adeniyi J O, Equatorial M(3000)F2 estimation of F2 layer models peak heights during low solar activity, *Adv Space Res (UK)*, 49 (2012) pp 711-715.

8 Bilitza D, International Reference Ionosphere 2000, *Radio Sci (USA)*, 36 (2) (2001) pp 261-275.

9 Adeniyi J O, Bilitza D, Radicella S M & Willoughby A A, Equatorial F2-peak parameter in the IRI model, *Adv Space Res (UK)*, 31 (3) (2003) pp 507-512.

10 Bilitza D & Reinisch B W, IRI 2007: Improvements and new parameters, *Adv Space Res (UK)*, 42 (4) (2008) pp 599–609.

11 Kazeem A K, Adeniyi J O & Adediji A T, Modelling of the equatorial ionospheric E-layer based on cos χ index, *Indian J Radio Space Phys*, 43 (2014) pp 205-212.

12 Huang X & Reinisch B W, Vertical electron density profiles from the digisonde network, *Adv Space Res (UK)*, 18 (6) (1996) pp 121-129.

13 Radicella S M & Adeniyi J O, Equatorial ionosphere electron density below the F2-layer peak, *Radio Sci (USA)*, 34 (5) (1999) pp 1153-1163.

14 Balan N & Bailey G J, Modelling studies of equatorial plasma fountain and equatorial anomaly, *Adv Space Res (UK),* 18 (3) (1996) pp 107-116.

15 Anderson D N & Matsushita S, Seasonal differences in the low-latitude F2 region ionization density caused by E × B drift and neutral wind, *J Atmos Terr Phys (UK)*, 36 (1974) pp 2001-2011.

16 Rajaram G & Rastogi R G, Equatorial electron densities-seasonal and solar cycle changes, *J Atmos Terr Phys (UK),* 39 (1977) pp 1175-1182.

17 Fejer B G, de Paula E R, Gonzalez S A & Woodman R F, Average vertical and zonal F-region plasma drifts over Jicamarca, *J Geophys Res (USA)*, 96 (A8) (1991) pp 13901-13906.

18 Ehinlafa O E & Adeniyi J O Comparison of observed h_mF2 and IRI 2007 model with M(3000)F2 estimation of h_mF2 at high solar activity for an equatorial station, *Indian J Radio Space Phys*, 42 (2013) pp 82–88.

19 Ouattara F & Zerbo J L, Ouagadougou station F2 layer parameters yearly and seasonal variations during severe geomagnetic storms generated by CMEs and fluctuating streams, *Int J Phys Sci (Egypt)*, 6 (20) (2011) pp 4854–4860.

20 Ouattara F & Amory-Mazaudier C, Statistical study of the diurnal variation of the equatorial F layer at Ouagadougou from 1966 to 1998, *J Space Weath Space Clim (Japan),* 2 (A19) (2012) pp 1 – 10.

21 Kouris S S, Bradley P A & Nissopoulos I K, The relationships of f_oF2 and M(3000)F2 versus R_{12}, in *Proceedings of the COST 238/PRIME/Workshop* (Eindhoven, The Netherlands), 1994, pp 155-167.

22 Ouattara F, Gnabahou D A & Amory-Mazaudier C, Seasonal, diurnal and solar cycle variations of electron density at two West Africa equatorial ionization anomaly stations, *Int J Geophys (Egypt),* (2012) pp 1–9, doi: 10.1155/2012/640463.

23 Ouattara F, Amory-Mazaudier C, Fleury R, Lassudrie Duchesne P, Vila P & Petitdidier M, West African equatorial ionospheric parameters climatology based on Ouagadougou ionosonde station data from June 1966 to February 1998, *Ann Geophys (Germany)*, 27 (6) (2009) pp 2503–2514.

24 de Jesus R, Sahai Y, Guarnieri F L, Fagundes P R, de Abreu A J, Pillat V G & Lima W L C, F-region ionospheric parameters observed in the equatorial and low latitude regions during medium solar activity in the Brazilian sector and comparison with the IRI-2007 model results, *Adv Space Res (UK)*, 47 (2011) pp 718–728, doi: 10.1016/j.asr.2010.10.020.

25 Bilitza D, Obrou O K, Adeniyi J O & Oladipo O, Variability of f_oF2 in the equatorial ionosphere, *Adv Space Res (UK)*, 34 (9) (2004) pp 1901–1906.