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Diurnal variation of F2-layer critical frequency under solar activity recurrent conditions during solar cycles 21 and 22 at Ouagadougou Station: Prediction with IRI-2012

Emmanuel Wambi Sawadogo[1], Jean Louis Zerbo[1,2*], Nour Ali Mahamat[1,3] and Frédéric Ouattara[1]

[1]Laboratoire de Recherche en Energétique et Météorologie de l'Espace (LAREME), Université Norbert Zongo (UNZ), BP 376, Koudougou, Burkina Faso.
[2]Unité de Formation et de Recherche en Sciences et Techniques (UFR/ST), Université Nazi Boni, Bobo-Dioulasso, Burkina Faso.
[3]Faculté des Sciences Exactes et Appliquées, Université de N'Djamena, Tchad.

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This paper presents foF2 data recorded at Ouagadougou Ionosonde Station and compares them with IRI-2012 model results through its two subroutines, Union Radio Scientifique Internationale (URSI) and Comité Consultatif International des Radio Communications (CCIR) during recurrent solar activity. Except for the solar cycle maximum period, measured data profiles corroborate with the signatures of E×B drift. IRI- 2012 subroutine URSI is not consistent with observed electrodynamics during any solar cycle phase, while CCIR predictions are consistent with the measured data during the solar maximum and declining phases. Investigation on the relative deviation module mean (RDMM) shows poor agreement between measurements and predictions with IRI most of the time. However, the deviation percentages indicate good correlation between URSI predictions and data from the ionosonde, except for solar ascending phase. Good correlation with CCIR is only obtained during the solar cycle minimum and maximum phases. From a quantitative point of view, this study shows that predictions with URSI are closer to experimental measurements. The investigations show good agreement between model and *in situ* measurement during the day. Significant differences are recorded at night, especially from midnight to sunrise. There is necessity to improve IRI model for equatorial regions to better predict foF2 variation.

Key words: Ionosphere, foF2, Solar cycle, IRI model.

INTRODUCTION

F2 layer is the most important part of the ionosphere used to propagate radio waves in the high frequency band because of its height and electron density. One of the suitable parameters for ionospheric study is the critical frequency of F2 layer, foF2. Many previous works (Adeniyi et al., 1995; Abdu et al., 1996; Batista et al.,1996;

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*Corresponding author. E-mail: jeanlouis.zerbo@gmail.com.

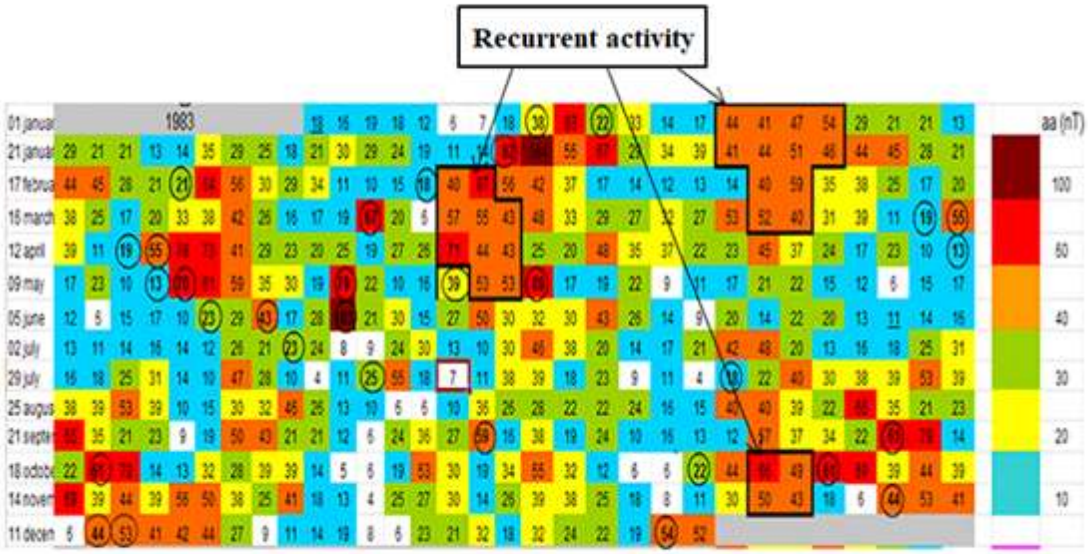

Figure 1. Illustration of recurrent activity during year 1983.

Bertoni et al.,2006; Bilitza et al., 2014, 2014; Ouattara and Fleury, 2011; Ouattara, 2013; Ouattara and Nanema, 2014; Tariku, 2015; Li et al., 2016) reported the variation of this ionospheric parameter through its *in situ* measurements, and compared the observations with predicted values from the International Reference Ionosphere (Rawer et al.,1978*;* Bilitza,1986; Melaku and Tsidu, 2019) developed in the 1960s by Committee on Space Research (COSPAR) and International Union of Radio Science (URSI).

The present study analyzes the ionospheric foF2 observations from an equatorial station, Ouagadougou (lat: 12,4°N ; long: 358,5°E, dip: 1,43°), and compares them with predictions by IRI-2012 model during different seasons and solar cycle phases, and under geomagnetic recurrent activity conditions. The aim of this investigation is to help to improve the IRI-2012 model for ionospheric data prediction for equatorial region. Our work covers the solar cycle 21(1976-1986) and the solar cycle 22 (1986-1996). The IRI-2012 model results are obtained through two subroutines, URSI (Union Radio Scientifique Internationale) and CCIR (Comité Consultatif International des Radio Communications).

MATERIALS AND METHODS

The ionospheric parameter studied is the critical frequency of the F2 layer (foF2) taken from Ouagadougou ionosonde station (Lat: 12.5°N, Long: 358.5°E, dip: 1.43°) in Burkina Faso. These are obtained from the database of Brest Telecom (formerly ENST Bretagne). Interval of the study covered by our investigation is 1976 to 1996, corresponding to the solar cycle 21(1976 – 1986) and the solar cycle 22 (1986 - 1996). The values of sunspots Rz are obtained from the SPIDR database (URL http://spidr.ngdc.noaa.gov/spidr/). The geomagnetic index aa are from http://isgi.unistra.fr/data_download.php. They are summarized in pixel diagram (Figure 1, an example for the year 1983) used to select recurrent activity according criterion described by Ouattara and Mazaudier (2009). The foF2 hourly predicted values are obtained by using the IRI-2012 model (http://omniweb.gsfc.nasa.gov/vitmo/iri2012).

The predicted fo F2 data are obtained with IRI-2012 subroutines, URSI and CCIR. The solar cycle phases are determined using sunspot number Rz and criteria fully described in many works (Zerbo et al., 2011; Ouattara, 2013): (1) the minimum phase: $Rz < 20$; (2) the ascending phase: $20 \leq Rz \leq 100$ and Rz greater than the previous year's value; (3) the maximum phase: $Rz > 100$; (4) the decreasing phase: $100 \geq Rz \geq 20$ and Rz less than the previous year values. Local (north hemispheric) seasons are classified as follows: winter (December, January, and February); spring (March, April, May); summer (June, July, August) and autumn (September, October and November).

Days under recurrent geomagnetic activity are selected through the geomagnetic activity classification (Legrand and Simon, 1989). According to this classification, (1) the quiet activity corresponds to the days with index Aa <20 nT, (2) the recurrent activity groups the days with index Aa ≥ 40 nT on at least one rotation (27 days in average), (3) the shock activity is characterized by dates of sudden impulse (SI^+) with the index Aa ≥ 40 nT for a duration not more than three days. The fluctuating activity includes all the other days not identified in the three previous class of activity. Figure 1 is an illustration of the different classes of geomagnetic activity. 173 days under recurrent conditions have been identified for the period covered by our investigation (1976 to 1996).

Our method of analysis consists of comparison between measured foF2 and predictions with IRI-2012 subroutines URSI and CCIR through: (1) a morphological or qualitative study based on temporal profiles behavior in agreement with types of profile reviewed by Faynot and Villa (1979) which will allow us to discuss the electrodynamics phenomenon in ionosphere. (2) Quantitative analysis based on a comparison between measurement and predictions. Appreciation can be made using:

(i) The relative deviation module means (RDMM) to quantify concordances between in situ data and IRI predictions. The relative

Table 1. Occurrence of recurrent activity.

Per solar cycle phases						
		Minimum	**Ascending**	**Maximum**	**Decreasing**	**Total**
Cycles	Number of days under recurrent conditions	12	07	30	124	173
21- 22	Occurrence	6.93%	4.04%	17.34%	71.67%	100%
Per season						
		Winter	**Spring**	**Summer**	**Autumn**	**Total**
Cycles	Number of days under recurrent conditions	33	71	29	40	173
21- 22	Occurrence	19.07%	41.04%	16.76%	23.12%	100%

module of deviation is estimated by $(\Delta) = \frac{1}{\mathrm{N}}\sum_{i=1}^{N}\frac{|x_i^0 - x_i^m|}{x_i^0}$ where x_i^0 and $x_i^m$are predicted and measured data respectively; and N the number of terms. If RDMM ≤ 0.06 then model and experience match from reasonable to good, if not they match from reasonable to bad (Bertoni et al., 2006);

(ii) The percentage of deviation (%D) gives by $\%\mathrm{D} = \frac{x_i^m - x_i^0}{x_i^0}\mathrm{x}100$, where x_i^0 and x_i^m are predicted and measured data respectively; It teaches about the gap between experimental data and predictions:$\%\mathrm{D}>$ 0 the model overestimates the measurements;$\%\mathrm{D}<$ 0 the model underestimates the measurements;$|\%\mathrm{D}| < 10\%$ the model is in an agreement with the measurements (Nanéma, 2016).

RESULTS AND DISCUSSION

For the 173 identified recurrent days, only 71.67% occurred during the decreasing phase of the solar cycle (Table 1) as previously reviewed (Ouattara, 2009; Zerbo et al., 2011). One can also see an equinoctial asymmetry in the seasonal occurrence of the recurrent activity. Table 1 shows clearly that recurrent activity is predominant during spring (41.04%).

Comparison by solar cycle phase

Morphological investigations

Figure 2 shows the hourly profile of *in situ* measurements (ionosonde) and IRI-2012 (URSI and CCIR) predicted values of the critical frequency (foF2).The panels (a), (b), (c) and (d) are devoted respectively to solar minimum, ascending, maximum and decreasing phases. During solar minimum, ascending, and decreasing phases the ionosonde experimental measured values show "noon bite out" or "B" profile characterized by a double peak testifying to signature of the vertical drift E×B (Fejer et al.,1979, 1981; Farley et al., 1986) and the presence of a strong electrojet (Vassal, 1982a, b). However URSI predictions show "Reversed" or "R" profile characterized by a single peak at evening indicator of the presence of counter electrojet when CCIR gives "Reversed" or "R" profile during solar minimum and ascending phases and "Noon bite out" during the decreasing phase. During the ascending and decreasing phases ionosonde data present tonight peaks which lead to the signature of the pre-reversal of the electric field (Fejer, et al., 1979, 1981; Farley et al., 1986; Rishbeth, 1971). At solar maximum phase measured data and CCIR prediction show “Morning Peak" or "M" profile characterizing the presence of moderate electrojet when URSI predictions present a "plateau" or "P" profile indicator of no electrojet effect. This investigation shows that IRI-2012 subroutine URSI does not teach about F2 layer electrodynamics process at any solar cycle phase when CCIR reproduced this phenomenon during solar maximum and decreasing phases. This qualitative investigation shows that CCIR predictions are closer to measured data during the solar cycle phases.

Quantitative analysis

Table 2 presents the value of relative deviation module mean (RDMM) between measured data and predictions with IRI-2012 two subroutines URSI and CCIR during solar cycle phases. Figure 3 shows the variations of the percentage of deviation (%D) between model and experience for solar minimum phase (panel a), ascending phase (panel b), maximum phase (panel c), and decreasing phase (panel d).

Except at solar maximum where CCIR predictions show good concordance with measured data (RDMM = 0.059), model and experience match from reasonable to bad for almost all the phases. The investigations on the percentage of deviation show that correlation between URSI and experience is good from 0800LT to 1800LT at solar minimum, maximum, and decreasing phases. During these phases, the best correlations are recorded at 0800-1100 LT (minimum), 1000-1300 LT (maximum) and 1000-110 0LT (decreasing) where the percentage of deviation is$|\%\mathrm{D}| < 5\%$. Tonight model and measurement match between1800LT and 2200 LT for minimum and decreasing phases. In this study we note important

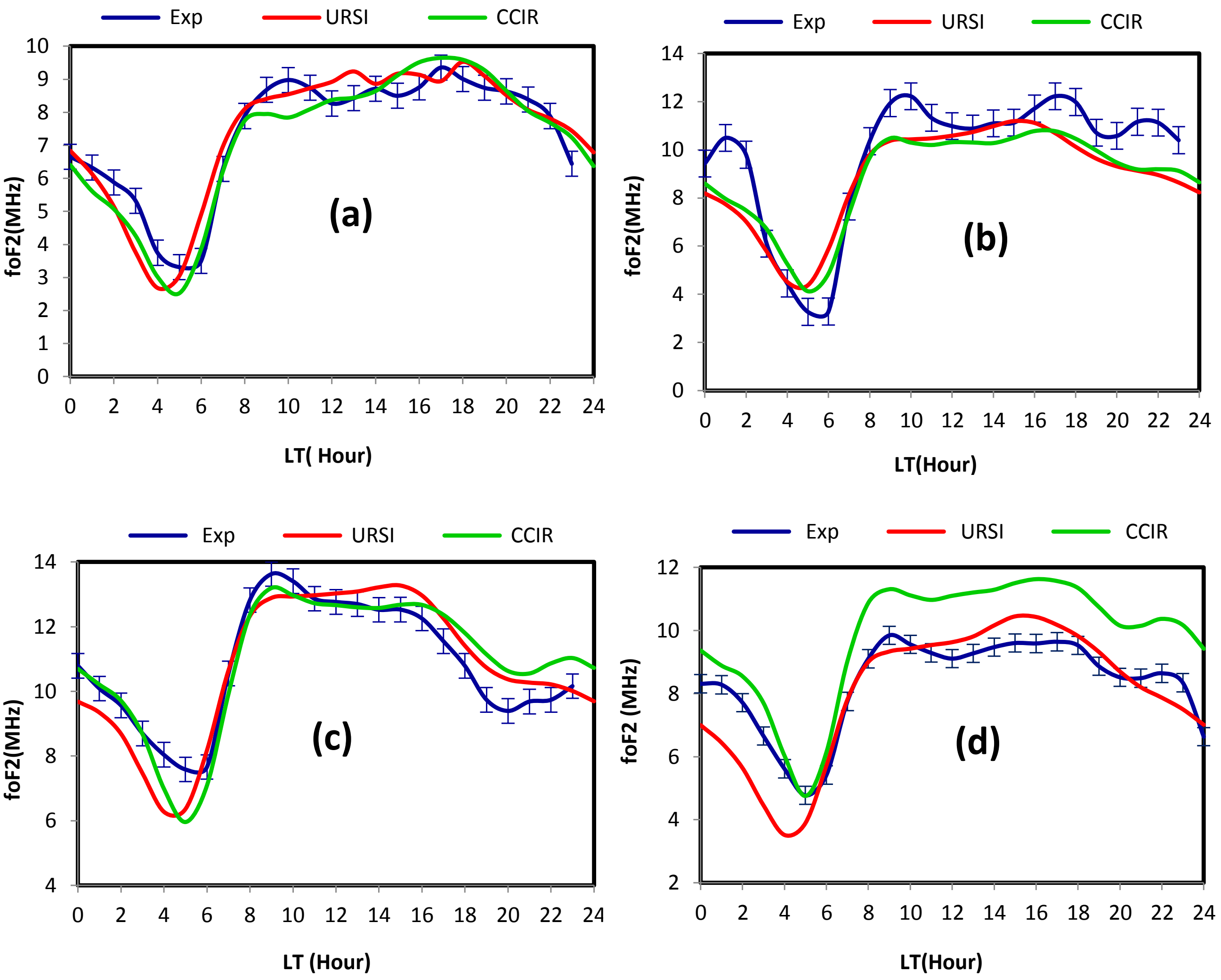

Figure 2. diurnal variations of foF2 from ionosonde and predictions with IRI-2012 under recurrent activity conditions during cycle 21-22 phases: (a) Minimum; (b) ascending; (c) maximum ;(d) decreasing.

Table 2. Relative deviation module mean **(**RDMM) per solar cycle phases.

Phase	**RDMM**	
	URSI	**CCIR**
Minimum	0.088	0.077
increasing	0.146	0.137
Maximum	0.069	0.059
Decreasing	0.100	0.175

gap between model and experience from 0000 to 0400 LT with very significant gaps at 0300 LT (-29.28% for solar minimum phase), and at 0400 LT (-21.94% and -37.34% respectively for maximum and solar decreasing phases). During solar increasing phase, correlation between URSI and experience matches between 1100 and 1600 LT. We noted that morning overestimation reached significant differences at 0600LT of 79.37%. Tonight, we note important gap of -28.36% during this solar cycle phase at 0200LT. During all the solar cycle phase URSI overestimates foF2 between 0600LT and 0700LT. overestimation can be also observed during time intervals 1200-1600 LT, 1100-2200 and 1100-2000 LT, respectively for solar minimum, maximum and decreasing

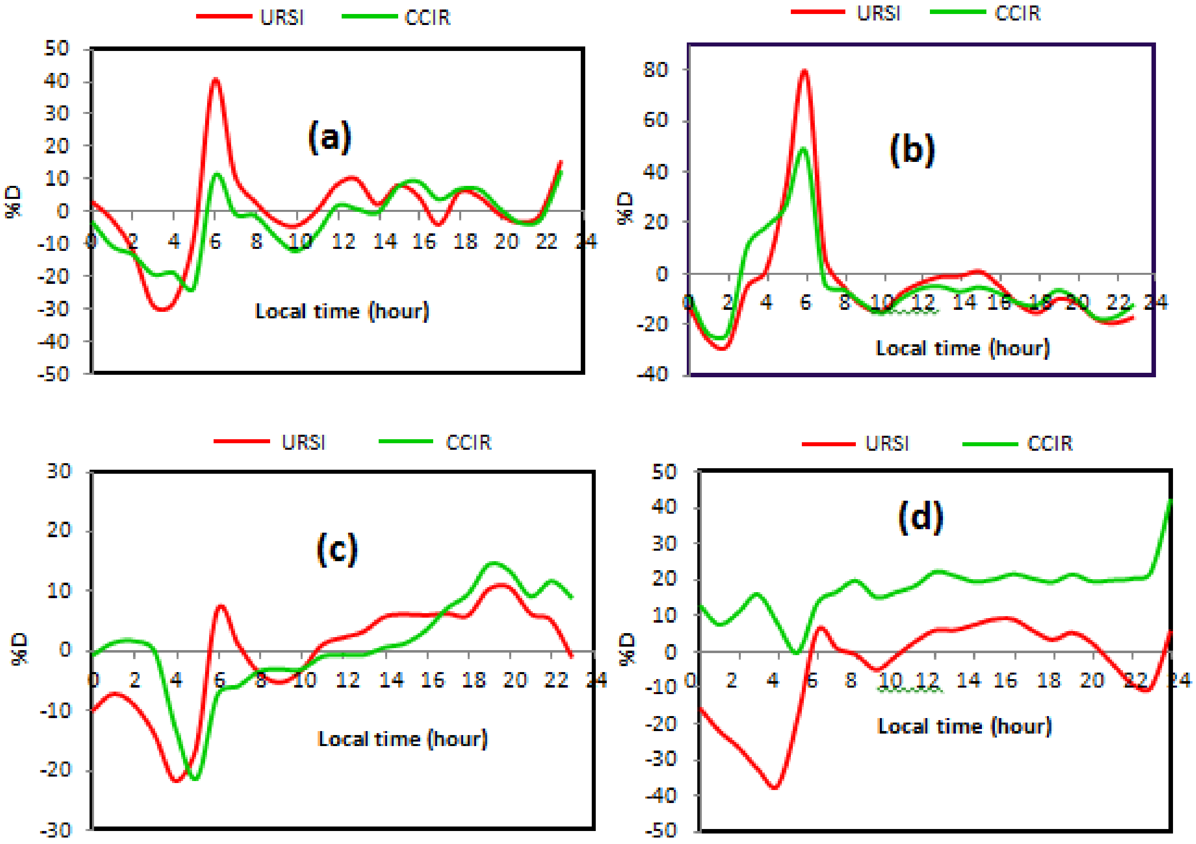

Figure 3. Percentage of deviation between IRI-2012 and *in situ* data from Ouagadougou ionosonde station during cycle 21- 22 phases under recurrent solar activity conditions: (a) Minimum; (b) increasing; (c)Maximum; (d) decreasing.

phases.

During solar minimum and maximum phases prediction with CCIR and measured data match from 0700LT and 1800LT with best agreement between $(|\%\mathrm{D}| < 5\%)$ 0700LT and 0800LT; 1200 to 1400LT at solar minimum and between 0800 and 1600 LT at solar maximum phase. Tonight correlation between model and experimental measurement match between 1800 and 2200 LT

At solar minimum CCIR underestimates (-23.83%) foF2 in the morning (0700-1100 LT) and in the evening from 2000LT till 0500LT. At solar maximum model's underestimation is observed from de 0300LT to 1300LT with important gap at 0500LT (-21.41%). During solar ascending phase CCIR predictions and *in situ* data match for the intervals 0700 – 0800 LT and 1100 -1600 LT and underestimates measurement for the other time. During solar decreasing phase CCIR overestimates the measurements most of the time with percentage of deviation in the range of 15 and 25%. From this investigation, we can see that URSI matches with all days during solar minimum, maximum and decreasing with an overestimation at sunrise and in the afternoon till sunset. During the ascending phase model matches only from 1100LT to 1600LT. With URSI, the significant underestimations and overestimations are recorded around 0400LT and 0600LT and there are observed when CCIR matches with experimental measurements daytime during solar minimum, maximum and underestimates measurement on solar ascending phase. CCIR predictions are bad during solar decreasing phase. IRI-2012 two subroutines (CCIR and URSI) predictions are similar during solar minimum, maximum and ascending phase but URSI seems to match with *in situ* data during solar decreasing phase.

Comparison per season

Morphological investigations

Figure 4 presents the seasonal variations of foF2 data from *in situ* measurement and their corresponding predictions by IRI-2012 subroutines URSI and CCIR. The panels (a), (b), (c) and (d) teach about winter, summer, spring and autumn profiles respectively. During

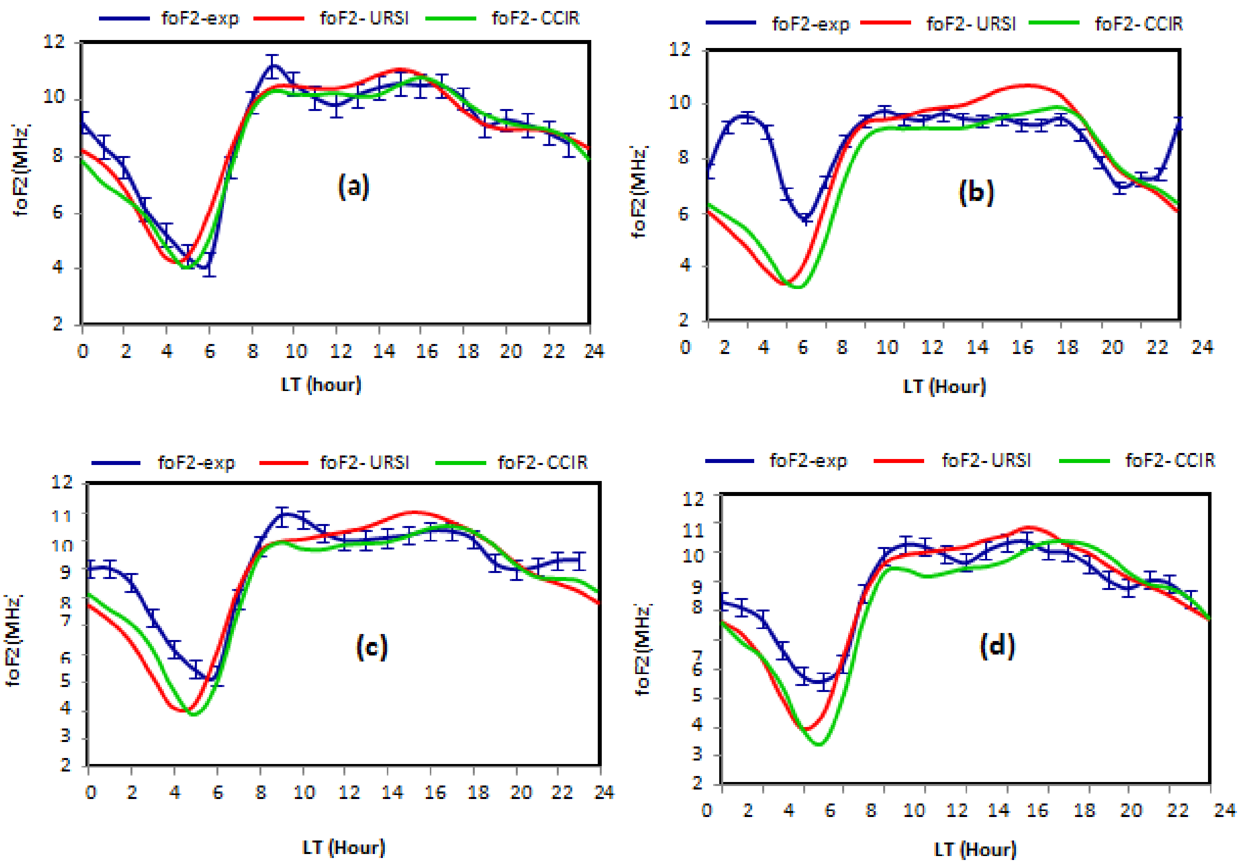

Figure 4. Diurnal variations of foF2 gived by IRI-2012 and in situ data from Ouagadougou ionosonde station during cycle 21- 22 phases under recurrent solar activity conditions: (a) winter; (b) Summer; (c) Spring; (d) Autumn.

winter, spring and autumn *in situ* measurements show "noon bite out" or "B" profile characterized by evening peaks observed at 2000LT (9.26MHz), 2300LT (9.28MHz), and 2100LT (9.03MHz). It happens when its summer profile presents "plateau" or "P" profile characterized by evening peak at 2400LT (9.3MHz) and a significant peak at 0200LT (9.95MHz). However, IRI- 2012 model shows "Reversed" or "R" profile without evening peak for all seasons. We can say that IRI-2012 model does not reproduce electrodynamics phenomenons expressed by experimental data. As a matter of fact, in situ data profiles express the signature of the E×B drift at the Ouagadougou station during winter, spring and autumn and the presence of strong electrojet in summer. At the same time IRI-2012 subroutines show the existence of a strong counter-electrojet. In addition model does not provide the signature of the pre-reversal of the electrics field (PRE) as indicated in ionosonde measurements.

Quantitative analysis

The seasonal values of RDMM (Table 3) show good agreement between model (URSI and CCIR) and experience during winter only. (RDMM = 0.052). For the other RDMM value is more than 0.06; then agreement runs from reasonable to bad. An investigation on the percentage of deviation (Figure 5) shows that during winter, spring, and autumn URSI predictions match with experience during the time interval 0700 – 2200 LT and underestimations foF2 data for the interval 0000 and 0500 LT with significant gaps around 0400 LT (-16.36% for winter, -34.27% for spring, and -31.44% for autumn). An important overestimation (43.20%) is recorded from 1100 to 1600 LT with URSI during winter and moderate overestimations are observed between 1200 and 2000 LT for two seasons (spring and autumn). Summer is characterized by agreement between URSI model and in situ data from 0700LT to 1400LT and from 1800 to 1900 LT. During this season, an underestimation is observed between 0000 and 0900 LT (-56.85% at 0300LT) when model overestimates data for the interval 1000 to 2100 LT. IRI- 2012's second subroutine (CCIR) matches with experience from 0800LT to 2300 LT during winter, spring, and autumn (|%D|<5%). For these three seasons, CCIR underestimates foF2 data from 0000LT till sunrise with significant gaps at 0200LT during winter (-14.48%) at 0500 LT during spring (-30.05%), and autumn (-38.71%). Overestimations are

Table 3. Relative deviation module mean (RDMM) per season.

Season	**RDMM**	
	URSI	**CCIR**
Winter	0.052	0.052
Summer	0.170	0.164
Spring	0.103	0.079
Autumn	0.074	0.100

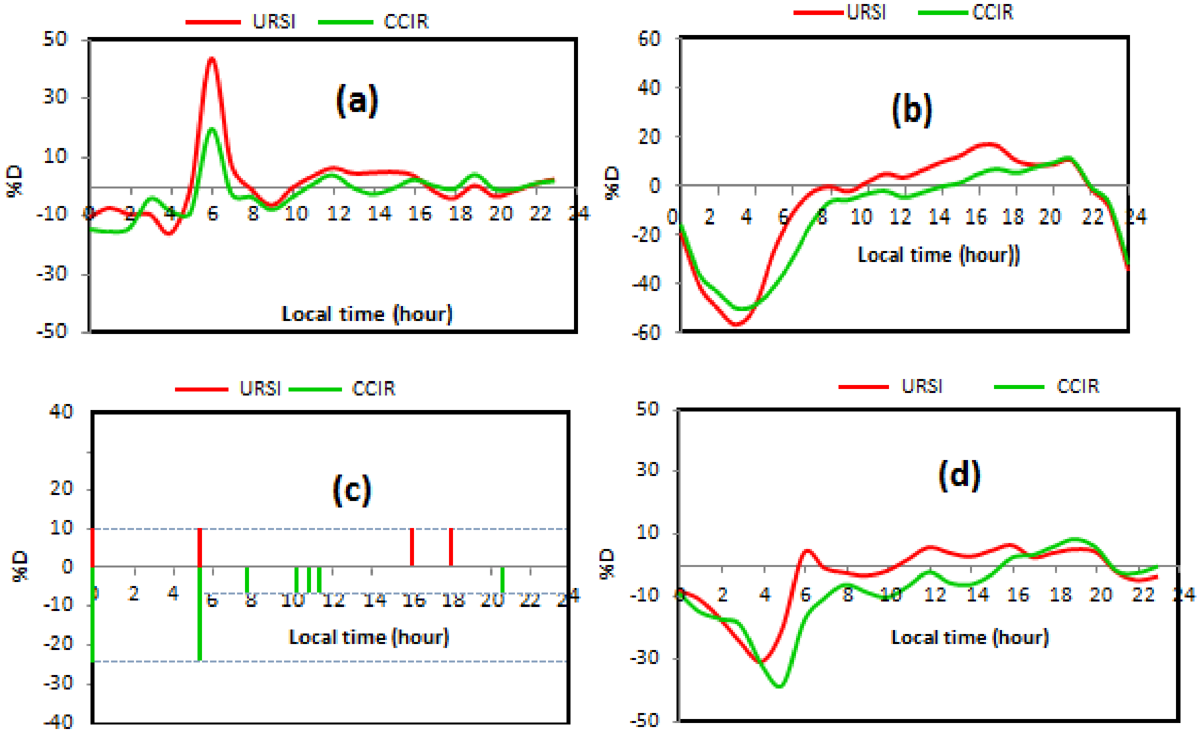

Figure 5. Percentage of deviation by IRI-2012 and in situ data from Ouagadougou ionosonde station during cycle 21-22 phases under recurrent solar activity conditions: (a) winter; (b) summer; (c) Spring; (d) autumn.

recorded with CCIR around 0600LT (19.68%) during winter with moderate overestimations during the intervals 1100LT -1200LT and 1600LT-1700LT. During spring and autumn, overestimation is observed only between 1600LT and 2000LT. In summer, CCIR predictions match with experience from 0800LT to 2000LT with (|%D|<5%). The most important gap (-50, 07%) is observed at 0300LT (-50, 07%).

In general, there are important gap between predicted and in situ measurements in the evening. Except for few differences in peaks during this period, URSI and CCIR predictions are similar.

Conclusion

Our morphological study shows differences between the profiles of observed *in situ* foF2 data and predictions by IRI-2012 model. The diurnal variations of observed foF2 during solar minimum, ascending, and maximum point out the presence of electrodynamics phenomenon (vertical drift E×B) not observed by IRI-2012 model subroutine CCIR during the solar cycle deceasing phase. The pre-reversal of electric field shown by the experimental data during solar ascending and decreasing phases is not reproduced by the model. Except during summer, the seasonal variation of *in situ* measurement expresses the signature of E×B phenomenon and pre-reversal of the electric field. This investigation shows that CCIR is closer to experience than URSI. Investigation on the relative deviation module mean (RDMM) shows that agreement between *in situ* data and predictions by IRI-2012's two subroutines runs from reasonable to bad for any solar cycle phase except for CCIR during solar maximum phase. This result is also observed for all seasons except winter where model matches with experience. The percentage of deviation shows that the best match is obtained with URSI. During the different solar cycle phases the most significant overestimations and underestimations are observed around 0600LT and 0400LT respectively. During the decreasing phase CCIR overestimates foF2 values all time. During daytime the model matches with experimental measurement but underestimates data between 0000LT and 0500LT. According to the quantitative investigation URSI gives best match than CCIR. Taking a look at the different gaps between model and experimental measurement, it is necessary to improve IRI-2012 model to consider the phenomenon shown by *in situ* measurements for better prediction of variability in ionosphere for Africa equatorial regions.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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