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### RESEARCH ARTICLE

#### MODELING CRITICAL FREQUENCY OF IONOSPHERE D-LAYER AT MINIMUM AND MAXIMUM OF THE SOLAR CYCLE 22 WITH IRI-2016

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#### Abstract

One of the interests of the study of the ionosphere lies in its importance for the transmission of radio waves in telecommunications. The ionosphere behaves as an obstacle to the passage of waves. Thus, the signals of short wavelengths are reflected by the F layer or the upper part of the sublayer E, while the D-layer is the seat of the reflection of low-frequency waves. The present study investigates the temporal variability of the critical frequency of the D-layer (for) using the 2016 version of the International Reference Ionosphere (IRI) model under quiet day conditions during at maximum and minimum phase of solar cycle 22. The work is conducted at the Ouagadougou station, located in West Africa. The methodology of the work adopted for the determination of the parameter foD is based on the calculation of the monthly hourly averages of this variable obtained with the help of the model during the months that characterize the seasons. The results obtained for the parameter for as a function of time during the minimum and maximum of the solar cycle 22 have been presented. The seasonal and temporal variations of the critical frequency of the ionosphere D-layer show that the foD values are lower during a minimum of the solar cycle and present maximum values at the Zenith (1200 TL) at a minimum and maximum. These results also reveal that this parameter varies with time, season, and geographical position. The results of this study show a critical frequency below 1 MHz during both phases of the solar cycle.

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#### Introduction:-

The D-layer is the most complex part of the ionosphere from the point of view of its composition (high pressure, air density, large number of photochemical reactions). The population of this region is mainly composed of O<sub>2</sub> and N<sub>2</sub> (Bittencourt et al., 1994). The lower region of the ionosphere (D) remains however inaccessible to most techniques applied to the upper ionosphere. The success and richness of the use of the International Reference Ionosphere (IRI) model for the study of the upper ionosphere lead to consider its use for the study of the D-layer. This method offers the advantage of being able to simultaneously measure several parameters such as electron density (NmD), critical frequency (foD), total electron content (TEC), and temperature (Bilitza et al., 1993, 1996, 2014, 2017; Sethi et al.,

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2002). Published in February 2016, the International Reference Ionosphere (IRI) model is an update of the 2012-version of IRI (Bilitza et al., 1993). It is a standard empirical model of the ionosphere, created in 1960 sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI). It generates time and date-dependent averages of the parameters at an altitude ranging from 50 to 2000 km. It includes a FORTRAN program, subprograms (CCIR, URSI), index files, etc., The model has a better representation of the ionosphere during very weak solar activity (Bilitza et al., 1993). It is executable on the Virtual Ionosphere Thermosphere Mesosphere Observatory (VITMO) site. To better understand the behavior of the ionosphere, many reports have highlighted the variability of the critical frequency (foF2) of the F-layer during various seasons, days, hours, solar events, and latitudes (Ouattara et al., 2011 ; Adeniyi et al., 1995 ; Abdu et al., 1996 ; Batista et al., 1996 ; Bertoni et al., 2006 ; Bilitza et al., 2014 ; Ouattara and Fleury., 2011 ; Tariku et al., 2015 ; Li et al., 2016 ; Sawadogo et al., 2019 ; Diabaté et al., 2019). This paper is a modeling of the low-latitude ionospheric D-layer critical frequency (foD) variability during at minimum and maximum phase of solar cycle 22. The variability of the peak of the critical frequency of the D-layer is determined for each season during the minimum and maximum of solar cycle 22 phase. The investigation in this work is carried out under quiet day conditions at the Ouagadougou station.

### Material and Method:-

The IRI model operation in its 2016 version allows examination of the foD parameter for a given station. It is available online ([www.irimodel.org](http://www.irimodel.org)). The station of Ouagadougou, located in West Africa, is the subject of our study, has the following characteristics: lat = 12.4°N, long = 358.5°E. The phase minimum of the solar cycle 22 is characterized by Rz < 20 and the phase maximum is defined by Rz > 100, where Rz is the monthly average sunspot number of Zürich (Ouattara and Amory., 2009 ; Ouattara and Zerbo., 2011 ; Zerbo et al., 2012). Quiet days are defined by Aa < 20 nT (Ouattara and C. Amory., 2009 ; Mayaud et al., 1972). The characteristic months of the season 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 foD parameter on the five quietest days of each characteristic month.

Thus, equation (1) defines the critical frequency as follows:

$$foD_h = \frac{\sum_{j=1}^5 foD_{h,j}}{5} \quad (1)$$

In relation (1), foD<sub>h</sub> denotes the critical frequency of the layer D at time h for the characteristic month considered, foD<sub>h,d</sub> is the value of the critical frequency at time h for day d. Thus, h ∈ [0,24], and j ∈ [1,5].

The IRI model allows the extraction of different values of foD<sub>h,j</sub>. It then becomes possible to determine the value of the critical frequency at time h foD<sub>h</sub> by calculating the average value of the parameters foD<sub>h,j</sub> over the five quietest days for each characteristic month.

The table below shows the five quietest days of each characteristic month of each season for the solar cycle considered.

**Table:-** Selection of the five quietest days (Ouattara et al., 2009).

Month	The five quietest days of the solar cycle 22 phase.	
	Solar minimum Year 1985	Solar maximum Year 1990
March	9, 13, 21, 22, 25	4, 10, 16, 17, 31
June	3, 14, 16, 18, 19	16, 17, 20, 21, 30
September	2, 3, 4, 5, 29	2, 3, 27, 29, 30
December	8, 9, 21, 23, 29	10, 11, 19, 21, 29

The peak of the critical frequency of the D-layer (foD) is related to the electron density by the relation:

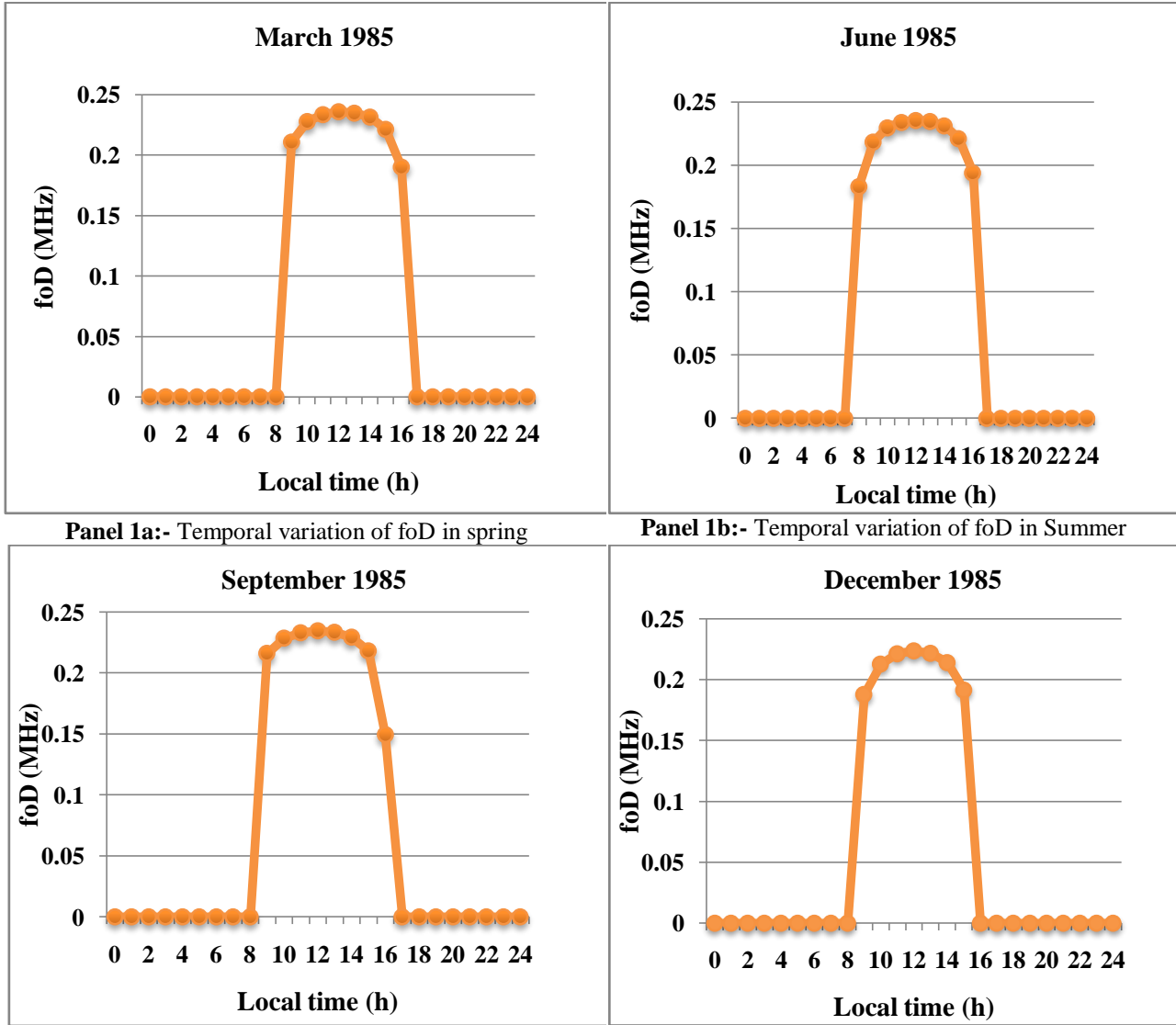
$$foD = 9. \sqrt[2]{NmD} \quad (2)$$

In this expression, the critical frequency foD is in MHz and the peak electron density NmD is in m<sup>-3</sup>.

**Results:-**

Figures 1 and 2 show the temporal variability of the critical frequency foD during the minimum and maximum of solar cycle 22, respectively. Panels 1a, 1b, 1c, 1d are the hourly profiles of foD in spring, summer, autumn and winter during the minimum, respectively, and those in panels 2a, 2b, 2c, and 2d are the hourly profiles of foD at the maximum.

Autumn and winter during the minimum, respectively, and those in panels 2a, 2b, 2c, and 2d are the hourly profiles of foD at the maximum.



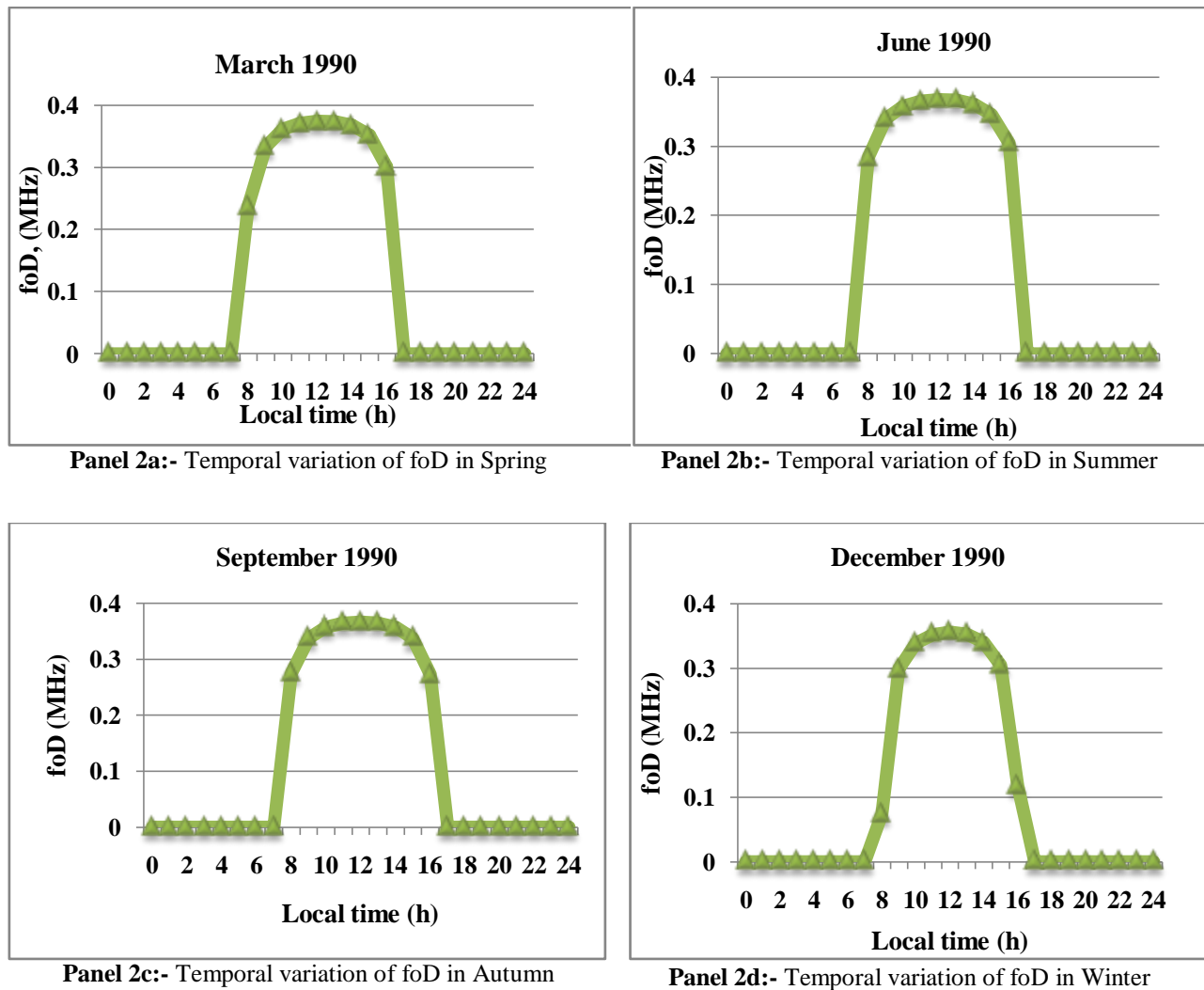
Panel 1a:- Temporal variation of foD in spring

Panel 1b:- Temporal variation of foD in Summer

Panel 1c:- Temporal variation of foD in Autumn

Panel 1d:- Temporal variation of foD in Winter

**Figure 1:-** Hourly variability of the critical frequency foD at minimum phase of the solar cycle 22



**Figure 2:-**Hourly variability of the critical frequency foD at maximum phase of the solar cycle 22.

### Analysis and Discussion:-

Figures 1 and 2 show the critical frequency (foD) in the D-layer time profiles during the minimum (1985) and maximum (1990) phase of the solar cycle 22. The vertical axis represents the critical frequency of the D-layer and the horizontal axis defines the TL time for the panel of each graph. All graphs in both figures show a parabolic profile. Sunshine increases during spring, peaks in summer, and decreases in autumn. Winter is the least sunny season. The ionization of particles in the ionosphere due to solar radiation is, therefore, lower in winter than in the other seasons. During the minimum phase, the critical frequency profile decreases between 12.00 TL and 17.00 TL, increases during the day between 08.00 TL and 12.00 TL, and has a maximum at 12.00 TL. During a maximum phase of the solar cycle, the critical frequency profile decreases between 12.00 TL to 17.00 TL, increases between 07.00 TL to about 12.00 TL, and a maximum at 12.00 TL. The electron density increases during the day and depends on the weather, the season, and the solar cycle phase. It varies with the intensity of the solar rays. At sunrise, the ionization is important and continues to ionize for a few hours after the position of the maximum (12.00 TL) of production until the disappearance of the electron density. For this, we also observe a profile of the critical frequency during this period. The recombination is very fast, so that this layer remains only at certain times when the photoionization has stopped. This explains the absence of foD during these hours. These results (figures 1 and 2) show a low value of foD in winter; this could be explained by a ray of weak sunshine, which is due to the fast recombination of electrons in this layer. The maximum critical frequency obtained in this study is less than 1 MHz. This explains why this layer does not appear on the ionograms (traces of the layers obtained by sounding) because of the low critical frequency (the highest frequency likely to return to the ground after vertical incidence) which is

lower than the classic limit frequency of the ionosondes (sounding device) 1 MHz. During the day, very long waves (kilometers) reflect at the bottom of the D-layer. The medium waves (hectometres) reflect higher and undergo a very strong absorption. The decametric waves cross entirely this layer with a weak absorption. The collision frequencies (Ven) electron-neutral and (Vin) ion-neutral are very high, resulting in a strong absorption of HF radio waves and an attenuation of waves of frequencies lower than 1 MHz. In addition, the collision frequency of electrons with neutral particles is inversely proportional to the square of the radio wave frequency and, therefore, the attenuation is greater. This is due to the fact that radio waves of lower frequency are too attenuated when passing through the D-layer, while those of higher frequencies will not be reflected because the maximum critical frequency is exceeded. These low frequencies are generally used in marine navigation and system LORAN C.

### Conclusion:-

This present work highlights the variability of the critical frequency (foD) in the D-layer during the solar cycle 22 phase minimum and maximum using the IRI model in its 2016 version. The ionization causes the difference in the foD values of the solar cycle phase and between different seasons of the year. In winter, the values of the critical frequency are lower than during the other seasons. This work does not highlight the winter anomaly. Our study also shows a peak foD at 12.00TL for all seasons. From this study, it appears that the critical frequency does not affect the radio waves when the D layer disappears.

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