Variation of the Critical Frequency of the Ionospheric F2 Layer during Moderate Geomagnetic Conditions: A Study Using Data from the Ouagadougou Ionosonde Station Across Solar Cycles 21 and 22

Abstract

This study investigates the variations in the critical frequency of the F2 layer (foF2) at the Ouagadougou ionosonde station during moderate geomagnetic activities, focusing on corotating and magnetic cloud events across the minimum and maximum phases of solar cycles 21 and 22. The analysis reveals significant perturbations in the diurnal profiles of foF2 during magnetic cloud activity at the solar minimum phase, compared to profiles observed during magnetically quiet activity. These perturbations indicate a disturbance of electrodynamic processes, including ionospheric currents and upward drifts. Conversely, corotating activity exhibits negligible impact on foF2 profiles at solar minimum phase. At solar maximum phase, the diurnal profiles observed during moderate geomagnetic activities are identical to those observed during very quiet days. Notably, ΔfoF2 values during moderate activities are generally below 20% during the day but show short-lived positive storms (>20%) at night, especially near sunrise. These findings enhance our understanding of equatorial ionospheric dynamics and the influence of geomagnetic activity, contributing to improved space weather predictions and ionospheric modeling.

Key words

Corotating, magnetic cloud, diurnal, ionospheric storm, solar phase.

1. Introduction

Region F is one of the most investigated ionospheric regions because of its important role in high-frequency communications. Many investigations have made it possible to establish the causes of its variation, among which we can cite the solar wind and geomagnetic activity (Legrand et Simon, 1989; Lotko, 1989; Simon et Legrand, 1989; Lal, 1998; Ouattara, 2009; Ouattara et al., 2009a and 2009b**)**.

Numerous works (Richardson et al., 2000, Richardson et Cane, 2002 and Du ZL, 2011) have made it possible to make a link between solar activity and transient variations in the Earth's magnetic field, also called geomagnetic activity. Particularly, the work of

Legrand et Simon (1989) led to the organization of geomagnetic activity into four classes, each linked to a solar event : (1) quiet activity is associated with slow solar winds, (2) the recurring activity is caused by solar winds coming from the coronal holes and lasting for one or more solar rotations, (3) the shock activity is caused by coronal mass ejections (CME) and (4) the fluctuating activity is due to fluctuations generated during the flow of moderate and fast solar winds. Each of these geomagnetic activities has particular influences on the variations of the ionosphere revealed by numerous authors such as Fejer et al. (1999), Araujo-Pradere (1997), Fuller-Rowell et al. (2000), Ouattara et al. (2015) and Ouattara et Zerbo (2011).

Following the classification of Legrand et Simon (1989), Zerbo et al. (2012) showed that fluctuating activity could be refined by taking into account the effect of active regions and the moderate winds drowned there. Their work resulted in the extraction of three geomagnetic activities in the fluctuating activity: (a) corotating activity, (b) magnetic cloud activity, and (c) unclear activity. The results of their work showed that the magnetic cloud activity and the shock activity are governed by the same solar mechanisms but with different energy levels. The same is true for corotating activity and recurrent activity which all arise from fast solar winds coming from the coronal holes.

Corotating and magnetic cloud activities have moderate magnetic effects in the vicinity of the terrestrial environment. Numerous studies have been carried out on the impact of different geomagnetic activities on variations in the ionosphere. However, studies that concern moderate activities are done either by drowning them in fluctuating activity (Ouattara et Amory-Mazaudier, 2012; Diabate et al., 2018) or by associating them with recurring and shocks activities (Sandwidi et Ouattara, 2022). In particular, we focus on the impact of these moderate activities only on variations in the critical frequency of the layer F2 (foF2). The study concerns values of foF2 recorded at the equatorial station of Ouagadougou (Lat: 12.5°N, Long: 358.5°E, dip: 1.43°) during the minimum and maximum solar phases of solar cycles 21 and 22.

In section 2 of our study, we present the materials and methods used. Section 3 concerns the presentation of results and discussions. We end with the conclusion in section 4.

2. Data and methodology

2.1. Data

- The ionospheric parameter studied is the critical frequency of the ionospheric layer F2 (foF2) of the Ouagadougou ionosonde station (Lat: 12.5°N, Long: 358.5°E, dip: 1.43°). The hourly values of foF2 concerning this station are provided by Télécom Bretagne.

- the annual average of the new version of the sunspot number (SN) are used to characterize solar activity. They are downloaded from the NASA OMNIWeb website: https://omniweb.gsfc.nasa.gov/form/dx1.html.

- The aa index values are used to identify geomagnetic activities. They are available on the site http://isgi.unistra.fr/data_download.php.

2.2. Methodology

a) *Identification of seasons:* the months of the year are classified into seasons. We have the winter (December-January-February), spring (March-April-May), summer (June-July-August) and autumn (September-October-November).

b) *Identification of the phases of the solar cycle*: The different phases of the solar cycle are identified by applying the criteria defined by Sawadogo et al. (2024), on the new version of the annual mean values of the sunspot number (SN). According to these criteria we have:

- *minimum phase*: $SN(t) < 0.122 \times SN_{max}$;
- *Increasing phase*: $0.122 \times SN_{max} \leq SN(t) \leq 0.73 \times SN_{max}$;
- *maximum phase*: $SN(t) > 0.73 \times SN_{max}$
- *decreasing phase*: $0.73 \times SN_{max} \geq SN(t) > SN_{min(next\ cycle)}$

$SN\ (t)$, SN_{max}, and SN_{min} are respectively the annual mean value of sunspot in a given year, the maximum value of sunspot numbers in a given solar cycle and the minimum value of sunspot numbers in the next solar cycle. Table 1 shows the years covered by our study and their distribution in the solar phases.

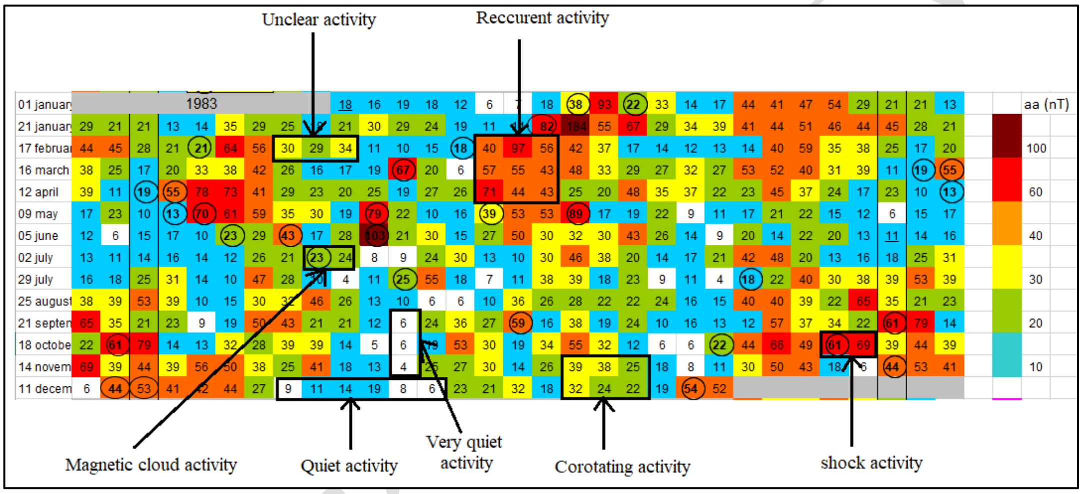
Table 1: Distribution of years at the minimum and maximum of solar ~~school~~ cycles 21-22

	Solar phases	
Solare cycle	**Minimum**	**Maximum**
21	1976	1979 -1980 - 1981
22	1986	1989 – 1990 - 1991

c) *Classification of geomagnetic activity*: we use the results of the work of Legrand et Simon (1989) and Zerbo et al. (2012). The work of Legrand et Simon (1989) allows us to organize geomagnetic activity into four classes: quiet activity, recurrent activity, shock activity and fluctuating activity. ~~Following on from work,~~ Zerbo et al. (2012) refined ~~have subdivided the~~ fluctuating activity into three new classes: magnetic cloud activity, corotating activity and unclear activity. The days covered by our study are days of very quiet, corotating and magnetic clouds activities. The variations observed during very quiet activity serve as a reference. To identify these different geomagnetic activities, these authors established the following criteria:

- Days of very quiet activity: days when $Aa < 10\,nT$ (white colors in the pixel diagram of Figure 1);
- Days of corotating activity: days when $20\,nT \leq Aa < 40\,nT$ without SSC (yellow and green colors in the pixel diagram of Figure 1);
- Days of magnetic cloud activity: SSC days whose effect lasts one, two or three days with $20\,nT \leq Aa < 40\,nT$ (yellow and green colors with a circle in the pixel diagram of Figure 1).

Figure 1 illustrates the identification of different geomagnetic activities.



01 januar	1983									18	16	19	18	12	6	7	18	38	93	22	33	14	17	44	41	47	54	29	21	21	13
21 januar	29	21	21	13	14	35	29	25	18	21	30	29	24	19	11	11	82	184	55	67	29	34	39	41	44	51	46	44	45	28	21
17 februa	44	45	28	21	21	64	56	30	29	34	11	10	15	18	40	97	56	42	37	17	14	12	13	14	40	59	35	38	25	17	20
16 march	38	25	17	20	33	38	42	26	16	17	19	67	20	6	57	55	43	48	33	29	27	32	27	53	52	40	31	39	11	19	55
12 april	39	11	19	55	78	73	41	29	23	20	25	19	27	26	71	44	43	25	20	48	35	37	22	23	45	37	24	17	23	10	13
09 may	17	23	10	13	70	61	59	35	30	19	79	22	10	16	39	53	53	89	17	19	22	9	11	17	21	22	15	12	6	15	17
05 june	12	6	15	17	10	23	29	43	17	28	103	21	30	15	27	50	30	32	30	43	26	14	9	20	14	22	20	13	11	14	16
02 july	13	11	14	16	14	12	26	21	23	24	8	9	24	30	13	10	30	46	38	20	14	17	21	42	48	20	13	16	18	25	31
29 july	16	18	25	31	14	10	47	28	30	4	11	25	55	18	7	11	38	39	18	23	9	11	4	18	22	40	30	38	39	53	39
25 august	38	39	53	39	10	15	30	32	46	26	13	10	6	6	10	36	26	28	22	22	24	16	15	40	40	39	22	65	35	21	23
21 septen	65	35	21	23	9	19	50	43	21	21	12	6	24	36	27	59	16	38	19	24	10	16	13	12	57	37	34	22	61	79	14
18 octobe	22	61	79	14	13	32	28	39	39	14	5	6	19	53	30	19	34	55	32	12	6	6	22	44	66	49	61	69	39	44	39
14 novem	69	39	44	39	56	50	38	25	41	18	13	4	25	27	30	14	26	39	38	25	18	8	11	30	50	43	18	6	44	53	41
11 decem	6	44	53	41	42	44	27	9	11	14	19	8	6	23	21	32	18	32	24	22	19	54	52								

Figure 1: Pixel diagram illustrating days of geomagnetic activity in the year 1983.

d) *Profile analysis*: The diurnal variations of foF2 in the equatorial sector are characterized by five types of profiles established by Faynot et Vila (1979) : i) the ''B'' or ''noon bite-out'' profile characterized by a double peak; ii) the ''M'' or ''morning peak'' profile with a peak occurring in the morning; iii) the ''D'' or ''Dome'' profile having the shape of a dome; iv) the ''R'' or ''Reversed '' profile characterized by a peak in the afternoon and v) the ''P'' or ''Plateau'' profile having the shape of a plateau.

~~The first relationship between the electrojet and an ionospheric parameter was discovered by Matsushita (1951) who showed that the latitudinal variation of the maximum frequency reflected by the sporadic E layer (fES) was very similar to that of the diurnal amplitude of the horizontal magnetic field. Knecht et McDuffie (1921) showed that the equatorial sporadic E layer occurred over a width of 700 km, which corresponded well to the width of the equatorial electrojet.~~

Subsequent studies have shown that the strength of the daily electrojet has a pronounced control on the foF2 in the equatorial trough and crest regions, whether on magnetically quiet or disturbed days (Rastogi et Rajaram, 1971). The role of the equatorial electrojet on the distribution of ionization at low latitudes was clearly demonstrated by Sethia et al. (1980). The work of Vassal (1982) on the Eastern Senegal sector allowed him to highlight a strong link between the variations of the horizontal magnetic field and that of foF2. This work led to the establishment of a link between the diurnal profiles of foF2 and the presence, absence and strength of the electrojet and counter-electrojet. Thus, profiles “D” and “P” express the absence of an electrojet; profile “M” indicates the existence of a moderate electrojet; profile “R” shows the presence of a counter-electrojet in the afternoon; and profile “B” indicates the presence of high intensity electrojet.

e) *Ionospheric storms*: We use the relative deviation ΔfoF2 (Vijaya et al., 2011) to quantify ionospheric storms caused by the two moderate activities. ΔfoF2 is defined by the following equation:

$$\Delta\mathrm{foF2} = \frac{\mathrm{foF2_m} - \mathrm{foF2_Q}}{\mathrm{foF2_Q}} \times 100 \qquad (1)$$

In this equation, $\mathrm{foF2_m}$ is the hourly mean value of foF2 during days moderate geomagnetic activity (corotating and magnetic cloud activities) and $\mathrm{foF2_Q}$ is that during days of very quiet activity. The storm is classified as positive or negative depending on whether $\Delta\mathrm{foF2} > 20\%$ or $\Delta\mathrm{foF2} < 20\%$, respectively.

Many studies (Forbes et al., 2000; Rishbeth et Mendillo, 2001; Buresova et Lastovicka, 2007; Vijaya et al., 2011 and Sandwidi et Ouattara, 2022) have used different threshold values to describe the intensity of ionospheric storms. For example, Rishbeth et Mendillo (2001) used a standard deviation of NmF2 ($\Delta\mathrm{NmF2}$) threshold of 20% during the day and 33% during the night to describe the maximum variability allowed during quiet periods. Based on the work of Vijaya et al., 2011, Buresova et Lastovicka (2007) considered a fluctuation of $\pm 20\%$ of $\Delta\mathrm{foF2}$ as an indicator of moderate storm and beyond this threshold, the storm is considered intense. Indeed, according to Lu et al. (2008), cited by Vijaya et al. (2011), both positive and negative storms occur when the absolute maximum value of ΔfoF2 exceeds 20%. In the present work, we consider as tolerable, a maximum variability of $\pm 20\%$ in moderate period compared to the very quiet period. Thus, a positive storm occurs when $\Delta\mathrm{foF2} > 20\%$ and a negative storm, when $\Delta\mathrm{foF2} < -20\%$.

3. Results and discussion

3.1. Results

3.1.1. At the solar phase minimum

Figure 2 shows the seasonal diurnal variations of foF2 (left) and ΔfoF2 (right) at solar phase minimum during days of corotating geomagnetic activities (red curves), magnetic clouds (blue curves) and very quiet (black curves). Panels a, b, c and d are dedicated to the winter, spring, summer and autumn seasons, respectively.

In winter, the hourly variations of foF2 during days of very quiet activity are of the Reversed type with a less noticeable trough at 11:00 UT. The same profile is observed during days of corotating activity. During days of magnetic cloud activity, a profile tending towards the plateau type is observed. During the night, the three profiles present the same decreasing trends. The variation curves of ΔfoF2 show positive values during corotating activity throughout the day except at 00:00 UT and 04:00 UT. During the day, these values do not reach 15%, which indicates that corotating activity does not cause ionospheric storms during the day. During the night, a fluctuation of ΔfoF2 values is observed with a peak of 38% at 03:00 UT. During magnetic cloud activity, ΔfoF2 is negative during the day (from 06:00 UT to 21:00 UT) and positive at night (22:00 UT to 05:00 UT). The absolute values never reach 20%, which means that magnetic cloud activity does not cause ionospheric storms in winter.

In spring, the diurnal variations of foF2 during days of very quiet activity and corotating activity show a profile identical to that observed in winter, i.e. a reversed profile. During days of magnetic cloud activity, a noon ~~bit~~ bite out profile is observed, with asymmetric peaks [the evening peak (17:00 UT; 10.20 MHz) being more pronounced than the morning peak (9:00 UT; 9.13 MHz)]. The variation curves of ΔfoF2 show mainly positive values for both moderate activities. During the day, these values vary between 15 and 20% during magnetic cloud activity and are always below 15% during corotating activity. During the night, significant increases in ΔfoF2 are recorded during both moderate activities. During corotating activity, ΔfoF2 is greater than 20% from 21:00 UT to 23:00 UT and from 03:00 UT to 05:00 UT. During magnetic cloud activity, from 20:00 UT to 21:00 UT and at 05:00 UT, ΔfoF2 is greater than 20%.

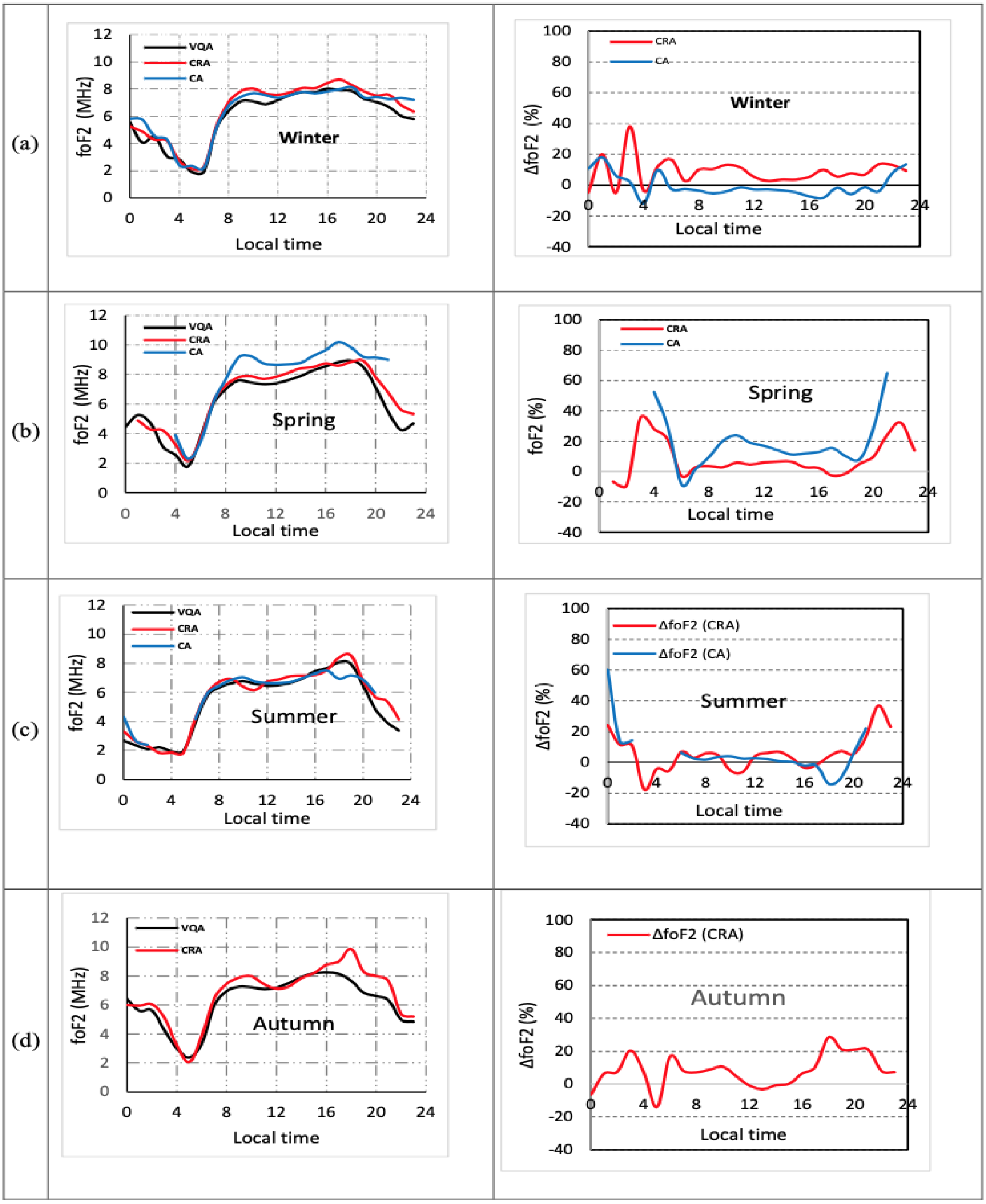


Figure 2: Influence of moderate geomagnetic activities on diurnal variations of foF2 as a function of the seasons of the solar phase minimum at the Ouagadougou station.

In summer, the diurnal profiles during the two moderate activities show the same evolutions as that of foF2 during the very quiet activity: Reversed profile. The ionization peaks are observed between 18:00 UT and 19:00 UT with values of 7.17MHz; 8.1MHz and 8.52 MHz respectively during the magnetic cloud, very quiet and corotating activities. During the night, the three profiles show similar decreases. The ΔfoF2 curves fluctuate between positive and negative with absolute values not reaching 10%. Only between 21:00 UT and 23:00 UT absolute value of ΔfoF2 exceeds 20% during the corotating activity with a maximum value of ~36% at 22:00 UT.

In autumn, we do not have data during the magnetic cloud activity. The hourly variations of foF2 observed during the quiet and corotating activities are of the ‘noon ~~bit~~ bite out’ type with the evening peak larger than the morning peak. However, there is a time difference at the troughs: the trough is observed at 11:00 UT during the very quiet activity and at 12:00 UT during the corotating activity. In addition, the trough is deeper during the corotating activity. The values of ΔfoF2 fluctuate between positive and negative with an absolute value not exceeding 20%.

3.1.2. At maximum solar phase

Figure 3 shows the seasonal diurnal variations of foF2 and ΔfoF2 at solar phase maximum.

During the winter, spring and autumn seasons, the diurnal profiles of foF2 during very quiet days are of the “morning peak” type with a maximum of ionization around 09:00 UT. After the peak, a decrease in the profiles is observed. This decrease becomes more significant from 16:00 UT to 17:00 UT. The same profile is observed during corotating and magnetic cloud activities. However, in winter, an ionization trough is observed at noon during very quiet and corotating activities. This trough is not observed during magnetic cloud activity. The absolute values of ΔfoF2 do not exceed 10% during the three seasons for the two moderate activities. However, just before sunrise (04:00-0500 UT) positive peaks of ΔfoF2 are observed with values reaching $30\ -\ 35\%$.

In summer, the diurnal variations of foF2 during very quiet activity is the ‘noon ~~bit~~ bite out’ profile with almost symmetrical peaks and the ionization trough occurs at 12:00 UT. The same variation profile is observed during corotating and magnetic cloud days. The ΔfoF2 variations show a peak between 01:00 UT and 02:00 UT with $\Delta\mathrm{foF2} \approx 29\%$ during corotating activity and $\Delta\mathrm{foF2} \approx 43\%$ during magnetic cloud activity. Outside this period, ΔfoF2 show low values not reaching 20% during all the rest of the time for both activities.

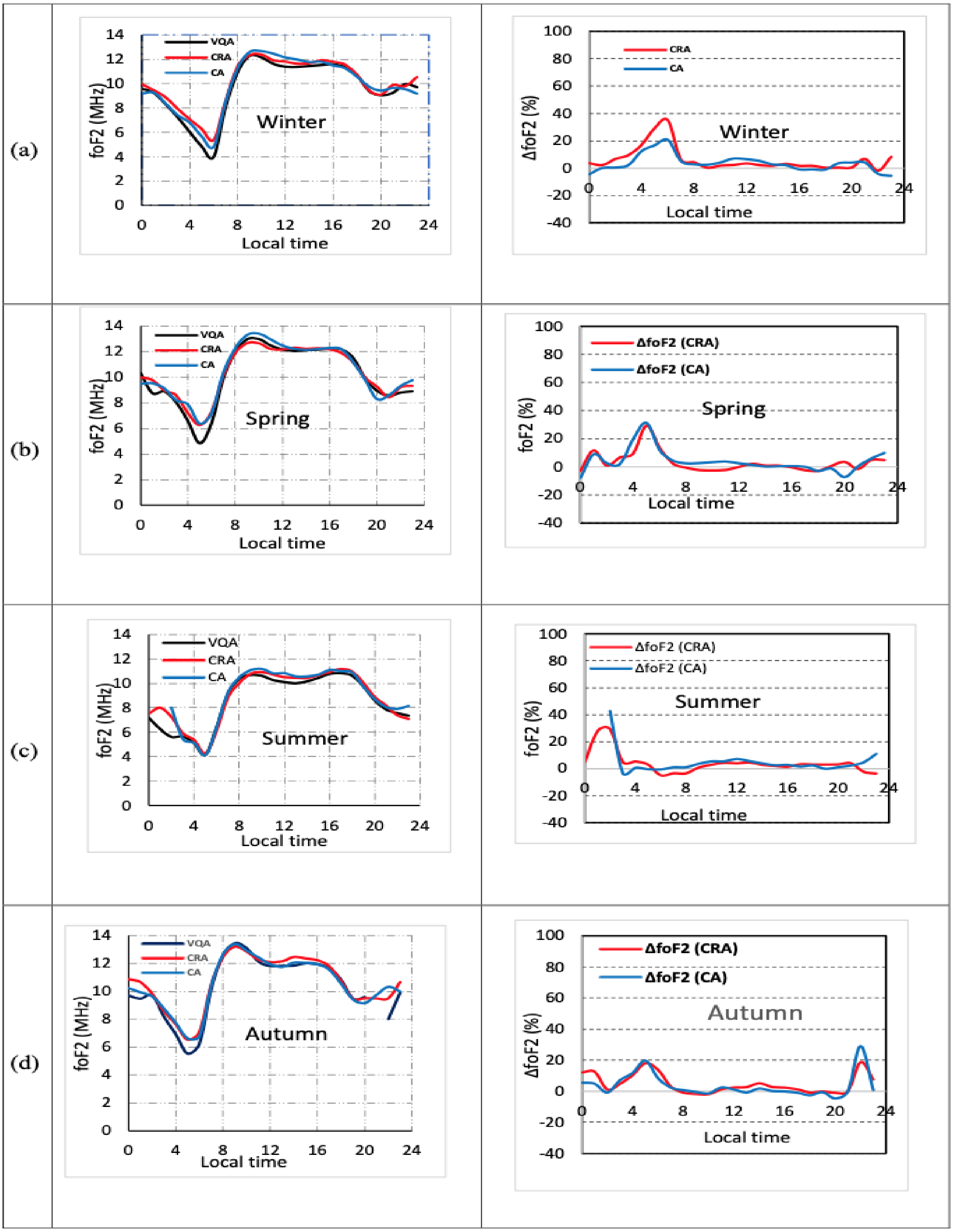


Figure 3: Influence of moderate geomagnetic activities on diurnal variations of foF2 as a function of the seasons of the solar phase maximum at the Ouagadougou station.

3.2. Discussion

We studied the variations of the critical frequency of the F2 layer during moderate geomagnetic activities of corotating and magnetic clouds at the equatorial station of Ouagadougou. The results obtained show that:

3.2.1. Diurnal profiles

- At solar minimum and in all seasons, the diurnal variations of foF2 during corotating activity days are characterized by profiles identical to those observed during very quiet activity for each of the four seasons. Referring to the link between the diurnal profiles of foF2 and the distributions of ionospheric currents in the E layer (Vassal, 1982), we can say that neither the ionospheric currents nor the EXB vertical drift are disturbed during days of corotating geomagnetic activity at solar phase minimum; dominated by a quasi-permanent presence of the counter-electrojet. However, the diurnal profiles observed during magnetic cloud activity differ from those observed during very quiet activity. This shows an inhibition of the counter-electrojet observed during very quiet activity in favor of a weak electrojet, except in summer.
- At the maximum phase of the solar cycle, the foF2 profiles observed during the two moderate geomagnetic activities are identical to those of the very quiet activity. These results allow us to conclude that the moderate corotation and magnetic cloud activities do not modify the electrodynamic process of the F2 layer. Like the very quiet activity, these activities are characterized by a permanent presence of an electrojet of medium intensity in the morning. The counter-electrojet is only observable during the summer. During the night, the foF2 variations are marked by an ionization trough at 20:00 UT followed by a peak between 21:00 UT and 22:00 UT. This phenomenon can be attributed to the manifestation of the pre-reversal phenomenon (PRE) with a late appearance during all three activities.

  These results show an anti-correlation between the equatorial counter-electrojet with solar activity: a quasi-permanent presence of the counter-electrojet during the solar minimum and an absence during the solar maximum. This property, observed by Rastogi (1974), Mayaud (1977) and Marriott et al. (1979) is disturbed during the activity of magnetic clouds at the solar phase minimum.

3.2.2. Ionospheric storms

At both solar minimum and solar maximum, the absolute values of ΔfoF2 do not reach 20% during the day, for the two moderate geomagnetic activities. It is only during the nights that ΔfoF2 values greater than 20% are often observed and this does not last more than three hours. We can therefore say that during the day, the geomagnetic activities of corotating and magnetic clouds do not cause ionospheric storms. On the other hand, during the nights, short-term positive ionospheric storms (01 to 03 hours maximum) are caused by these two activities. These ionospheric storms are more frequent at solar minimum than at solar maximum. Sandwidi et Ouattara (2022) had also noted a frequency of positive storms during the night (when chemical recombination is predominant). In their work on the variability of the F2-layer, Rishbeth et Mendillo (2001), attributed a large part of this variability to geomagnetic activity. In particular, they suggested that the greater nocturnal variability of the F2-layer is due to enhanced auroral energy input, and to the lack of the strong photochemical control of the F2-layer. Based on these different results, we can say under the activity of magnetic clouds this mechanism (strong auroral energy input and strong decreased of photochemical control) is more developed.

4. Conclusion

The present study on the diurnal and seasonal variations of foF2 at the equatorial station of Ouagadougou shows that:

- The moderate geomagnetic activities of corotation and magnetic clouds, all extracted from the fluctuating activity, present different influences on the variation of foF2 according to the solar activity: the diurnal profiles of foF2 observed during the corotation activity are almost identical to those observed during the very quiet activity at both the solar minimum and maximum. On the other hand, the magnetic cloud activity considerably modifies the diurnal profiles of foF2 during the solar phase minimum.
- During the day, the two moderate geomagnetic activities do not significantly modify the hourly values of foF2 observed during the magnetically quiet period. However, at night, they are at the origin of a considerable increase in foF2. This increase is short-lived (01 to 03 hours) and generally occurs around 20:00 UT and as sunrise approaches.

Disclaimer (Artificial intelligence)

Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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