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RESEARCH ARTICLE

EFFECT OF FLUCTUATING GEOMAGNETIC ACTIVITY ON THE TEC DURING SOLAR CYCLE 24: CORRELATIONS WITH F10.7 SOLAR INDICES, EUV AND COSMIC RAYS AT THE KOUDOUGOU GPS STATION.

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Abstract

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This study examines the response of total electron content (TEC) to solar and geomagnetic activity at the Koudougou station (Lat 12° 15'N; Long: -2°20' E) (Burkina Faso), focusing on periods of fluctuating activity during solar cycle 24. The data covers the period 2009-2017 and includes F10.7 solar indices, EUV and cosmic rays. The approach is based on a fine classification of geomagnetic days via the Pixel diagram. In this manuscript, we present the monthly variation of the TEC according to the phases of the solar cycle, in relation to the F10.7 solar fluxes, the EUV, and the cosmic rays. We also examine the dependence of the TEC on solar activity and the impact of geomagnetic activity on it. The results show that the EUV and F10.7 fluxes correlate best with the TEC, particularly during the ascending and maximum phases of the cycle. Conversely, cosmic rays generally show an anti-correlation with the TEC, except during the quiet period at solar maximum. These results underline the significant influence of geomagnetic activity on equatorial ionospheric dynamics and provide essential insights for regional ionospheric forecasting.

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Introduction

The study of variations in total electron content (TEC) is essential for understanding the dynamics of the ionosphere, particularly in equatorial regions where it is strongly influenced by solar and geomagnetic conditions. While much research has explored the correlation between TEC and F10.7 solar fluxes (Rao et al. 2013; Opio, D'ujanga, and Ssenyonga 2015; Chauhan, Singh, and Singh 2011; Van Dierendonck et al. 1996; Prasad et al. 2012; Galav et al. 2010; Dabas, Lakshmi, and Reddy 1993; Liu et al. 2009; M'Bi et al. 2019) , few of them (Rao et al. 2013; Chauhan, Singh, and Singh 2011; Van Dierendonck et al. 1996; Liu et al. 2009) have paid particular attention to the EUV flux, which is more directly linked to atmospheric ionisation. Furthermore, the interactions between TEC and cosmic rays have not yet been fully explored in this context. These studies show that the correlation between these solar indices and the TEC is a function of the seasons, solar activity and the solar zenith angle. The intensity of solar flux entering the atmosphere at a given altitude is modulated as a function of the zenith solar angle. As the zenith solar angle increases, atmospheric absorption intensifies, reducing the EUV flux received. The F10.7 flux, which comes from the solar transition region, is less directly linked to ionization than the EUV flux, which

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comes mainly from the chromosphere and corona. During periods of high solar activity, the F10.7 flux fluctuates significantly Prasad et al (2012) Cosmic rays are high-energy particles, studied mainly for their influence on climate. As they penetrate the Earth's atmosphere, they interact with air nuclei, generating secondary particles that can be detected down to the ground (Pallé Bagó and Butler 2000a; 2000b; Wagner et al. 2001; Udelhofen and Cess 2001; Ahluwalia et al. 2015; Dorman 2012) . The objective of this manuscript is to analyse the variations in the TEC during the AF during solar cycle 24 at the Koudougou station (Geo.lat 12°15'N ; Geo log :-2°20'E) by considering three parameters: the F10.7 solar flux, the EUV solar flux and the cosmic rays. The present study stands out for its focus on the Koudougou station, a strategic equatorial site in Burkina Faso, by analyzing the response of the TEC to the various solar indicators (F10.7, EUV, cosmic rays) during solar cycle 24, with particular attention to periods of fluctuating geomagnetic activity. By mobilizing the new classification (NC) via the Pixel diagram, this study offers a novel reading of the relationship between solar activity and local ionospheric dynamics. Section 1 is devoted to Materials and methods. Section 2 presents the Results and discussions and section 3 the conclusion.

1. Data And Methods.

1.1. Data.

Data used in this study comes from the Koudougou GPS station (Lat. 12°15'N; Long. -2°20'E), equipped with a receiver supplied by the Ecole Nationale of Telecommunication of Bretagne (ENST Bretagne) (now Institut Mines-Telecom, IMT) as part of the AHI project. This receiver, installed at the Norbert Zongo University since November 2008, provides TEC measurements over the period 2009-2017. The solar indices used include:

- Flux F10.7: available on the OMNIWEB portal (https://omniweb.gsfc.nasa.gov/),
- Sunspot number Rz: available on the OMNIWEB portal (https://omniweb.gsfc.nasa.gov/),
- EUV flux: supplied by the Solar EUV Monitor (SOHO), via the LISIRD website (http://lasp.colorado.edu/lisird/whi_ref_spectra/),
- Cosmic rays: measured by the Tsumeb station (Lat. -19.2°N; Long. 17.58°E), accessible via https://cidas.isee.nagoya-u.ac.jp.

The geomagnetic indices aa and the dates of SSC (Sudden Storm Commencements) were obtained from the ISGI website http://isgi.unistra.fr), enabling the Pixel diagram to be constructed.

1.2. Methods.

Methods for classifying geomagnetic activity.

Legrand and Simon(1989) and Richardson et al. (2002; 2000)) have carried out the first classification of days of geomagnetic activity based on the pixel diagram. According to this classification, geomagnetic activity can be divided into four classes: (1) quiet activity associated with slow solar winds ($V< 450\ /kms$); (2) recurrent activity caused by fast solar winds from coronal holes (V > 450 $/kms$) ;(3) shock activity associated with shock waves from CMEs and (4) fluctuating activity caused by fluctuations in the Sun's neutral plate. Ouattara and Amory-Mazaudier (2009) continued the work of Legrand and Simon(1989) and Richardson et al. (2002; 2000)) by developing criteria for selecting days of activity using the pixel diagram.

This classification was improved by Zerbo et al.(2012) who pushed back the limits of the old classification (AC) by shedding light on the solar origin of around 20% of geomagnetic storms in addition to the 60% explained by the AC. In the new classification (NC), days of calm activity, associated with slow solar winds, correspond to days when $Aa < 20\ nT$ and disturbed activity to days when Aa ≥ 20 nT. Disturbed days include: (i) fluctuating activity days (AFs) or fluctuating events (EFs) caused by fluctuations in the Sun's neutral plate, (ii) shock events (SEs) including CA shock activity (SA) and magnetic cloud activity (MCA), and (iii) recurrent event days (REs) including CA RAs plus moderate corotation activity (MCA) due to stable corotating neutral winds. Geomagnetic days are selected using the pixel diagram (**Figure1**) proposed by Simon and Legrand (1989) and improved by Ouattara and Amory-Mazaudier (2009) . The latter defined a color code to make it easier to identify the different types of geomagnetic activity. A line in the pixel diagram corresponds to the period of one solar rotation (27 days). The SSC dates are represented by circles surrounding the value of the index aa corresponding to the SSC day. The dates of the day on which the Bartels cycle begins, the legend and the year are shown on the left, right and top of the pixel diagram respectively. According to the color code of the pixel diagram, the days of geomagnetic activity are selected as follows

1) Quiet activities corresponding to index days$aa \leq 20nT$ which are represented by white and blue boxes;

2) Recurring Events (RE): these are made up of:

i) recurrent activities (RA) of the old classification corresponding to days when $aa \geq 40nT$ and extending over one or more Bartels rotations without SSC; these days are represented by orange, red and bright red boxes on at least two successive days without SSC and over at least two solar rotations;

ii) and days of co-rotation activity (ACR) corresponding to days when $20nT \leq aa < 40nT$ and extending over one or more Bartels rotations without SSC; these days are represented by yellow or green boxes on at least two successive days without SSC and over at least two solar rotations;

3) Shock events (ES): these are made up of:

i) CA SAs (shock activity) corresponding to SSC days where $aa \geq 40nT$; these days are represented by a set of 1, 2 or 3 days represented by orange, red and/or olive red boxes with SSC at the start of the phase and no recurrence of SSC during 1, 2, 3 or 4 Bartels rotations;

ii) ANMs corresponding to SSC days where $20nT \leq aa < 40nT$; these days are represented by a set of 1, 2 or 3 days represented by yellow and green boxes with SSC at the start of the phase and no recurrence of SSC during 1, 2, 3 or 4 Bartels rotations;

4) Fluctuating events (FE) which include all the days not included in the three previous classes.

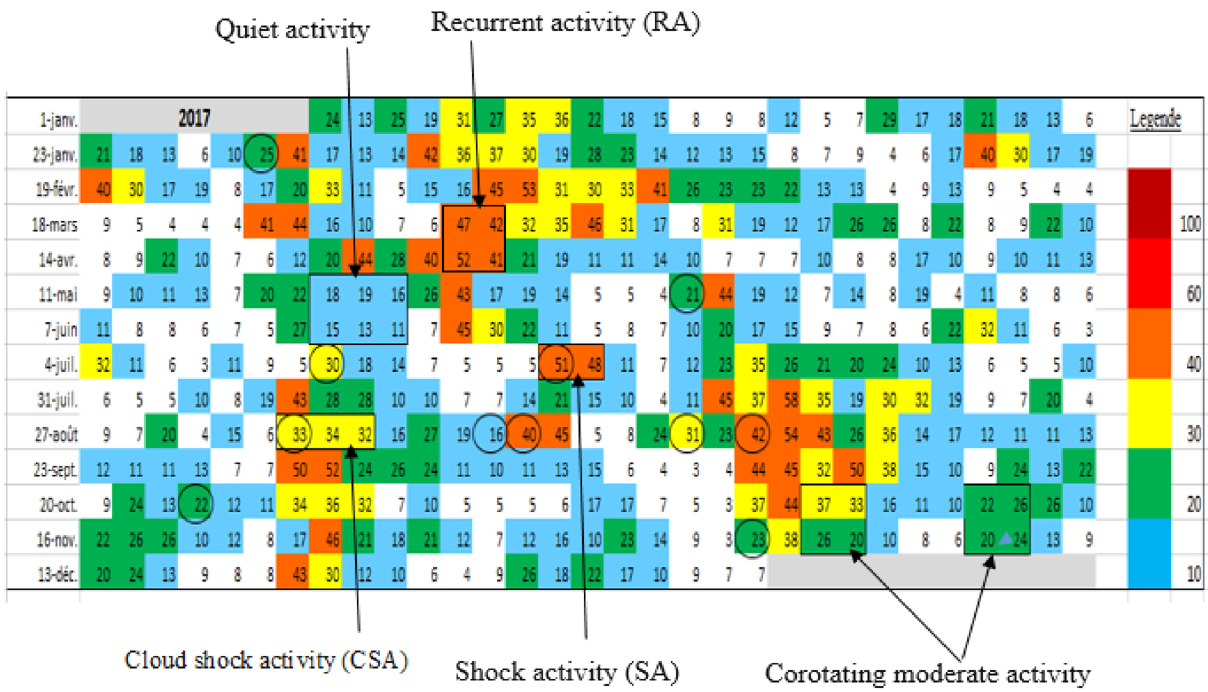


Figure1 : Pixel diagram showing the different geomagnetic activities according to NC

1.2.1. Criteria for dividing the solar cycle into phases.

The solar cycle is divided into phases according to the criteria proposed by Sawadogo et al (2024) . Table 1 summarises the years per phase of the solar cycle.

Phases	Years
Minimum	2008 – 2009
Ascending	2010 -2011
Maximum	2012 – 2014
Descending	2015-2018

Table 1: Results of dividing cycle 24 into phases.

2. Results and Discussion.

Results.

Solar energy, in the form of radiation and charged particles, is the main source of ionization in the Earth's atmosphere. Extreme ultraviolet radiation (EUV), in particular, plays a key role in the formation of the ionosphere by ionizing the gases in the upper atmosphere.

This radiation is absorbed by the atmosphere, leading to ionization, excitation and heating of the upper layers, such as the thermosphere. The EUV flux, measured in the 0.1 to 50 nm band, is expressed in photons/cm²-s and comes from data from the SOHO satellite (via the Solar EUV Monitor).

These data are available on the LISIRD website. Unlike EUV, F10.7 solar radio flux can be measured from the ground, whatever the weather conditions, making it a good indirect indicator of solar activity. Before the space age, it was used as a substitute for EUV flux, which was difficult to access. Figures 2, 3 and 4 show the profiles of monthly variations in TEC, EUV solar flux, F10.7 solar radio flux and cosmic rays during periods of quiet and fluctuating activity.

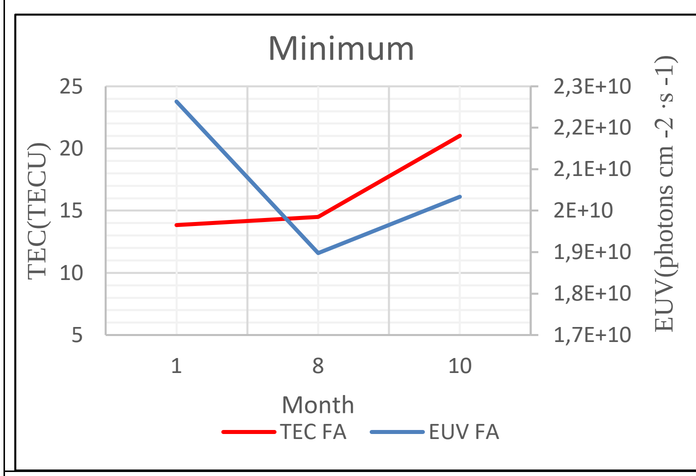
The red curves represent the TEC profiles and the blue curves those of the EUV solar flux, F10.7 solar radio flux and cosmic rays. The panels "a ,b" "c ,d" "e ,f" and "g, h" refer to the minimum, ascending, maximum and descending solar phases respectively.

Variation in TEC with EUV solar flux

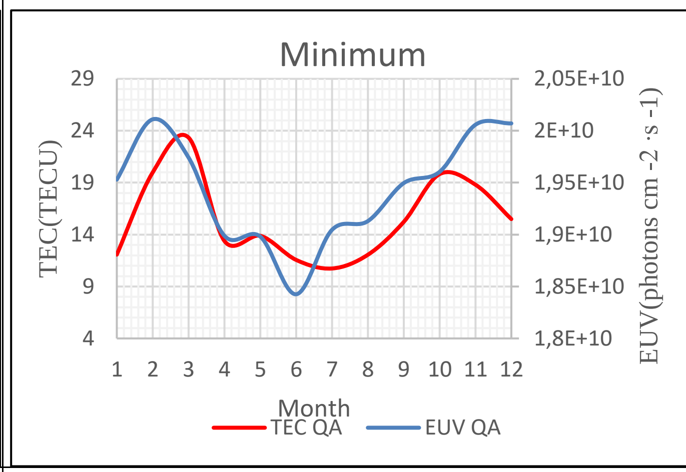
Most of the EUV spectrum contributes to the ionization of the atmosphere. Radiation between 100 Å and 1000 Å produces mainly ${N_2}^+$ andO^+ ions, maximum production around 160 km altitude, while radiation between 10 Å and 100 Å produces the three main ions ${N_2}^+, O^+$ and ${O_2}^+$ around 110 km altitude. The graphs for panels "a", "b", "c", "d", "e", "f", "g" and "h" in Figure 2 do not show different morphologies. Furthermore, the correlation coefficients will enable us to qualitatively assess the evolution of the TEC with the EUV flux during the different phases of the solar cycle 24.

For the minimum phase, the two graphs, as shown in Figure 2.a, do not show the same trend. We can see that the TEC values increase during all the months of the minimum phase, while the EUV solar flux decreases between January and August. This is because atmospheric absorption is stronger and the EUV flux from the Sun is lower when the zenith angle is at its maximum.

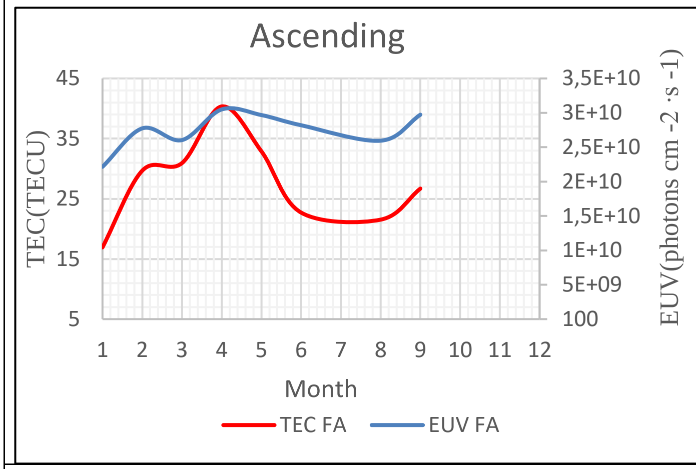
The increase in TEC during this period may be linked to the increase in electron density due to transport (Prasad et al.2012) . However, during the quiet period in Figure 2.b, the graphs have the same morphology with a peak shift of one month. The correlation coefficients between TEC and EUV flux during quiet and disturbed periods are 0.70 and r=-0.23 respectively. The values of these coefficients show that the effect of solar flux on the TEC is felt more positively during periods of calm activity than during disturbed periods. This tells us that the geomagnetic activity impacted by the action of the EUV flux plays an important role in TEC variations.



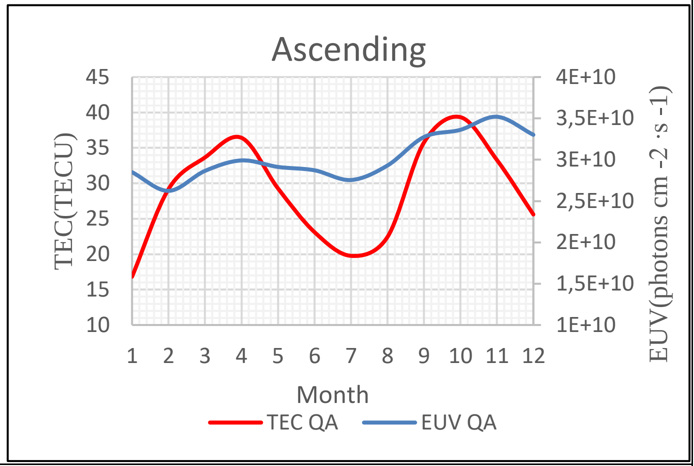
a



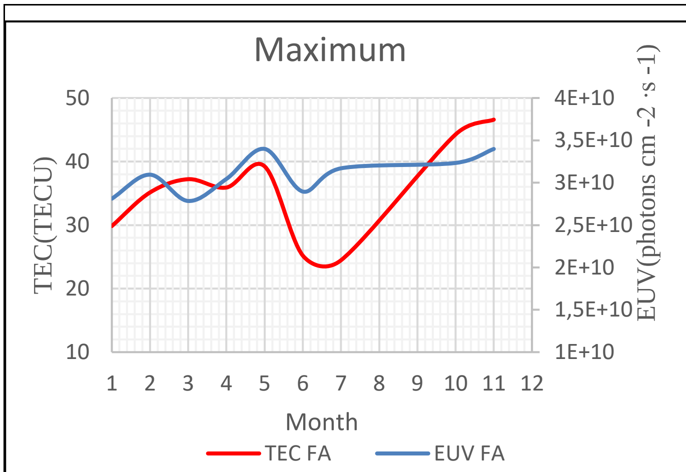
b



c



d



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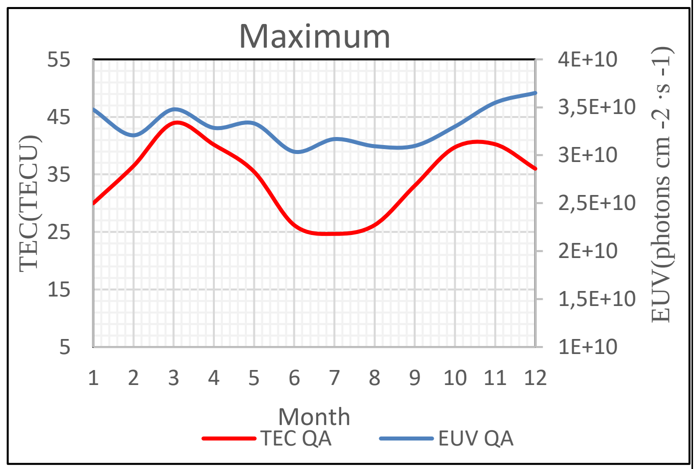
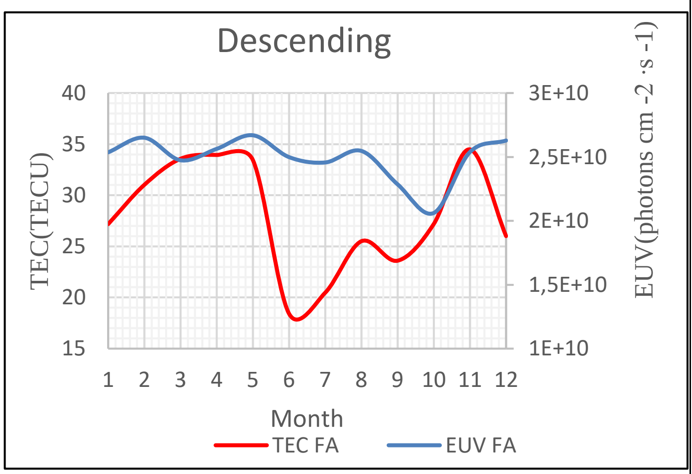
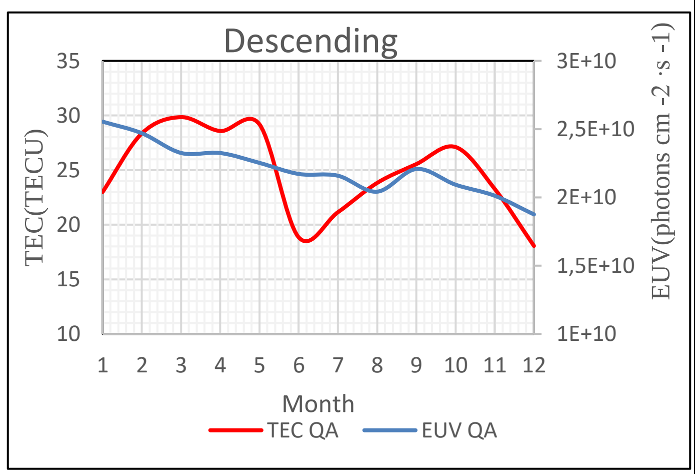


f



g



h

Figure 2: TEC phase variation with EUV

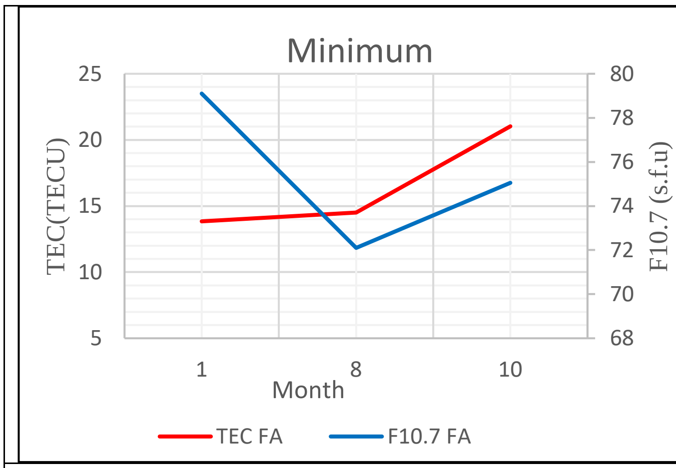
In Figure 2 (panels c and d), the TEC and EUV solar flux curves show similar profiles throughout the ascending phase, both in periods of calm activity and in fluctuating periods. This concordance suggests a regular evolution, little disturbed by major physical events. The correlation coefficients obtained, 0.52 in the quiet period and 0.75 in the fluctuating period, indicate a strong relationship between the TEC and the EUV flux, confirming that, during this phase, the EUV flux is a determining factor in the variation of the total electronic content.

The graphs for panels e and f in figure 1 show phase oppositions between the two graphs for each panel, particularly in March and between October and November during fluctuating activity, and from January to March during the magnetically quiet period. The decrease in TEC values observed between May-June and November-December may be due to the sharp drop in the ionization rate associated with low solar activity. During this phase, the correlation coefficients between these two parameters during quiet (0.60) and fluctuating (0.56) geomagnetic activity indicate a positive correlation between ultraviolet radiation and total electron content. This shows the significant contribution of EUV flux to ionization.

In Figure 2.g and h (the descending phase), the two graphs in each panel do not follow the same pattern at all times. On panel g, we see that between February-March and November-December the two graphs are in phase opposition during fluctuating activity. In addition, between February-March and November-December the TEC values decrease while the EUV solar flux increases. Furthermore, it is also observed that between January and May during periods of magnetic calm, the TEC increases while EUV decreases. This irregular variation of the TEC in relation to the EUV flux could be due to the production phenomenon which increases the quantity of electrons in the lower atmosphere. The decrease in EUV values is due to the value of the solar zenith angle, which could be at its maximum. At this time, atmospheric absorption is stronger and the EUV flux from the Sun is less important. In fact, in the periods when the two curves have the same trend, the regular variations in the total electronic content in relation to the solar EUV flux have not been disrupted. In addition, the fluctuating activity inhibits the action of the solar flux on the TEC. This is justified by the correlation coefficients obtained in quiet (0.51) and fluctuating (0.30) periods. Nevertheless, the solar flux shows a positive correlation with the TEC in quiet and fluctuating periods during the waning phase.

Variation of TEC with solar radio flux F10.7

F10.7 is the radio flux emitted by the Sun at a wavelength of 10.7 cm. The radio flux is a basic indicator of solar activity because it tracks the change in solar ultraviolet radiation, which has an influence on the Earth's upper atmosphere and ionosphere.



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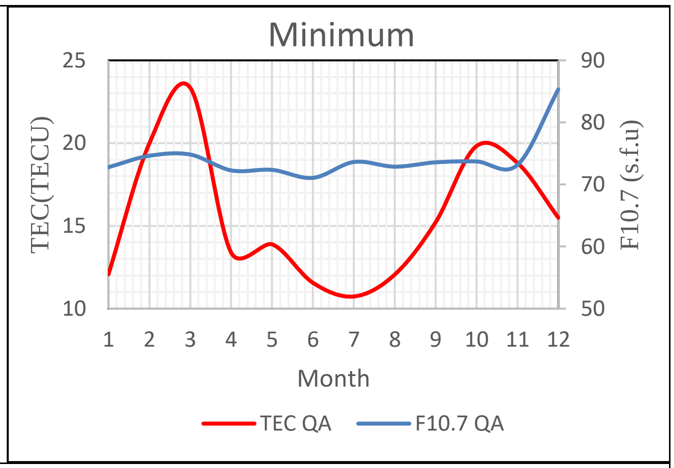

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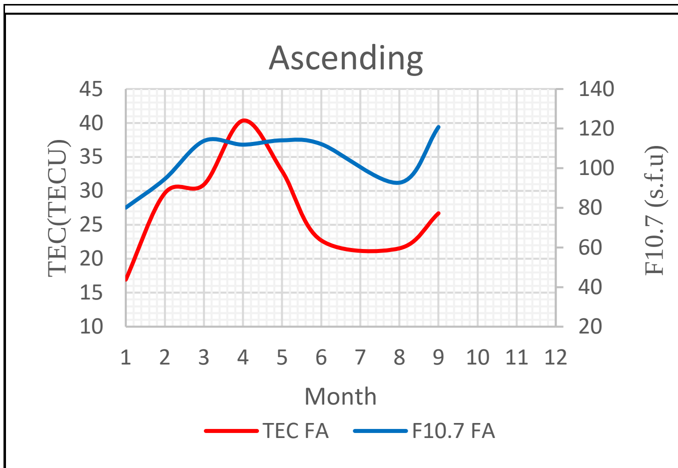
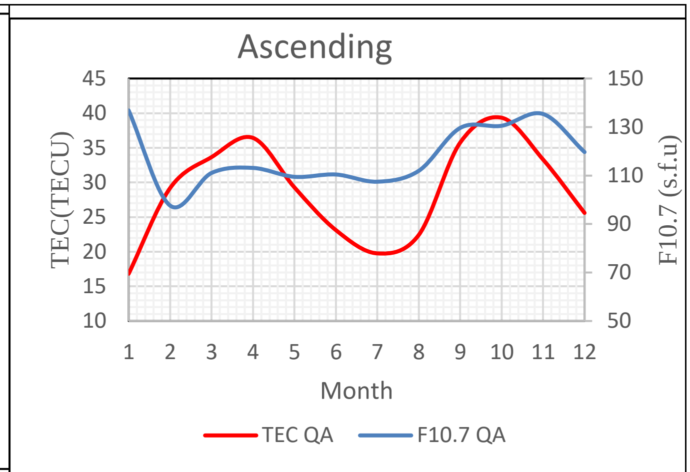
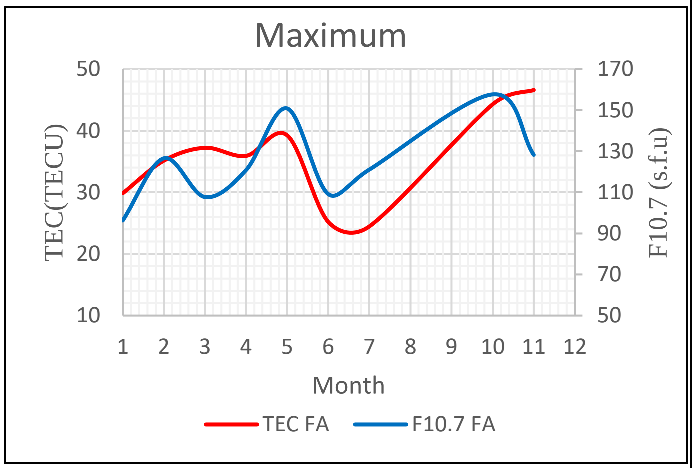


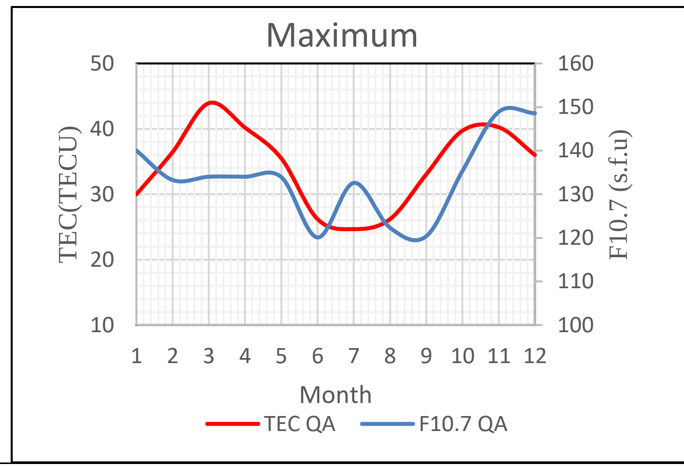
c



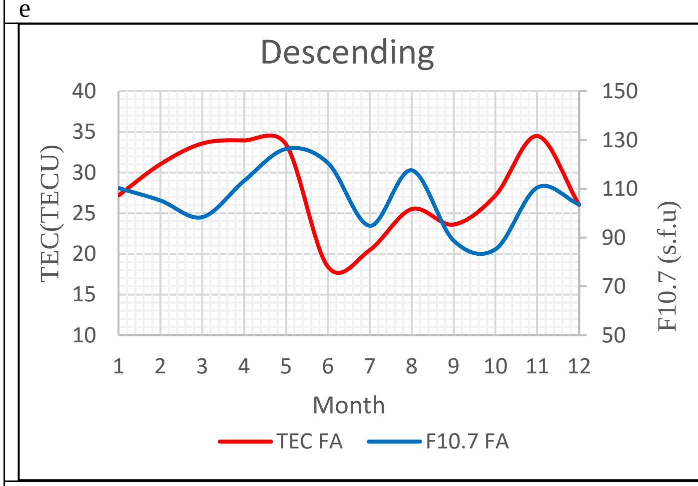
d



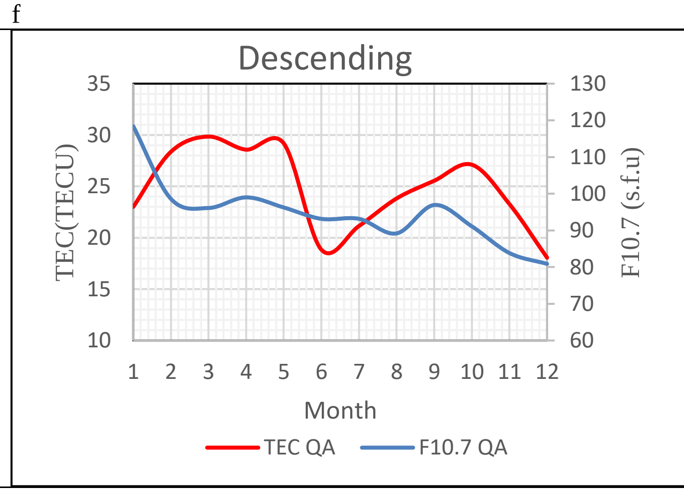
e



f



g



h

Figure 3: TEC variation by phase with F10.

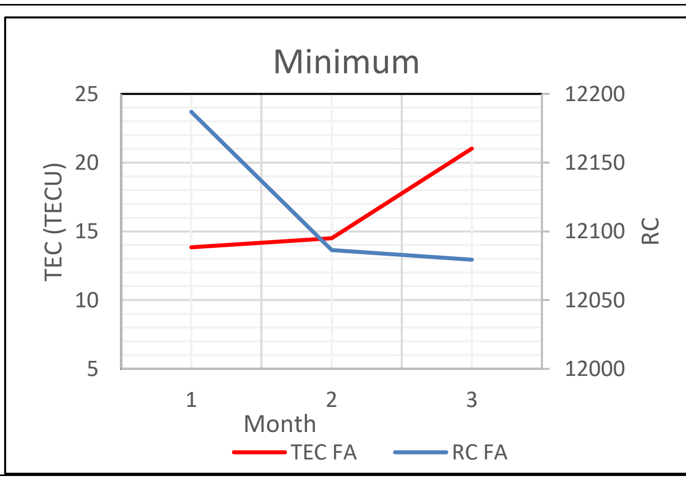
At solar minimum (Figure 3.a), the two graphs show the same trend between August and October during the fluctuating period. We can see that the TEC values increase during all the months of the minimum phase, while the F10.7 solar radio flux decreases between January and August. The same observation is made with the EUV solar flux at the same period and during the same phase of the solar cycle. Moreover, as the F10.7 flux follows the EUV solar flux, these results could be attributed to the variation in the solar zenith angle, and also to the season. And the increase in TEC during this period may be related to the growth in electron density due to the transport of particles (protons, ions, electron) (Prasad et al. 2012). Regarding the magnetically quiet period (Figure 3 panel b), the solar flux F10.7 is almost constant throughout the minimum phase except between the months of November and December. During this phase, the correlation coefficients between the two graphs for each panel in the quiet and fluctuating periods are 0.20 and -0.17 respectively. These results show that the contribution of the F10.7 solar flux to the variation in the TEC is more significant during periods of calm activity than during periods of fluctuating activity, and that the inhibiting effect of fluctuating activity on the solar flux is remarkable. Other physical phenomena favoring the production of electron density mean that TEC values are higher between May and October in the FA period than in the AQ period.

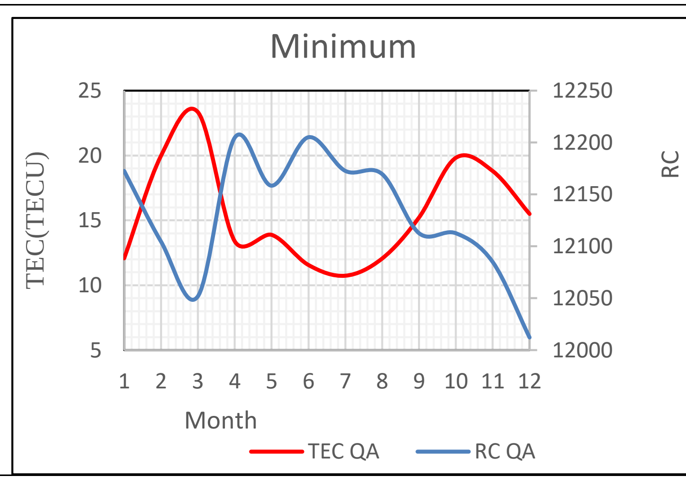
The graphs in figure 3.c show the same pattern. The same result is obtained with the EUV solar flux during the same solar phase. This type of evolution between the graphs could be explained by the effect of the fluctuating winds that occur during the ascending phase (F. Ouattara et al. 2009) and are caused by the fluctuation of the neutral blade (J. Legrand and Simon 1989) . It can also be seen that the graphs in Figure 3.d have the same profile except between January and February when the graphs are in phase opposition. The correlation coefficients of the TEC with the F10.7 during the two periods of geomagnetic activity show that the solar flux has a positive correlation with the TEC and that it is during periods of fluctuating activity that the correlation is stronger.

At the peak of the solar cycle, the two graphs for each panel show more correlated variations at all times except between March and April and from October to November for the disturbed period and from January to May and between June and August for the calm period. In fact, the periods when the F10.7 flux values decrease and those of the TEC increase could be explained by the effects of production and dissociation phenomena. The correlation coefficients explain qualitatively that the effect of the F10.7 flux on the TEC depends on the fluctuating activity. Fluctuating activity had a positive effect on the action of the F10.7 flow on the TEC. This is because the correlation coefficient of the TEC with the F10.7 is 0.50 in calm periods compared with 0.61 in fluctuating periods. The mechanisms responsible for the disturbances that appear in the Earth's upper atmosphere when geomagnetic activity increases are particle precipitation in the auroral zones, and the intensification of ionospheric currents that induce Joule heating. This leads to an increase in electron density and the TEC

Panel g in Figure 3 shows a trend of strong correlation between the F10.7 index and the TEC between the months of May and December. So as the values of the F10.7 solar index increase, so do the values of the TEC. Contrary to what we observe, between January and May, the two graphs show a very clear difference in profile. When F10.7 values rise, TEC values fall. The decrease in TEC values may be due to the effect of the Barth mechanism (Barth (1964)), which involves recombination of atomic oxygen during a triple collision. This mechanism occurs in the lower atmosphere. This would lead to a fall in electron density. For the quiet period in Figure 3.h, the two graphs have the same profile between August and December. The correlation coefficients of the TEC with the solar radio flux during these periods of geomagnetic activity show that the fluctuating activity has had a negative impact on the action of F10.7 on the TEC. The correlation coefficients obtained in the quiet and fluctuating periods were 0.30 and 0.19 respectively.

2.1.1. Variation of the TEC with cosmic rays





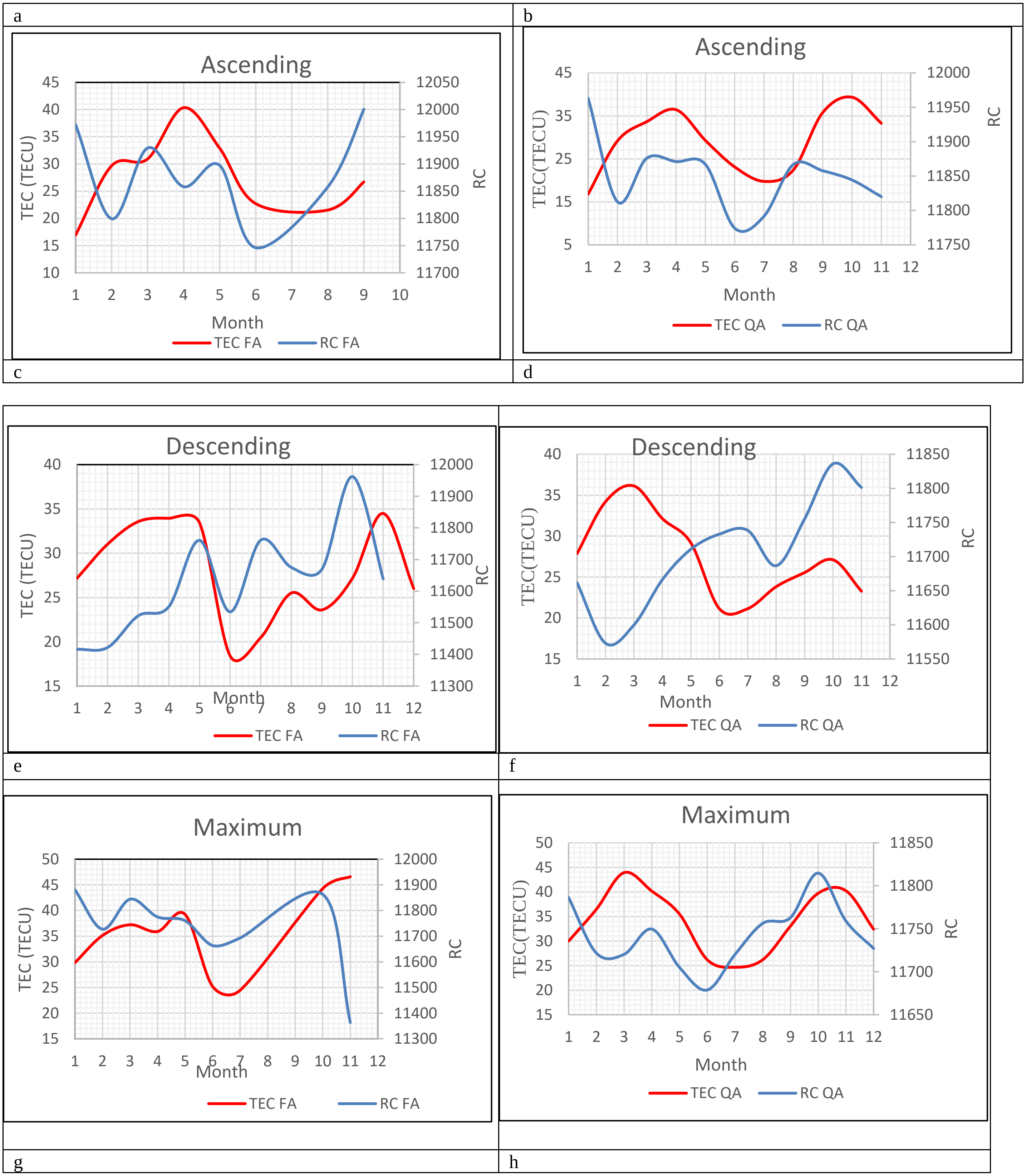


Figure 4: Phase variation of the TEC with cosmic rays

At solar minimum (Figure 4a), the two graphs do not evolve in the same way throughout the phase. The TEC graph shows an increasing trend, while the cosmic ray graph shows a decreasing trend. The two graphs for each panel show an anti-correlation at all times except between October and December for the solar minimum. This shows that the two graphs for each panel evolve in phase opposition except between October and December for panel b. Furthermore, as cosmic rays are correlated with solar flares, the drop in the quantity of cosmic rays could be linked to the lack of solar flares during the solar minimum. And the increase in TEC during this period may be linked to the growth in electron density due to the transport of particles (Prasad et al. 2012). During this phase, the correlation coefficients between these two parameters in quiet and fluctuating periods are -0.71 and -0.6 respectively. This indicates a strong anti-correlation between cosmic rays and total electron content.

In Figure 4.c and d (ascending phase), the graphs of the TEC and cosmic rays have the same profile from August to September for the fluctuating period and from February to November for the quiet period. During fluctuating activity (Figure 4.c), the correlation coefficients between the TEC and cosmic rays throughout the ascending phase and during the months of May to September are -0.11 and 0.46 respectively. These values show that the impact of cosmic rays on the TEC depends on the seasons and phases of the solar cycle. The same constants are found between April and October of the maximum phase, where the correlation coefficient is 0.94 compared with -0.24 for the entire maximum phase of the solar cycle. And also 0.25 between May and December of the descending phase against -0.14 for the whole phase. The observations made during these three phases of the solar cycle (ascending, maximum and descending) indicate that the contribution of cosmic rays to the increase in electron density is most noticeable on a seasonal scale, and in our case from the last month of the spring season (April) until autumn. This could be due to the fact that during this period solar activity is intense. During periods of calm activity, there are negative correlations between the TEC and cosmic rays during all phases of the cycle except the maximum phase.

Table 2 below summarizes the correlation coefficients of the mean TEC with the three solar parameters over the four phases of solar cycle 24, i.e. solar minimum, rising phase, phase maximum and falling phase in quiet and fluctuating periods.

Table 2: Summary of correlation coefficients

	TEC correlation coefficient with F10.7, EUV and cosmic ray flux					
Phase of the solar cycle	F10 .7		EUV		Cosmic rays	
Geomagnetic activity	Calm	Fluctuating agent	Calm	Fluctuating agent	Calm	Fluctuating agent
Minimum phase	0.20	-0.17	0.70	-0.23	-0.71	-0.61
Ascending phase	0.15	0.60	0.52	0.75	-0.10	-0.11
Maximum phase	0.50	0.61	0.60	0.56	0.25	-O.24
Descending	0.30	0.19	0.51	0.30	-0.71	-0.14

Discussion.

Analysis of the variation of the TEC with solar activity during periods of fluctuating activity shows that :

(1) The F10.7 and EUV solar fluxes show positive correlations with the TEC in periods of calm and fluctuating activity and during all phases. except at solar minimum and in periods of fluctuating activity when a negative correlation is observed. Patel et al (2017) studied TEC variations during quiet and disturbed periods in the Indian sector and found a positive correlation between F10.7 and EUV fluxes and TEC for the year 2013. This shows that the phase of the solar cycle could have an effect on the variation of the TEC with the two solar fluxes. The positive correlation found between TEC and solar fluxes during solar cycle phases is in agreement with the results of Patel et al (2017) and Bhuyan. P. and Hazarika. R . (2013)

(2) During the ascending and maximum phases. the correlation coefficients of the TEC with the F10.7 and EUV solar fluxes are higher during periods of fluctuating activity than during quiet periods. This shows that fluctuating geomagnetic activity has a positive effect on the action of solar fluxes on the variation in the TEC. On the other hand. during the minimal and descending phases. fluctuating activity inhibits the action of solar fluxes on the TEC.

(3) In general. the correlation coefficient of TEC with EUV is better for all phases than for F10.7 and cosmic rays. The change in solar zenith angle could be one of the reasons for the lower correlation between the TEC parameter and the EUV and F10.7 solar fluxes at the Koudougou station. The EUV flux is the index most correlated with TEC compared with F10.7 cm and cosmic rays during periods of fluctuating activity.

(4) The value of the correlation coefficient for cosmic rays is negative for all phases of solar cycle 24 except at phase maximum in the quiet period. when a positive value is observed.

Conclusion

This study. carried out at the Koudougou station. highlights the combined influence of F10.7 solar flux. EUV and cosmic rays on the variability of the TEC during solar cycle 24. particularly during periods of fluctuating geomagnetic activity.

The results show a significant positive correlation between the TEC and the EUV flux. particularly in the ascending and maximum phases. with coefficients of up to 0.75. During periods of fluctuating activity. this correlation remains strong. although less homogeneous during the minimum and descending phases. indicating possible attenuation by geomagnetic activity. The F10.7 radio flux. often used as a proxy for the EUV flux. shows similar trends but slightly weaker correlations. A moderate positive correlation is observed during the ascending and maximum phases. suggesting a significant but indirect contribution from F10.7 to the variability of the TEC. The analyses reveal an overall anti-correlation between cosmic rays and the TEC. confirming that these particles have an inverse effect on ionization of the ionosphere. A notable exception is observed during the quiet period at the maximum of the cycle. when a positive correlation appears. suggesting a seasonal interaction or one linked to other ionospheric mechanisms. The methodology using the new classification and the Pixel diagram is proving to be robust in dissociating the impact of each parameter on ionospheric dynamics.

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