ijar
ISSN (O): 2320-5407
ISSN (P): 3107-4928

Journal Homepage: - www.journalijar.com

INTERNATIONAL JOURNAL OF ADVANCED RESEARCH (IJAR)

Article DOI: 10.21474/IJAR01/22914
DOI URL: http://dx.doi.org/10.21474/IJAR01/22914

RESEARCH ARTICLE

INVESTIGATION OF THE INFLUENCE OF SOLAR ACTIVITY ON TOTAL ELECTRON CONTENT (TEC) AT THE KOUDOUGOU STATION DURING RECURRENT GEOMAGNETIC ACTIVITY DURING SOLAR CYCLE 24: A DETAILED ANALYSIS

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Manuscript Info

Manuscript History
Received: 04 January 2026
Final Accepted: 08 February 2026
Published: March 2026

Key words:-
TEC,recurring geomagnetic days, Cycle solaire 24, Linear and quadratic model.

Abstract

The objective of this article is to examine the dependence of total electron content (TEC) on solar activity parameters such as the sunspot number (SN) index, the F10.7 solar radio flux and the EUV flux. Daily, monthly and annual average TEC data, as well as solar indices, were used for the study. TEC observations were made in Koudougou (12°15'N; -2°20'E), Burkina Faso, using a dual-frequency GPS receiver. The working period covers the years 2010 to 2017, focusing on recurring geomagnetic days. To model the variation in TEC as a function of solar parameters, a quadratic fit was used as a model to describe the daily, monthly and annual variation in TEC. Linear and non-linear coefficients were calculated to understand the trends in the variation. The results show that the variation in TEC corresponds well to the trend in solar parameters for most of the days observed during the study period. Maximum TEC values were recorded at the equinoxes, while minimum values were observed at the solstices. Other parameters will therefore need to be taken into account to explain this difference. In addition, the variation in TEC as a function of EUV showed relatively small deviations from the variation due to F10.7 flux and SN. This suggests that EUV may be more appropriate for modelling solar variation in TEC, particularly for long-term trends. Finally, although the linear trend in solar variations in TEC was frequently observed, significant saturation and amplification trends were also noted across the months and years analysed. This complexity in the solar variation of TEC highlights the need for further studies to understand the effect of solar parameters on TEC.health.

Introduction:-

Solar radiation is the main source of energy that causes the formation of the ionosphere. Research has established that extreme ultraviolet (EUV) solar radiation and solar X-rays are the main sources of Earth's ionosphere formation (from Adler et al., 1997). This solar radiation varies on different timescales, which has a significant impact on the

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structure of the upper atmosphere, climate, and weather conditions, leading to remarkable changes in the Earth's thermosphere and ionosphere (Hedin, 1984; Gorney, 1990). The critical parameter of the ionosphere, total electron content (TEC), is attracting growing interest among researchers, particularly for studies of the equatorial ionosphere. The Global Positioning System (GPS), widely used for space and terrestrial navigation, plays an essential role in scientific research. Signals emitted by GPS satellites, propagating through the ionosphere located approximately 60-1000 km above the Earth, are used to monitor the ionosphere on a global and regional scale (Rama Rao et al., 2009; D’ujanga et al., 2012; Paznukhov et al., 2012) . The L1 (1575 MHz) and L2 (1228 MHz) frequencies emitted by GPS satellites allow dual-frequency receivers to measure the ionospheric delay between them, generally considered to follow the same path through the ionosphere. This approach has proven valuable for ionospheric studies and opens up new research opportunities in this field. The amplitude of the TEC varies considerably in space and time, depending on geomagnetic latitude, local time, season, solar activity, and geomagnetic activity (Soicher, 1988; Jakowski et al., 1999; B. Tsurutani et al., 2004) . By modelling TEC, it becomes possible to evaluate ionospheric errors and correct them, particularly in the case of differential GPS.

Considerable research has been conducted worldwide to characterise the effects of solar activity on several ionospheric parameters, such as electron density (Ne), plasma temperatures at different altitudes, total electron content (TEC), maximum electron density (NmF2) and maximum height (hmF2) of the F2 layer, in terms of both observations and theoretical models (Su et al., 1999; Kane, 2003; Lei et al., 2005; H. Liu et al., 2007) . In addition to different regions of the globe, several researchers have studied the morphological characteristics of TEC, such as diurnal, monthly, seasonal, latitudinal and solar activity variations, using various techniques, e.g. in AfricaZoundial., , in South America ; on China (Zhao et al., 2007; G. Liu et al., 2013) , Huo et al.(2009) , and Perevalova et al.(2010) ; on North America, Zakharenkova et al.(2013); on Japan, on Brazil , and manyothers. Significantresults have been reported in the variability of TEC, whichis the parameterstudied in thiswork, in relation to the solar cycle. Several authors have reported the dependence of TEC on solar activity at high, mid and low latitudes (Balan et al., 1993; Afraimovich et al., 2008; Y. Chen et al., 2008) . Liu and Chen(2009)observed three types of patterns (linearity, saturation and amplification) in TEC as a function of F10.7 radio flux. Therelationship between TEC and solar indices (sunspot number (SN) and F10.7) or EUV solar flux is approximately linear (Balan et al., 1993; Afraimovich et al., 2008) and quadratic (Y. Chen et al., 2008; L. Liu & Chen, 2009) . Recent work shows that ionospheric parameters increase approximately linearly with solar indicators during low and medium solar activity levels; however, they tend to saturate during high solar activity levels (Balan et al., 1994, 1994, 1996; Gupta & Singh, 2000; Richards, 2001; Sethi et al., 2002; Lei et al., 2005) . The true manifestation of this saturation effect is not yet fully understood.

Although TEC variations related to solar activity have been measured in different parts of the globe, little work of this type has been undertaken around the equatorial region of the African continent, which has limited our understanding of the equatorial ionosphere above Africa. Long-term records of TEC measurements are essential for more accurately tracking the effects of solar activity on the equatorial ionosphere. During solar cycle 24, characterised by different periods of solar activity and recurring geomagnetic events, it is essential to understand how these solar variations affect the TEC at specific locations. The Koudougou station offers an ideal environment for this study due to its geographical location and proximity to the magnetic equator. The ionospheric disturbances observed at Koudougou are likely to be influenced by variations in solar activity and geomagnetic phenomena, providing a unique opportunity to examine the impact of these factors on TEC. Using a detailed analysis approach that includes statistical analysis techniques and accurate data on solar activity such as sunspots, solar flux F10.7 and EUV flux, we aim to provide valuable insights into the relationship between solar activity and TEC at the Koudougou station. The results of this study could contribute to a better understanding of the underlying physical mechanisms and have significant implications for various fields such as satellite communications, navigation and weather forecasting.This article presents the TEC values measured by a SCINDA (Scintillation Network and Decision Aid) dual-frequency GPS receiver located at Norbert Zongo University in Koudougou, Burkina Faso (Geo Lat 12°15'N; Geo Long: -2°20'E) during solar cycle 24. The data used and the description of the methodology employed are presented in Section 2. Section 3 concerns the analysis and interpretation of the results obtained.

Data and methodology used:-

Data used:-

The TEC data used in this work were obtained at the Koudougou GPS station (Geo lat 12°15'N; Geo long: -2°20'E, dip: + 8.24). The GPS receiver at the Koudougou station was donated by the Ecole Nationale Supérieure des Télécommunications de Bretagne (ENST-Bretagne, now Télécom-Bretagne) as part of the International

Heliophysical Year (IHY) project. This project mainly brings together three types of networks : (1) IGS (International Geodesy System); (2) AMMA (Multidisciplinary Analysis of the African Monsoon), and (3) SCINDA (Scintillation Network Decision Aid). The Koudougou station is one of the stations in the SCINDA GPS network located at the equatorial latitude and dedicated to the study of ionospheric scintillations (OUATTARA et al., 2011). Not listed in the global GPS station network, the Koudougou GPS station has been operating since December 2008 and provides in situ data in RINEX format. The RINEX files used contain data recorded every 30 seconds. These RINEX files are then transformed to obtain the VTEC. At the same time, precise measurements of solar activity, such as daily values for sunspot number (SN), solar flux F10.7, and SOHO/SEM EUV flux (in wavelength ranges from 0.1 to 50 nm) were used to understand variations in solar activity and its effects on TEC. The F10.7 index, which measures the radio flux at a wavelength of 10.7 cm emitted by the Sun, and the sunspot number (SN) index, which indicates the number of sunspots present on the Sun's surface and measures their intensity, are available on OMNIWeb at https://omniweb.gsfc.nasa.gov/form/dx1.html. EUV (Extreme Ultraviolet) solar radiation, which is a form of electromagnetic energy emitted by the outer layer of the solar atmosphere, can be downloaded from http://lasp.colorado.edu/lisird/Whi_ref_spectra/.Geomagnetic indices were also used in this work to select days of recurring geomagnetic activity. The indices used are the disturbed storm time index (Dst), which indicates the hourly variation in the horizontal component of the Earth's magnetic field (K. Patel et al., 2019) (http://isgi.unistra.fr/data_download.php) and the interplanetary indexKp , which indicates the level of geomagnetic activity(Perira, 2004) . The Kp values from the OMNIweb database are available at https://omniweb.gsfc.nasa.gov/form/dx1.html.

Methodologies used:-

Statisticalanalysis and modeling:-

To analyse seasonal variations in TEC at the Koudougou station, we used TEC measurements for the spring equinox (March, April, May), the summer solstice (June, July, August), the autumn equinox (September, October, November) and the winter solstice (December, January, February) for the years 2010-2017. To indicate the variability of solar activity, daily values for sunspot number (SN), solar flux F10.7 and EUV flux were used.In order to see the variations in TEC during the different phases of a solar cycle, the annual average values of the SN solar index from 2008 to 2018 (solar cycle 24 period) were used to divide the solar cycle into phases. The years 2008 and 2009, with average sunspot numbers (SN) of 2.8 and 3.1 (low solar activity) respectively, represent the minimum phase of solar cycle 24, the years 2010 and 2011, with average SN numbers of 24.86 and 80.84 (moderate solar activity) respectively, represent the ascending phase of cycle 24, the years 2012, 2013 and 2014, with average SN numbers of 84.53; 94.02 and 113.34 (intense solar activity) respectively represent the maximum phase of solar cycle 24, and the years 2015, 2016, 2017 and 2018, with an average number of SNs of 69.82; 39.82; 21.74 (moderate solar activity) and 6.97 (low solar activity) respectively represent the descending phase of solar cycle 24. However, the TEC data available from the Koudougou station covers the period from 2010 to June 2017.

To assess the linear relationship between TEC and the SN, F10.7 and EUV solar indices, Pearson's correlation coefficients, denoted R, were calculated for the annual, monthly and daily variation of TEC. A Pearson correlation coefficient of 1 indicates a perfect positive linear correlation, a coefficient of -1 indicates a perfect negative linear correlation, and 0 indicates no linear correlation. For all data used in this document, correlation coefficient values (R) > 0.5 are considered highly significant. Two regression models were also used to study the dependence of TEC on solar activity above Koudougou. The first regression model is a linear approximation to describe the relationship between solar indices and TEC. A linear model was proposed by Bassa et al.(1994) , Bilitza(2000) ; Liu et al.(2003)to study the relationship between TEC and solar activity. Its mathematical expression can be given by:

$$\mathrm{TEC}\ (\mathrm{S}) = \mathrm{A}_1\mathrm{S} + \mathrm{A}_0 \qquad (1)$$

The second regression model is the quadratic relationship between solar indices and TEC. A quadratic model was proposed by Gupta et al.(2000) ; Sethi et al.(2002) ; Adewale et al.(2012) ; Kassa et al.(2017) to model the variation in solaractivity of TEC. Itsmathematical expression can begiven by:

$$\mathrm{TEC}(\mathrm{S}) = \mathrm{A}_2\mathrm{S}^2 + \mathrm{A}_1\mathrm{S} + \mathrm{A}_0 \qquad (2)$$

whereA_0 ,A_1 , andA_2 are the unknown coefficients to be determined, and S represents solar activity, which could be evaluated by the number of sunspots (SN), the solar flux F10.7, or the EUV flux. The sign ofA_2 indicates the possible non-linear trend, namely a tendency towards amplification for a positiveA_2 , a tendency towards saturation for a negativeA_2 , and a linear trend for an unknownA_2 .

Identification of recurring geomagnetic days:-
Recurrent geomagnetic activity refers to periodic variations in the Earth's magnetic field caused by the interaction between the fast solar wind and the Earth's magnetosphere or by co-rotating interaction regions (CIRs) (B. T. Tsurutani et al., 2006) . Legrand and Simon(1989) have classified geomagnetic activity into four classes: (1) quiet activity characterised by $Aa < 20$ nT , (2) shock activity caused by SSCs and characterised by $Aa \geq 40$ nT , (3) recurrent activity characterised by $Aa \geq 40$ nT without SSCs and repeating over two or more Bartels rotations, and (4) fluctuating activity, which is activity not covered by the other three classes. This classification was later improved by Ouattara and Amory Mazaudier(2009) , who introduced a colour-coding system to graphically represent the different classes on a pixel diagram. More recently, Zerbo et al.(2012) have also made improvements to this classification. This present work focuses on the class of recurrent geomagnetic activity days. This work considers geomagnetically disturbed days that meet the following criteria to be recurring days: $Kp \geq 27$ and $Dst \leq -30$ nT , with a periodicity of 27 days. In order to eliminate the influence of other geomagnetic events, all recurring days preceded by an SSC (Sudden Storm Commencement) or an SI (Sudden Impulse) occurring in the previous three days were excluded. Taking into account the conditions set, the occurrence of recurring geomagnetic days is established in Table 1. It should be noted that these days correspond to the days when TEC data are available at the Koudougou station.

Table 1: Occurrence of recurring geomagnetic days during cycle 24

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Recurringdays	0	1	9	31	37	31	69	133	100	50	0

Results and Discussions:-

Correlation between the average annual TEC and the SN, F10.7, and EUV solar indices:-
In order to verify the dependence of TEC on solar activity during recurring geomagnetic periods, we obtained the statistical correlation between the average annual TEC and the number of sunspots (SN), the solar flux F10.7 and the EUV flux at the Koudougou station. Figure 2 shows the scatter plots and correlation analysis between the annual average TEC values and the number of sunspots (SN), solar flux F10.7 and EUV flux during the period 2010-2017. Panels a, b and c of Figure 2 show the scatter plots of the annual TEC values as a function of SN, F10.7 and EUV, respectively. To model the average annual variations in Total Electron Content (TEC) as a function of solar activity, linear and quadratic adjustments were applied. Pearson's correlation coefficients (R) between the average annual TEC and the index (SN), solar flux F10.7 and EUV flux during recurring geomagnetic periods in Koudougou are calculated and presented in Table 2.

The graphs in Figure 2 clearly show that all solar indices are strongly correlated with the average annual TEC at the Koudougou station. The average annual variation in TEC as a function of the three solar indices considered showed a positive correlation. The correlation coefficients of SN, F10.7 and EUV flux with TEC are 0.94, 0.98 and 0.93, respectively. This shows that TEC follows an almost one-to-one correlation with these solar indices. This strong correlation between TEC and solar activity indicates a strong positive linear relationship between these two series. The high degree of correlation obtained for these solar activity indices suggests that the production and ionisation of the ionosphere and its dynamics are entirely controlled by the level of solar radiation received by the ionosphere and that the ionosphere varies closely with it. Consequently, the variability of the ionosphere will also follow the cyclical variability of solar activity.

Table 2: Correlation coefficients between TEC and solar parameters (SN, F10.7 and EUV) on a time resolution of one year

Solar indices	SN	F10.7	EUV
Annual TEC	0.94	0.98	0.93

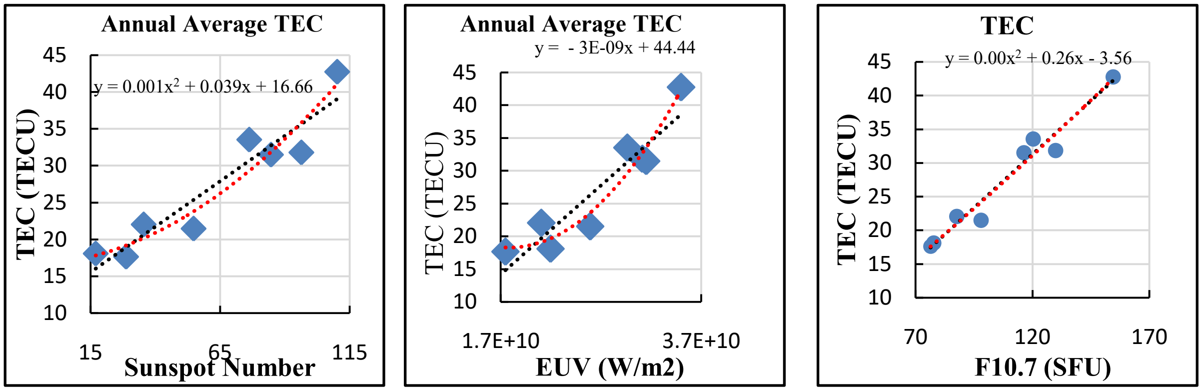


Figure 2: Scatter plots of annual mean TEC values and solar parameters (SN, F10.7 and EUV) from 2010 to 2017 during recurrent geomagnetic activity.

From the general expression of the quadratic model given by equation (2), we can deduce the degree of linear and non-linear variation in the TEC observation as a function of solar parameters. The sign of the coefficientA_2 indicates possible non-linear variations (trends) in the TEC due to variations in the corresponding solar indices SN, F10.7 or EUV . The graphs in Figure 2 show linear and non-linear trends. Panel c of Figure 2 shows a linear variation of the TEC as a function of the solar index F10.7. However, panels a and b indicate a non-linear variation of the TEC as a function of SN and EUV. The quadraticequations for thesedifferent variations are:

$$\mathrm{TEC} = 0{,}0016(\mathrm{SN})^2 + 0{,}0399(\mathrm{SN}) + 16{,}664 \quad (3)$$

$$\mathrm{TEC} = 8.10^{-20}(\mathrm{EUV})^2 - 3.10^{-9}(\mathrm{EUV}) + 44{,}443 \quad (4)$$

$$\mathrm{TEC} = 0{,}00(\mathrm{F10.7})^2 + 0{,}26(\mathrm{F10.7}) - 3{,}56 \quad (5)$$

The coefficientA_2 of equation (5) indicates the existence of a linear relationship ($A_2 = 0$) between the average annual variation in TEC and the solar flux F10.7. This assumes that the average annual TEC varies proportionally to the solar index F10.7, with a constant slope. However, equations (3) and (4) illustrate the existence of an amplification($A_2 > 0$) between the average annual TEC and the number of sunspots and the EUV flux, respectively. This allows us to model a quadratic relationship between the TEC and solar activity. Furthermore, no hysteresis effect was observed in this annual variation. This absence of hysteresis can be explained by the large time gap between two consecutive values in the time series (up to one year). Therefore, let us aim for an analysis with a time interval.

Monthly variation in TEC with solar indices SN, F10.7, and EUV:-

To study the seasonal variation of GPS-TEC for different years (2010–2016), each year was classified into four seasons, namely the spring equinox (March, April, May), the autumn equinox (September, October and November), the summer solstice (June, July and August) and the winter solstice (December of the previous year and January, February of the current year). To do this, graphs showing monthly TEC variations based on solar indices for each year will be considered. The curves in Figure 3 illustrate these variations above Koudougou. These curves are produced taking into account all recurring geomagnetic days. The left column shows the variation in TEC as a function of SN, the middle column describes the average monthly TEC as a function of F10.7, and the right column shows the variation in TEC as a function of EUV from 2010 to 2016. In all panels, the red histograms indicate the average monthly TEC, and the black curves show the variations in solar indices. The seasonal variation is studied for each year from 2010 to 2017 to determine in detail the effect of the phases of the solar cycle and the characteristics of the different levels of solar activity. Consequently, the panels are classified by year in ascending order from top to bottom.

The month-to-month variation in TEC shown in Figure **3** explains the variation in TEC in response to solar activity by superimposing the values of the solar parameters on the same graph. The solar parameters indicate that 2010 was a relatively quiet year, recording moderate values. The curves show that the solar parameters SN, F10.7 and EUV have similar monthly variations in 2012 and different variations in other years. In addition, identical variations in the SN and F10.7 parameters are observed in 2011 and 2016, with significant increases in SN in 2016. For F10.7 and EUV, identical variations are observed in 2013 and 2015.

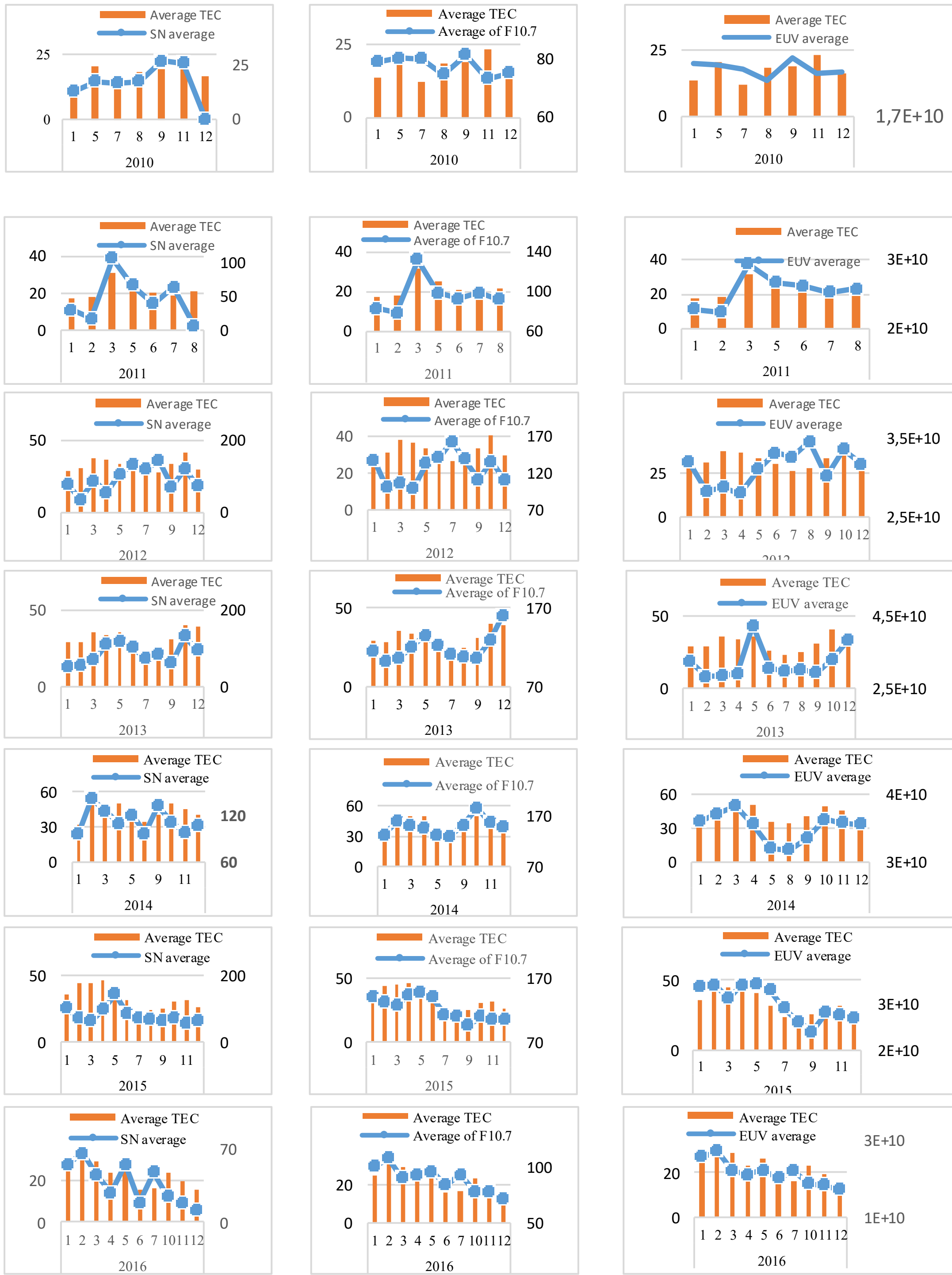


Figure 3: Monthly variations in TEC as a function of the solar parameters SN, F10.7 and EUV from 2010 to 2017

Such differences in the variation of solar indices have been reported by Chakrabarty et al.(2012) , who observed divergences in these parameters above the region of the equatorial anomaly ridge. With regard to the variation of these parameters with TEC, they reported a direct solar influence on TEC. In our results (Figure 3), we observe that while the TEC trend tends to follow that of the solar parameters, the rate of increase of these solar parameters is much higher than that of the monthly mean TEC. Such results were reported by D'ujanga et al.(2016) in the Kampala region of Uganda. In general, the mean TEC values are relatively high in March, April, May, October, and November and low in January, June, July, August, and December. However, solar parameters show random variations during the study period. In particular, the months of June, July, and August 2012 saw drastic increases in solar parameters, which did not correspond to the increase in TEC during these months. At the same time, the maximum F10.7 solar flux in 2013 was observed in December, with a corresponding increase in EUV, while TEC values showed higher values in March and October 2013. In fact, the equinoctial months of March, April, and May (vernal) and September, October, and November (autumnal) showed much higher TEC values than the solstice months during the observation period. This is consistent with most research conducted in equatorial regions (Gupta & Singh, 2000; Chauhan et al., 2011; Olwendo et al., 2013). Upon closer examination, however, it can be observed that the TEC for the solstice months of July and August 2012 is higher than for the same months in 2010 and 2011, when the SN, F10.7 solar flux, and EUV flux were relatively weaker. This shows the interdependence of seasonal and solar parameters, while noting that the TEC responds more to seasonal variations than to variations in solar parameters at the Koudougou station.

It was also observed that the autumn months (September, October, and November) had slightly higher TEC values than the spring equinoxes (March, April, and May) in 2010, 2012, and 2013, years that saw a sharp increase in solar activity (Figure 3). In contrast, the years 2015 and 2016 (descending phase of solar cycle 24) showed a reverse equinoctial asymmetry, with the TEC of the spring equinox being slightly higher than that of the autumn equinox. However, the year of the solar maximum (2014) shows almost equal TEC values at both equinoxes. Indeed, during the solar maximum, it is known that during the equinoxes, the Sun crosses the equator and, as a result, the period of maximum sunshine is the same at the spring and autumn equinoxes at equatorial stations. The equinoctial asymmetry observed during the ascending phase (2010, 2012, and 2013) differs from that observed by various researchers who reported the opposite when studying different parameters. For example, Sripathi et al.(2011) observed higher TEC values during the spring equinox than during the autumn equinox, and a higher occurrence of scintillation was observed during the spring equinox than during the autumn equinox by Rama Rao et al.(2006). In all these cases, equinoctial asymmetry was attributed to differences in meridional winds, leading to changes in neutral composition during the equinoxes. The difference observed in equinoctial asymmetry during the descending phase (2015-2016) could be due to the direct effects of solar activity, since during these years, spring recorded higher solar parameter values (SN, F10.7, and EUV) than autumn, leading to higher ambient ionisation during this period. The difference in equinoctial asymmetry during the different phases of cycle 24 could be due to the geomagnetic activity class chosen. Indeed, the occurrence of recurring days shows a higher number of days in 2015 and 2016 than in other years.

Compared to other seasons, the summer TEC is lowest for the years 2013, 2014, 2015, and 2016. However, for the years 2010, 2011, and 2012, the lowest TEC is observed during the winter months. Furthermore, the increase in TEC in winter compared to summer for the years mentioned at low latitudes above the Koudougou station shows a "winter anomaly". The most motivating aspect of TEC observations at low latitudes, which has been studied by a number of researchers, is the presence of a winter anomaly in the ridge region of the**;** while other researchers have also studied the disappearance of the "winter anomaly"(Balan et al., 1993; Bhuyan & Hazarika, 2013; Galav et al., 2010; Lin et al., 2007). The "winter anomaly" is defined by the fact that winter electron density remains higher than summer electron density Rishbeth and Garriot). The winter anomaly is caused by the increase in the (O/N2) ratio in the thermosphere between the southern hemisphere and the northern hemisphere, as reported by a number of authors. Thus, the appearance of the winter anomaly in the peak strength of the EIA has been attributed to a difference in energy input between the southern hemisphere and the northern hemisphere (Torr & Torr, 1973); to the change of season by a neutral gas composition (Mukherjee et al., 2010; Aggarwal et al., 2012). Research conducted by Kumar et al.(2014) added that this could be due to a combined effect of the geometry of the magnetic field and the zenith angle of the sun.

The differences observed in the monthly TEC values may also be due to geomagnetic storms, which can sometimes affect the ionosphere and alter it in complex and unpredictable ways, especially since the class chosen is a class of disturbed geomagnetic activity. A review of the (Dst) and (Kp) indices for the years 2010-2016 indicates that 2010 did not experience any severe geomagnetic storms, except for a few moderate storms (Dst> -100) over a few days, while 2011, 2012 and 2013 experienced a few intense geomagnetic storms (Dst< -100) in September and October

2011, March, October and November 2012, and March and June 2013. However, many more moderate and intense geomagnetic storms were observed in 2015 and 2016. It has been reported that magnetic storms have effects on the TEC in the equatorial region, with some showing an increase in TEC and others a decrease in TEC, accompanied by ionospheric scintillations (Akala, Rabiu, et al., 2013; D'ujanga et al., 2013). These effects on TEC can cause intense phase and amplitude scintillations in satellite signals, thereby negatively impacting satellite communication and navigation systems. To quantify the impact of solar activity on monthly TEC variations at the Koudougou station, linear and quadratic adjustments between monthly TEC variations and the SN, F10.7, and EUV solar indices will be established.

Correlation of the monthly average TEC with the SN, F10.7, and EUV solar indices:-

To statistically analyse the variation in the average monthly TEC based on the SN, F10.7, and EUV solar indices, a series of scatter plots was constructed for each year from 2010 to 2016, as shown in Figure 4, in order to determine which solar index correlates well with the TEC in Koudougou. The left-hand columns illustrate the relationship between TEC and the SN index, while the middle column shows the relationship between TEC and the F10.7 index, and, finally, the right-hand column shows the relationship between TEC and the EUV index. To determine the best possible relationship between monthly TEC values and the SN, F10.7, and EUV solar indices, linear (represented by black dotted lines) and quadratic (represented by red dotted lines) adjustments were applied to the data. In order to analyse the correlation, Pearson's correlation coefficients between the monthly average TEC and the SN, F10.7, and EUV solar indices for each year were calculated. These coefficients are presented and ranked in Table 3.

The scatter plots from 2010 to 2016 (Figure 4) show that there is a significant difference in the relationship between the average monthly TEC and the solar indices for the different years considered. The correlation between the two is remarkable (high) during years of fairly moderate solar activity (2011 and 2016). Negative correlation coefficients between TEC and the F10.7 and EUV solar indices are observed in 2010 and 2012, and between TEC and SN in 2012. Significant correlation coefficients ($R > 0{,}5$) between TEC and SN are observed in 2011, 2013, and 2016.$R > 0{,}5$ is observed in the relationship with F10.7 in 2011, 2013, 2014, 2015, and 2016, and with EUV in 2011, 2014, 2015, and 2016. The positive and negative correlation coefficients with the various solar indices have also been reported by other researchers (Kumar & Singh, 2009; N. C. Patel et al., 2017). However, Patel et al. (2017) found positive correlation coefficients between TEC and F10.7 and between TEC and EUV in 2010 and 2012 and negative correlation coefficients between TEC and all three solar indices in 2013, which is contrary to our results. Furthermore, work by Kumar and Singh(2009) during the period 2007-2009 showed weaker correlation coefficients between TEC and SN. On the other hand, research conducted by Galav et al.(2010) for the period 2005 to 2009, and Opio et al.(2015) in 2011 showed higher coefficients ($R>0.70$) between TEC and F10.7. At the Koudougou station, with a monthly time resolution, the correlation coefficients are relatively higher with the F10.7 index than with the SN and EUV indices. Also, a weaker correlation is observed between TEC and SN, with the exception of 2011 and 2016. This indicates that the monthly variation in TEC is weakly related to sunspot activity. The weak correlations observed in some years suggest that the production and ionisation of the ionosphere and its dynamics are not entirely controlled by the level of solar radiation received by the ionosphere.

The scatter plots in Figure 4 show the ability of the quadratic model to represent the non-linear variation of the TEC as a function of SN, EUV flux and F10.7. In general, the model output showed varying degrees of agreement with the values measured during the different months. From the general expression of the quadratic model given by equation (2), we can deduce the degree of linear and non-linear variation of the TEC as a function of solar parameters. Therefore, Figure 4 indicates the existence of linearity ($A_2 = 0$) between TEC and SN in 2015 and 2016, TEC and F10.7 in 2011 and 2013, and between TEC and EUV in 2014, 2015, and 2016. The existence of amplification ($A_2>0$) between TEC and SN is observed in 2010, 2011, and 2013, and saturation ($A_2<0$) in 2012 and 2014. Saturation and amplification trends between TEC and F10.7 are observed in 2012, 2014, and 2015, and 2010, 2016, respectively. With the EUV index, saturation trends are observed in 2017 and amplification trends in 2010, 2011, and 2012. The linear fit between TEC and solar indices shows an increasing trend in all years except 2012 and 2010 with the F10.7 index and the EUV index. The analysis of quality statistics illustrated by the graphical equations presented in each panel of Figure 4 shows that the non-linearity coefficient is relatively low (close to 10^{-3}) for all years and for all solar indices considered. This shows that quadratic and linear adjustments give almost similar results for all months and years considered. This result shows that, for application purposes, linear or quadratic regressions may be a good choice and that higher-order regressions do not significantly improve the fit.

Table 3: Correlation coefficients between TEC and solar parameters (SN, F10.7, and EUV)

Year / Solar Indices	2010	2011	2012	2013	2014	2015	2016	2017
SN	0.49	0.77	-0.16	0.52	0.44	0.40	0.72	0.59
F10.7	-0.38	0.91	-0.43	0.62	0.74	0.74	0.66	0.47
EUV	-0.14	0.90	-0.33	0.50	0.67	0.79	0.66	0.49

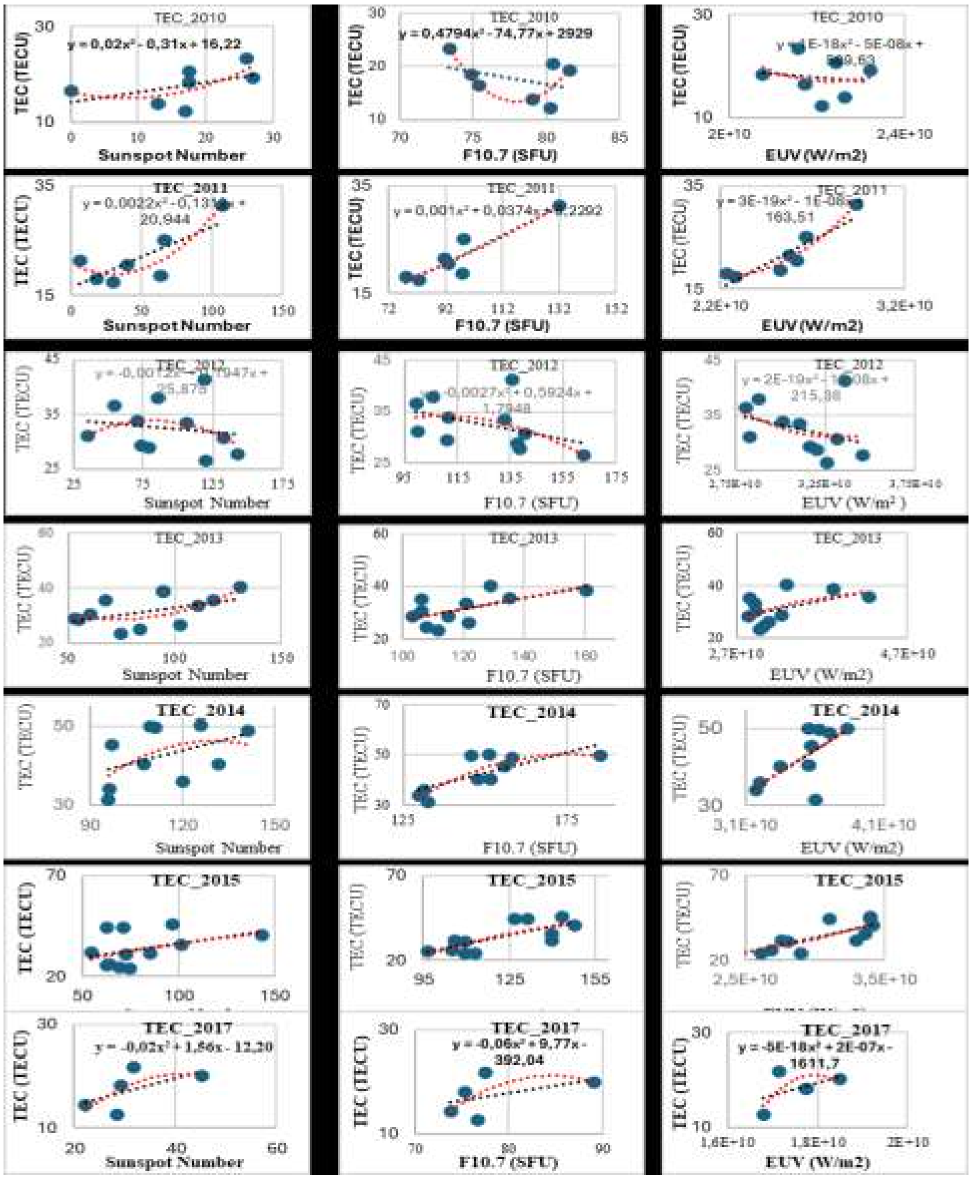


Figure 4: Scatter plots of monthly mean TEC values and solar parameters (SN, F10.7, and EUV) from 2010 to 2017 during recurrent geomagnetic activity

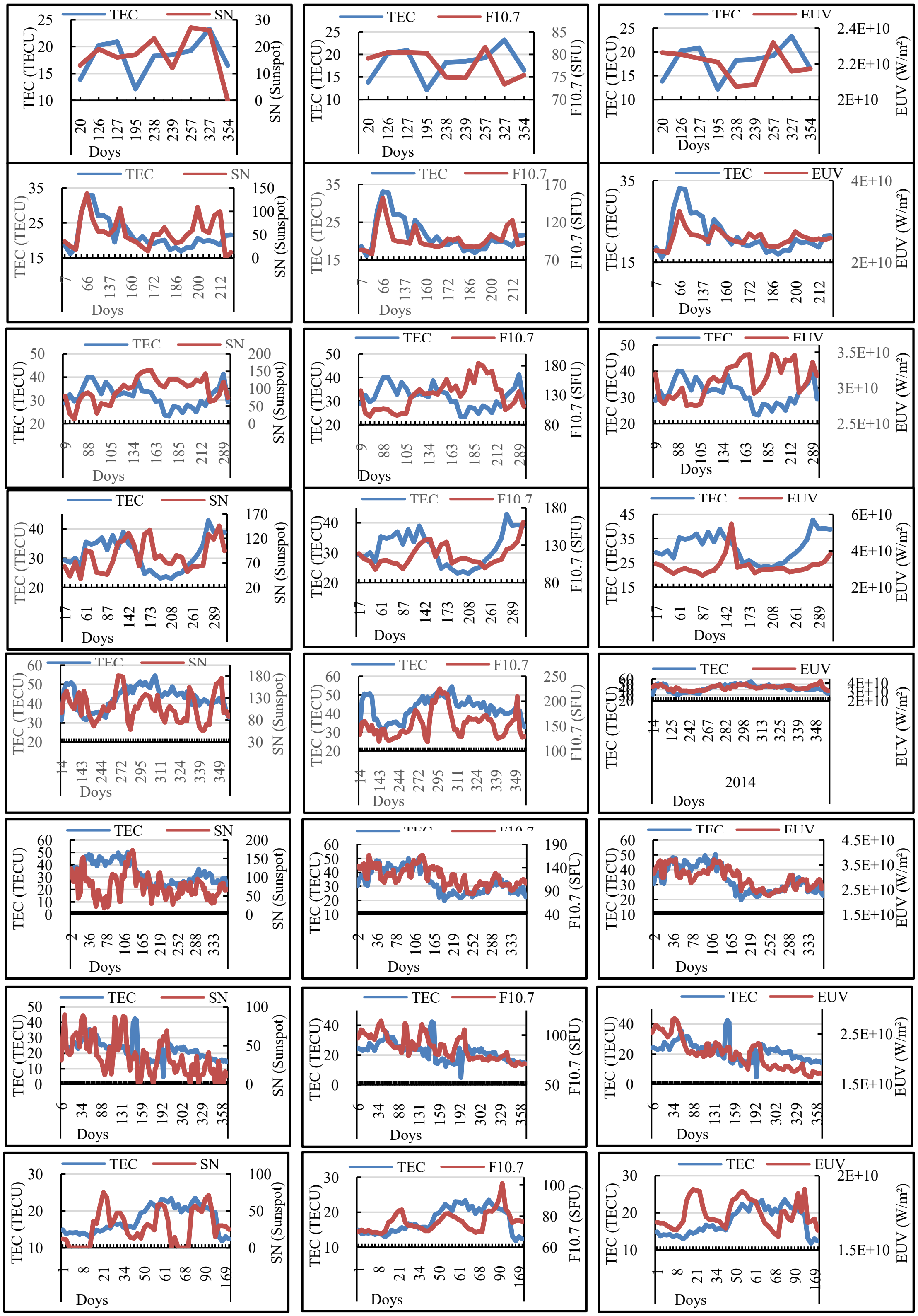
Variation in average daily TEC with solar indices SN, F10.7, and EUV:-

The daily variations in TEC as a function of sunspot number, solar flux F10.7, and EUV flux during the period 2010-2017 are shown in the top, middle, and bottom panels of Figure 5, respectively. The blue curves indicate the daily variations in TEC, and the red curves indicate those in solar indices. Each graph representing the daily variation for a given year is constructed considering all recurring geomagnetic days of the year. The study of daily variation is intended to verify the behaviour of TEC as a function of solar activity on a reduced time scale for the period 2010 to 2017 in order to identify the effects of short-term solar activity on TEC.

As shown in the panels in Figure 5, the curves of the daily variations in solar indices did not show good agreement with the daily TEC values for all the years considered. Contrary results were reported by Kassa et al.(2017) during the final phase of solar cycle 23 and the ascending phase of solar cycle 24, who found good agreement between the TEC curves and those of the SN and F10.7 solar indices on a daily scale. Nevertheless, it was found that the TEC curve and the solar indices curve appeared to be much more in phase in 2011, 2015, and 2016 than in other years. In contrast, in 2012, a high TEC value corresponded to a low SN, F10.7, and EUV value, except on the 182nd day of the year, when the trough of the TEC curve and that of the solar indices overlap. In 2010, 2013, and 2014, the two curves evolve in phase, but with the peaks of the solar indices slightly offset from those of the TEC. The same phenomenon is observed during the descending phase of cycle 24, but with a less pronounced effect. In all the graphs presented (2010-2016), the TEC curve is more in phase with the F10.7 solar flux and the EUV flux than with the number of sunspots, and much more in line with the EUV flux. According to Prasad et al.(2012), the F10.7 index comes mainly from the high-temperature transition region of the solar atmosphere, but the solar EUV flux comes from the irregular layer above the photosphere ("Chromosphere") and, to a lesser extent, from the transition region and the corona. During periods of high solar activity, the F10.7 flux undergoes greater fluctuations, and the EUV emissions from the most excited atoms in the solar atmosphere correlate with TEC.

A very important notable feature is the daily uncertainty in TEC variation, which is of great concern for forecasting as well as for navigation systems. This uncertainty in the daily and seasonal variation of TEC (Kane, 1980; Rama Rao et al., 2006; Rao et al., 2013) can be attributed to: 1) changes in the activity of the Sun itself and related changes in the intensity of incoming radiation; 2) the zenith angle (χ) at which they reach the Earth's upper atmosphere, in addition to changes in the Earth's magnetic field; 3) the strength of the equatorial electrojet (EEJ), added to the effects due to EIA dynamics; and 4) neutral meridional winds. The diurnal variation in TEC may also be due to the movement of ionised particles through geomagnetic fields by tidal winds (Tariku, 2015). Recently, Jonah et al.(2015) studied the variation in TEC during phases of high and low solar activity over the South American sector. They indicated that a diurnal uncertainty in the variation in TEC contains a component induced by planetary waves enhanced by tides as they propagate upwards. Strong vertical coupling through increasingly propagating waves can also give rise to a daily oscillation in TEC. Their study also shows that, apart from the effect of solar radiation, variations in the meridional or zonal wind also play an important role in TEC variations.

Figure 5: Daily variation **in TEC as a function of solar parameters SN, F10.7, and EUV from 2010 to 2017**



Correlation of average daily TEC with solar indices SN, F10.7, and EUV:-

The correlation coefficients between solar indices (SN, F10.7, and EUV) and the average daily TEC in Koudougou for all years during the period 2010–2016 were determined in order to find the dependence of TEC on solar activity at a fairly short time interval. These coefficients are presented and classified in Table 4. Only geomagnetically disturbed days with (Kp>27) and with a periodicity of 27 days were selected to highlight the effect of this class of geomagnetic activity on the TEC from one day to the next. Scatter plots between SN and TEC, F10.7 and TEC, and EUV and TEC were also constructed. Since the scatter plots were constructed for series with a time resolution of one day, the daily average series of solar activity parameters were used. Figure 6 shows these scatter plots for each year from 2010 to 2016. The left column illustrates the relationship between TEC and the SN index, while the middle column shows the relationship between TEC and the F10.7 index, and finally, the right column shows the relationship between TEC and the EUV index. Linear (represented by black dotted lines) and quadratic (represented by red dotted lines) adjustments were also applied to observe trends in the relationship between these two parameters.

Table 4 shows that the correlation coefficients between TEC and solar indices are weaker daily than on a monthly and annual basis between 2010 and 2016 at the Koudougou station. This means that the impact of solar activity on TEC variation is reduced when the time interval considered is also reduced. This implies that there may be other parameters besides solar proxies that can affect TEC variation daily. A detailed analysis of Table 4 shows a negative correlation coefficient between the average daily TEC and the three solar indices in 2012 and between TEC and F10.7 and EUV in 2010. A significant positive correlation between average daily TEC and SN is observed only in 2011 (R= 0.52). However, between TEC and F10.7, it is significant and positive in 2011 (R= 0.67), 2014 (R= 0.59), and 2015 (R=0.68), and negative in 2012 (R= - 0.55). Only a significant positive correlation is observed between TEC and EUV in 2011 (R= 0.79), 2014 (R= 0.59), 2015 (R= 0.76), and 2016 (R= 0.51). The panels in Figure 6 show that the trend between TEC and solar indices is increasing for all years except 2012 and 2010 with the F10.7 index and the EUV index.

he correlation analysis results presented show relatively high and relatively low correlations between the TEC series and solar parameters. Therefore, the linear regression method (high correlation) and the quadratic regression method (low correlation) can be used to reconstruct TEC variations using solar parameters as inputs. This will prove the physical relationships between ionospheric and solar parameters. However, to obtain the best possible prediction quality, we can use parameters as inputs that could be related to each other (both by physical and statistical processes). Similar, but not exactly the same, approaches were adopted by Chen et al.(2015)and Li et al.(2019) to model TEC variations over large areas as a function of solar activity (F10.7 index) and geomagnetic activity (Ap index). Similarly, in the article published by Morozova et al.(2020), this approach was adopted to achieve the best possible prediction quality between TEC series and space weather parameters in the Iberian Peninsula.

Table 4: Correlation coefficients between TEC and solar parameters (SN, F10.7, and EUV) at a temporal resolution of one day.

Year / Solar indices	2010	2011	2012	2013	2014	2015	2016	2017
SN	0.44	0.52	-0.26	0.31	0.17	0.31	0.44	0.28
F10.7	-0.26	0.67	-0.55	0.39	0.59	0.68	0.44	0.42
EUV	-0.10	0.79	-0.29	0.23	0.59	0.76	0.51	0.29

In general, the model output showed varying degrees of agreement with the values measured during the different months. In almost all cases, the daily variation in TEC for each year showed positive correlations with solar indices. Linear correlations between solar indices and TEC were also observed. Our observations are consistent with the report by Liu and Chen(2009), who showed a very close correlation between maximum TEC and the number of sunspots in March, May, August, September, and December, while a weak correlation was observed in February and July of the 2003 high solar activity period in Hong Kong. From a detailed analysis of the graphs in Figure 6, we can deduce the degree of linear and non-linear variation in TEC as a function of solar parameters. Figure 6, therefore, indicates the existence of linearity (A_2 = 0) between TEC and SN in 2012, TEC and F10.7 in 2011 and 2013, and TEC and EUV in 2011 and 2012. The existence of amplification (A_2>0) between TEC and SN is observed in almost all years except 2012, 2014, and 2016, where saturation (A_2<0) is observed. The saturation trends between TEC and

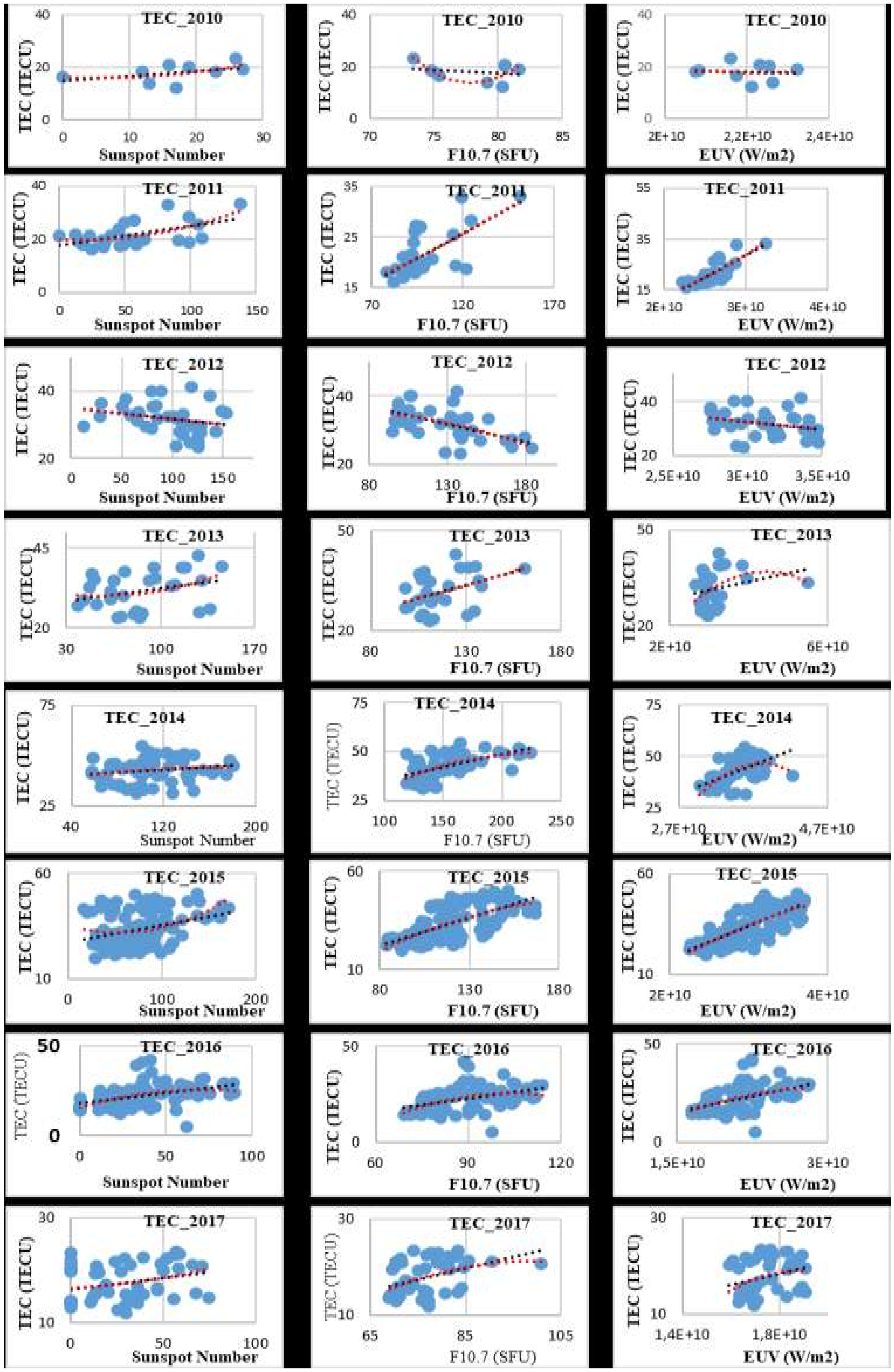


Figure 6: Scatter plots of average TEC values and solar parameters (SN, F10.7 and EUV) from 2010 to 2017 during recurrent geomagnetic activity with a time resolution of one day.

F10.7 are observed in 2012, 2014, 2015, 2016 and 2017 and amplification in 2010. With the EUV index, amplification trends are observed in 2010 and saturation in 2013 and 2017. The linear fit between TEC and solar indices shows an increasing trend in all years except 2012 and 2010 with the F10.7 index and the EUV index. Relatively small deviations were observed in the modelling of TEC as a function of EUV compared to the variation due to F10.7 flux and SN. This may indicate that EUV may be more appropriate for modelling solar variation in TEC. Analysis of the quality statistics shows that the non-linearity coefficient is relatively small (10^{-3}) for all years and for all solar indices considered. This shows that quadratic and linear adjustments give almost similar results for all years considered. This result shows that, for application purposes, linear or quadratic regressions may be a good choice and that higher-order regressions do not significantly improve the fit.

Consequently, the effects of solar activity on electron density in the ionosphere show an interesting altitude dependence (Su et al., 1999) and the behaviour of TEC and NmF2 may differ in some respects. Linear and saturation effects are observed in the dependence of solar activity on diurnal NmF2 or foF2 (Lei et al., 2005; L. Liu et al., 2006; Zhang & Holt, 2007) . The amplification effect can sometimes be detected in nocturnal NmF2 (L. Liu et al., 2004) . Linearity, saturation and amplification patterns can all be found at low latitudes at different local times (L. Liu & Chen, 2009) ; this explains why the dependence of solar activity on TEC at this altitude varies according to local time, season and location. Complex patterns are also observed, as shown in the results in Figure 6. The most fascinating feature is the amplification of TEC. Previous studies (Balan et al., 1994; Afraimovich et al., 2008; Chakraborty & Hajra, 2008) have mainly focused on linearity and saturation. This amplification effect in the TEC is a new feature.

Ion production in the ionosphere is proportional to EUV flux, which can be related to ambient electron density. However, ionisation by direct solar flux is not the only cause of changes in electron density. Changes can also occur due to alterations in neutral density, temperature, and composition, ionospheric chemistry, neutral winds (L. Liu et al., 2004) , and electric fields, all of which vary with solar EUV and whose relationship to electron density may not be linear (Kane, 2003) . The complex patterns in the effects of solar activity on the TEC can be explained qualitatively in the discussion by Chen et al.(2009) and Liu et al.(2007) , if we realise that the neutral compositions in the upper atmosphere, ionospheric scale heights, and dynamic processes also vary with solar activity (Kutiev et al., 2006; L. Liu et al., 2004) . We can understand the TEC amplification effect qualitatively as follows. As a first approximation, the electron density profile obeys a Chapman-type function; the TEC is therefore related to the scale height H and the maximum electron density NmF2.

Conclusion:-

This study showed that annual variations in Total Electron Content (TEC) at the Koudougou station are closely linked to solar parameters such as sunspot number (SN), solar flux F10.7 and extreme ultraviolet flux (EUV). The results revealed that TEC follows an extraordinary synchronisation with solar activity during periods of recurrent geomagnetic activity. Variations in TEC showed a strong correlation with solar indices, indicating a positive linear relationship between these two series. The graphs showed that TEC primarily tracks variations in EUV flux rather than those in solar flux F10.7 and sunspot number. This is consistent with previous research that established extreme ultraviolet (EUV) solar radiation as the primary source of Earth's ionosphere formation. Analysis of monthly and daily data showed that the impact of solar activity on TEC variation decreases when the time interval considered is shorter. This suggests that other parameters, in addition to solar indices, could influence daily TEC variation. Using linear and quadratic regression models, it is possible to reconstruct TEC variations using solar parameters as inputs. However, to obtain better prediction quality, it may be beneficial to include other parameters that are interrelated, both physically and statistically.

Furthermore, it has been found that during the solstice months of the year, TEC shows a downward trend in line with the decrease in solar parameters. It has also been demonstrated that the solstice is a relatively stable season with insignificant average day-to-day TEC variation, indicating a reduced influence of external factors. Also, the linear trend of TEC as a function of solar activity indices, accompanied by some non-linear solar variations (saturation and amplification) of TEC, has been observed. This mixed trend of solar variation in TEC implies the need for further study of the effect of solar parameters on TEC. However, based on a long-term dataset, we have concluded that solar variations in TEC are dominated by a linear model. From a general perspective, estimating TEC using the quadratic model is valid, but on certain specific days, external factors highlight the occurrence of significant errors. Therefore, further research may be necessary to delve deeper into this complex relationship and explore other factors that may influence TEC variability.

Data availability:-

The total electron content (TEC) data used to support the results of this study are included in the supplementary file(s). The F10.7 solar flux index and the Kp index are available on the OMNIWeb website (https://omniweb.gsfc.nasa.gov/form/dx1.html). The geomagnetic index (Dst) data used are available on the ISGI website (http://isgi.unistra.fr/data_download.php). The sunspot number data used in this work are available on the SILSO website (https://www.sidc.be/silso/datafiles).

Conflicts of interest:-

The authors have declared no conflicts of interest.

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