Scientific Research Publishing

International Journal of Astronomy and Astrophysics, 2023, 13, 259-280
https://www.scirp.org/journal/ijaa
ISSN Online: 2161-4725
ISSN Print: 2161-4717

Total Electron Content during Recurrent and Quiet Geomagnetic Periods at the Koudougou Station in Burkina Faso

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How to cite this paper: Sawadogo, S., Gnabahou, D.A., Pahima, T. and Ouattara, F. (2023) Total Electron Content during Recurrent and Quiet Geomagnetic Periods at the Koudougou Station in Burkina Faso. *International Journal of Astronomy and Astrophysics*, **13**, 259-280.
https://doi.org/10.4236/ijaa.2023.133015

Received: August 12, 2023
Accepted: September 23, 2023
Published: September 26, 2023

Abstract

In this work, the comparative study of total electron content (TEC) between recurrent and quiet geomagnetic periods of solar cycle 24 at Koudougou station with geographical coordinates 12˚15'N; - 2˚20'E was addressed. This study aims to analyze how geomagnetic variations influence the behavior of TEC in this specific region. The geomagnetic indices Kp and Dst were used to select quiet and recurrent days. Statistical analysis was used to interpret the graphs. The results show that the mean diurnal TEC has a minimum before dawn (around 0500 UT) and reaches a maximum value around 1400 UT, progressively decreasing after sunset. In comparison, the average diurnal TEC on recurrent days is slightly higher than on quiet days, with an average difference of 7 TECU. This difference increases with the level of geomagnetic disturbance, reaching 21 TECU during a moderate storm. The study also reveals significant monthly variations, with March and October showing the highest TEC values for quiet and recurrent days, respectively. Equinox months show the highest mean values, while solstice months show the lowest. Signatures of semi-annual, winter and equatorial ionization anomalies were observed. When analyzing annual variations, it was found that the TEC variation depends significantly on F10.7 solar flux, explaining up to 98% during recurrent geomagnetic activity and 92% during quiet geomagnetic activity.

Keywords

Total Electronic Content, Geomagnetic Activity, Quiet-Day Activity, Recurrent-Day Activity, Solar Flu

1. Introduction

The ionosphere, a region extending from about 60 to 1000 km altitude and divided into several layers, is characterized by the presence of ions and electrons. It is affected by various geophysical factors [1], including fluctuations in geomagnetic activity. The strongest geomagnetic disturbances, such as magnetic storms, generally lead to considerable deviations of its parameters from its normal state. Ionospheric disturbances linked to strong geomagnetic activity are global and the mechanisms involved are highly complex. These disturbances affect temperature and humidity at the time of storm, leading to changes in thermospheric composition, neutral winds and ionospheric electric currents. Ionospheric storms have been the subject of numerous studies, including case studies and statistical analyses, due to their major impact on space environments. Some recent studies have presented the progress made in the study of ionospheric storms, for example, [2] [3] [4].

TEC (Total Electron Content) is an essential parameter for studying ionospheric dynamics, analyzing its variation as a function of local time, seasons and solar activity [5]. In recent decades, the spatio-temporal variability of ionospheric TEC has been extensively studied by numerous authors [6]-[14]. The equatorial and low-latitude F regions of the ionosphere have an electron density distribution characterized by a double-peak configuration. There is a trough centered on the magnetic equator and two peaks on either side of it, generally around ±20˚ latitude. This phenomenon is known as the "Appleton Anomaly" or the "Equatorial Ionization Anomaly" (EIA). It results in the formation of a fountain-like structure. As a result, there is an increase in the TEC (peak) on either side of the magnetic equator and a decrease in the TEC (trough) on the equator itself [15] [16] [17]. TEC is a measure used to estimate the propagation delays experienced by radio signals as they pass through the ionic layer. Thus, the TEC plays a crucial role in assessing the propagation delays of radio signals through the ionosphere. In recent years, GPS has become a valuable tool for studying the characteristics of the ionosphere [8] [18] [19] [20]. The growing demand for GPS-based navigation devices on satellites, aircrafts, and other means of transportation has increased the importance of studying TEC [21]. Therefore, a thorough understanding of the variability of the TEC is essential at different geographical locations and under different geomagnetic conditions (quiet and disturbed). This study is part of this dynamic and is a contribution to refine TEC estimates for applications in telecommunications and transport systems, in order to improve positioning and synchronization accuracy.

Geomagnetic storms, the most crucial phenomenon in space weather, can cause major disturbances in the ionosphere compared with periods of magnetically quiet days, resulting in significant variations in the TEC. These fluctuations can have adverse consequences for communication and navigation systems, both in space and on Earth [22]. When the electron density increases due to thunderstorm activity, this is called a positive ionospheric storm effect, while a decrease in the electron density is called a negative ionospheric storm effect [23]. Several researchers have examined variations in the ionospheric TEC under disturbed geomagnetic conditions. They have used different methodologies to study geomagnetic effects, considering one or more geomagnetic storms [24] [25] [26] [27] [28]. Variation of TEC in some West African areas during different geomagnetic disturbances has been studied by [12] [28] [29] [30]. To better understand the effect of geomagnetic disturbances on ionospheric parameters, Legrand and Simon [31] subdivided geomagnetic activity into four classes: 1) quiet-day activity, 2) shock-day activity, 3) fluctuating-day activity, and 4) recurrent-day activity. This classification was improved by Zerbo *et al.* [32]. This work focuses on recurrent day activity and quiet day activity.

Although numerous studies have been carried out on the TEC, this comparative research on the TEC at the Koudougou station (Burkina Faso) during recurrent and quiet geomagnetic periods, during Solar Cycle 24, presents characteristics specific to this cycle. In addition, the little-explored site of Koudougou offers an exceptional opportunity to analyze the specific geomagnetic and ionospheric features of this region. Comparing periods of geomagnetic calm with periods of disturbance will deepen our understanding of TEC variations in response to geomagnetic activity. By taking into account local factors specific to Koudougou, such as geography and geology, the results will be unique to this region.

This study aims to assess the impact of recurrent geomagnetic days on TEC fluctuations during solar cycle 24. To do so, in situ measurements of TEC were used at the Koudougou station, located in the equatorial region of Africa. To better understand the impact of quiet and recurrent geomagnetic conditions on ionospheric variability, we analyzed the morphological characteristics of the TEC. The data and methodology used are detailed in Section 2, while the results are discussed in depth in Section 3. Section 4 concludes with a summary of the results obtained.

2. Data and Methodology

2.1. Data Used

Data obtained from the Koudougou GPS station (Geo lat 12˚15'N; Geo long: −2˚20'E, dip: +8.24) were used in this work. 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. The project comprises three main networks: 1) IGS (International Geodesy System); 2) AMMA (Analyse Multidisciplinaire de la Mousson Africaine) and 3) SCINDA (Scintillation Network Decision Aid). The Koudougou Station is one of the SCINDA GPS network stations located at equatorial latitude and is dedicated to the study of ionospheric scintillations. [33]. Not listed in the global GPS station network, the Koudougou GPS station has been operating since December 2008, providing in situ data in binary format. These GPS extinction files are then transformed into RINEX files at 30 s intervals using Novatel convert software. These RINEX files are then processed to obtain the vertical TEC (VTEC) used for this study.

To segment the solar cycle into phases, sunspot number (SN) data, also known as Wolf number, were used. These data can be obtained from the Sunspot Index and Long-term Solar Observations (SILSO) website at https://www.sidc.be/silso/versionarchive. The F10.7 solar flux index was also used to estimate the TEC dependence on solar activity under quiet and disturbed geomagnetic conditions. The F10.7 index data can be downloaded from the OMNIWEB database (https://omniweb.gsfc.nasa.gov/form/dx1.html).

Geomagnetic indices were used in this work to select days of quiet and recurrent geomagnetic activity. Indices used are the disturbed storm weather index (Dst), which indicates the hourly variation in the horizontal component of the Earth's magnetic field [34] and the interplanetary index Kp which indicates the level of geomagnetic activity [35]. The Kp index data are available on the website (https://omniweb.gsfc.nasa.gov/form/dx1.html) and the Dst index data are available on the website (http://isgi.unistra.fr/data_download.php).

2.2. Methods Used

2.2.1. Delineating the Solar Cycle and Determining Cycle Phases

The determination of the different phases of solar cycle, also known as the solar activity cycle, was carried out using the sunspot method. This method is based on the observation and counting of sunspots, which are dark regions on the Sun's surface associated with intense magnetic activity. The complete solar cycle lasts around 11 years and is characterized by a regular increase and decrease in the number of sunspots. Daily sunspot numbers are available at https://www.sidc.be/silso/versionarchive. By representing these data over a period of several years, as shown in **Figure 1**, it is possible to determine the different cycles of solar activity during this period. The period between two successive sunspot minima is considered to be the duration of the solar cycle. Thus, solar cycle 24 runs from 2008 to 2018. The shape of the curve can be used to determine the different phases of the solar cycle.

2.2.2. Identification of Geomagnetic Quiet Days and Recurrent Days

Geomagnetic variation can be divided into two main groups: quiet variation, which has a regular appearance and is mainly caused by solar electromagnetic radiation, and geomagnetic disturbances, which have an irregular appearance

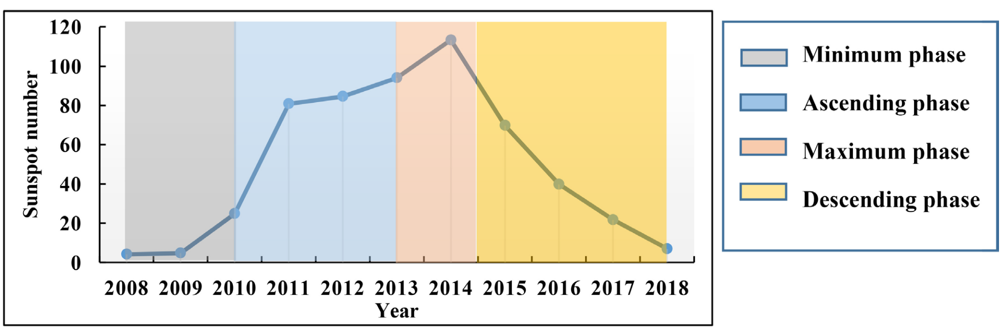

Figure 1. Sunspot evolution curve and phase breakdown of solar cycle 24.

and are mainly due to fast solar winds [36]. To distinguish between quiet and disturbed activity, several methods have been proposed. According to Sckopke [37] and Tsurutani *et al.* [38], a day is said to be geomagnetically quiet when the index Dst > −30 nT and disturbed otherwise. In this work, geomagnetic activity was classified into intensity levels according to two criteria: (1) Dst criterion of Gonzalez *et al.* [39] whose classification scheme is shown in **Table 1**, and Kp criterion whose classification is given in **Table 2**. Dst criterion classifies geomagnetic storms by disturbance level, and Kp criterion classifies geomagnetic activity in general.

To identify truly quiet geomagnetic days, only 48-hour quiet days were considered. These days are characterized by Kp < 27 et Dst > −30 nT on the daily variation. Called CK-Days by ISGI, they can be downloaded at https://isgi.unistra.fr/data_download.php.

Legrand and Simon [31] classified geomagnetic activity into four classes: 1) quiet activity characterized by Aa < 20 nT 2) shock activity caused by SSCs, characterized by Aa ≥ 40 nT 3) recurrent activity characterized by Aa ≥ 40 nT without SSC and recurrent over two or more Bartels rotations and 4) fluctuating activity, which is activity not taken into account by the other three classes. This classification was improved by Ouattara and Amory Mazaudier [40], who introduced a color-coding system to graphically represent the different classes on a pixel diagram. More recently, Zerbo *et al.* [32] have also made improvements to this classification. 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 regions of co-rotational interactions (CIRs) [41]. When these variations are caused by CIRs, the activity is called co-rotational geomagnetic activity. This work considers as recurrent days geomagnetically disturbed days that meet the following criteria: Kp ≥ 27 or Dst ≤ −30 nT with a periodicity of 27 days. To eliminate the influence of other geomagnetic events, all recurrent days preceded by an SSC (Sudden Storm Commencement) or SI (Sudden Impulse) occurring within the preceding three days were excluded.

Table 1. Classification of geomagnetic activity into intensity levels according to Dst criterion.

Geomagnetic activity level	Intense	Moderate	Low	Quiet
Dst	Dst ≤ −100 nT	−100 < Dst ≤ −50 nT	−50 < Dst ≤ −30 nT	Dst > −30 nT

Table 2. Classification of geomagnetic activity by Kp criterion.

Geomagnetic activity level	Quiet	Agitated	Active	Minor storm	Moderate storm	Intense storm	Severe storm	Extreme storm
Kp	Kp < 27	27 ≤ Kp < 37	37 ≤ Kp < 47	47 ≤ Kp < 57	57 ≤ Kp < 67	67 ≤ Kp < 77	77 ≤ Kp < 87	87 ≤ Kp ≤ 90

3. Results and Discussion

A study was carried out at the Koudougou station to examine annual and monthly diurnal variations in TEC and its correlation with the F10.7 solar flux on quiet and recurrent geomagnetic days during solar cycle 24. To better understand the impact of geomagnetic activity on TEC, a comparison was made between TEC during quiet days and those during recurrent days, classified according to the geomagnetic disturbance level (agitated, active, minor storm and moderate recurrent activity). The study covers the period from 2008 to 2018, however, due to technical problems, only data from January 2009 to June 2017 were available, but also contained missing days.

3.1. TEC Dependence on Solar Flux under Quiet and Recurrent Geomagnetic Conditions

To verify the solar flux dependence of TEC during quiet and recurrent geomagnetic periods, the statistical correlation between TEC and the F10.7 solar flux for the Koudougou station from 2010 to 2017 was established. Figure 2, structured in panels a, b, c, d, e and f, illustrates the statistical correlation between TEC and solar flux F 10.7 cm during quiet days, recurrent days as a whole, agitated recurrent days, active recurrent days, minor recurrent storms and moderate recurrent

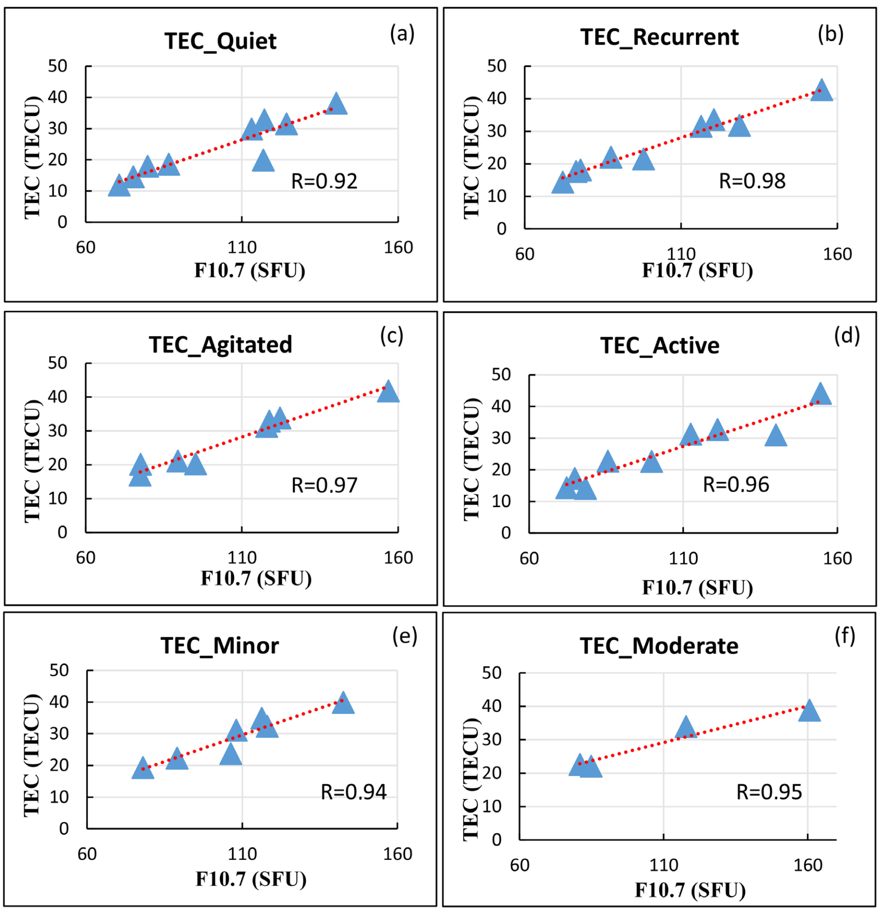

Figure 2. Correlation between TEC and F10.7 solar flux on an annual scale.

storms, respectively. In each graph, the blue clouds of points indicate the correlation and the red straight line gives the trend line.

Generally speaking, these graphs show that the correlation coefficient values are higher on recurrent days (ranging from 0.94 to 0.98) than on quiet days (0.92) at the Koudougou station. However, taking into account the seasonal variation in TEC at three stations in India, Lissa *et al.* [42] found that the correlation coefficient values of TEC with F10.7 are higher in quiet periods than in disturbed periods. This observed difference could be explained by the position of the stations or also by the effect of the contribution of the seasons to the variation of the TEC. The highest correlation coefficient value (R = 0.98) is observed when the recurrent days are considered as a whole (panel b). This R value, which is very close to 1, means that there is a very strong linear relationship between TEC and the solar index F10.7 during recurrent geomagnetic disturbances. In both quiet and disturbed periods, the correlation between TEC and F10.7 remains very high (>0.90) at the Koudougou station during solar cycle 24. These results are in agreement with those reported by Prasad *et al.* [43], who reported that the correlation coefficients of TEC with F10.7 are higher near the equatorial stations. Results also confirmed by Oluwadare *et al.* [44], Liu *et al.* [45], Feng *et al.* [46].

Interestingly, under recurrent geomagnetic conditions, the correlation is highest (R = 0.98) during global recurrent activity (that is, without distinction of disturbance level). Similarly, the comparison of the correlation between different levels of recurrent activity disturbance in the present study reveals a reduced correlation of TEC with F10.7 during conditions of high geomagnetic disturbance (minor geomagnetic storm and moderate geomagnetic storm). Although solar flux F10.7 indicates the intensity of solar ionizing radiation, during active space weather conditions, the effects due to geomagnetism are less significant than those due to exposure to solar radiation. Furthermore, effects resulting from electric fields and winds induced by geomagnetic storms have an impact on the low-latitude ionosphere. This would have resulted in a weaker correlation of TEC with F10.7 during more disturbed periods.

During less disturbed (agitated and active) periods, in addition, non-stormy recurrent geomagnetic activity is mainly caused by co-rotational interaction regions (CIRs), and stormy recurrent activity is caused by fast solar winds from coronal holes. In fact, in terms of geomagnetic activity, the most important feature of CIRs is that they are characterized by intense magnetic fields [47]. This could be the cause of the strong correlation with F10.7 during recurrent co-rotation activity.

3.2. TEC Variations under Quiet and Recurrent Geomagnetic Conditions

3.2.1. Diurnal Variations in TEC by Solar Cycle Phase

Figure 3 shows the mean diurnal variation of TEC at the Koudougou station for quiet and recurrent days during each phase of solar cycle 24. Panels a, b and c

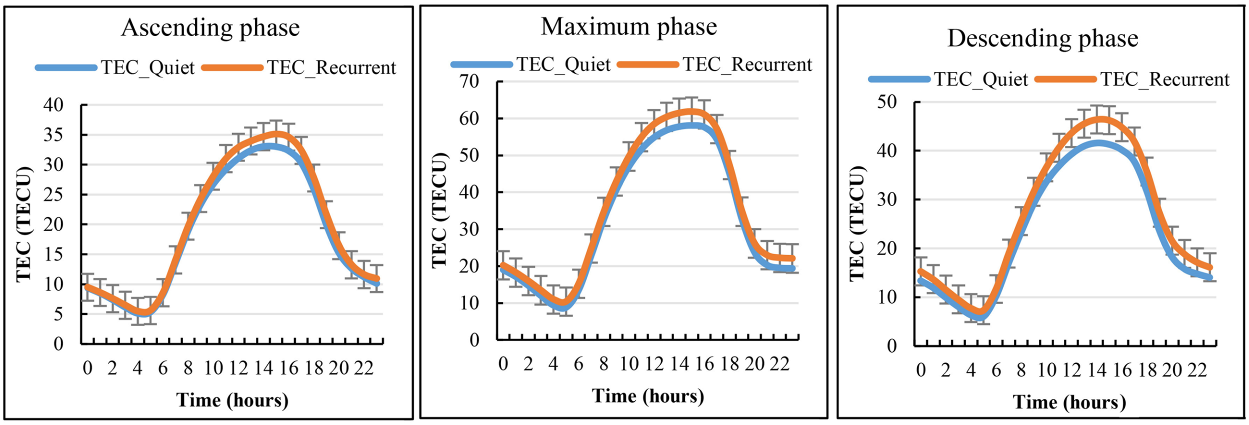

Figure 3. Curves showing the average diurnal variation in TEC for quiet and disturbed days per phase over solar cycle 24.

illustrate this variation during the ascending, maximum and descending phases of solar cycle 24 respectively. The absence of a minimum phase is justified by the lack of data during this period at the Koudougou station. True 48-hour quiet periods and recurrent disturbed periods for each year were taken into account. The diurnal averages of TEC under quiet and recurrent geomagnetic conditions were calculated for each phase of the solar cycle. For all graphs shown, the blue curve illustrates the average TEC for quiet days, and the orange curve illustrates the recurrent days. We have placed the error bars ($\sigma = \sqrt{\Delta}$, where Δ is the variance defined by $(1/N)\sum_{i=1}^{N}(x_i - \bar{x})^2$ with $\bar{x}$ mean value) on the TEC curve for recurrent days in **Figure 3** to provide a reference for the significance of the differences with the TEC for quiet days.

Panels a, b, and c of **Figure 3** show that the maximum mean diurnal TEC value lies between 1300 and 1500 UT at the Koudougou station, for quiet and disturbed days, regardless of the phase of the solar cycle. Ghimire *et al.* [48] found a range between 0900 UT and 1100 UT at two nearby stations, BESI (28.228˚N; 84.739˚E) and GHER (28.375˚N; 84.739˚E) in Nepal, while Lissa *et al.* [42] found a range between 1300 UT and 1500 UT at the Bangalore, Waltair, and Hyderabad stations in India. This means that the diurnal variation in TEC is influenced by the station position. In general, at the Koudougou station, the diurnal variation in TEC is minimal before dawn (0400 UT - 0500 UT), a steady increase in the early morning (0600 UT), followed by a maximum in the afternoon (between 1300 UT and 1700 UT) and then a gradual decrease after sunset. The variation in TEC during the day is greater than the variation at night. The increase in TEC, particularly at equatorial stations during the day, may be associated with the upward drift of plasma caused by the fountain effect resulting from the E × B drift and the resulting force of gravity and pressure gradient, which form two peaks known as the equatorial ionization anomaly (EIA) [8] [49]. The maximum values (101.80 TECU) and minimum (0.88 TECU) of TEC during the quiet days of solar cycle 24 were observed on March 27, 2014 at 1500 UT and June 21, 2016 at 0400 UT, respectively. However, the highest TEC value (96.22 TECU) during recurrent days was observed on October 28, 2014 at 1400 UT and the lowest

(1.075 TECU) on February 06, 2011 at 0500 UT. During the three phases of solar cycle 24 considered, the maximum diurnal means TEC value increases from 29.31 TECU to 75.37 TECU and from 22.14 TECU to 67.83 TECU between 2010 and 2014 and decreases from 75.37 TECU to 30.32 TECU and from 75.37 TECU to 25.97 TECU between 2014 and 2017, respectively, during recurrent geomagnetic days and quiet days. This trend follows the solar activity cycle illustrated in **Figure 1**, meaning that the variation in TEC is influenced by solar activity.

However, the panels in **Figure 2** show that the diurnal variation of the TEC under quiet and recurrent geomagnetic conditions from 2010 to 2017 differs from one phase to the next. Indeed, during the descending phase of solar cycle 24, the diurnal variation curve of the TEC on recurrent days is higher than that on quiet days for all hours of the day. But this difference, quantified by the error bars on the graphs, is significant between 1100 and 1700 UT. This shows a positive effect of the recurrent class of geomagnetic activity on the TEC during this phase. In a similar vein, the TEC curves for quiet and recurrent days are almost identical during the ascending phase of solar cycle 24 (2010 and 2011). During this phase, the curves for the two classes of geomagnetic activity are almost merged, with TEC values for recurrent days slightly higher than those for quiet days, especially during the night hours (between 0000 - 0500 UT and between 1800 - 2300 UT). During daytime hours, the difference between the TEC of recurrent days and that of quiet days is quite noticeable, but remains insignificant because the error bars placed on the curve of disturbed days also touch the curve of quiet days. However, the graph for the maximum phase of solar cycle 24 (2012, 2013 and 2014) shows a morphology similar to the ascending phase, but with the TEC of recurrent days much higher than that of quiet days between 1200 and 1700 UT and between 2200 and 2300 UT. This explains the positive effect of recurrent geomagnetic disturbances on the TEC during the ascending, maximum and descending phases of solar cycle 24, but the significant effect during the descending phase. This result confirms Lissa *et al.* [42] with data from other equatorial stations in the Indian sector, who showed that the positive effect of thunderstorms is more marked during the minimum and descending phases of solar cycle 24. The low impact of recurrent geomagnetic activity observed during the ascending and maximum phases, as well as the positive effect observed during the descending phase, can be justified by the occurrence of recurrent geomagnetic days. Previous studies have shown that recurrent days are more prevalent during the minimum and descending phases than during the ascending and maximum phases [50] [51] [52]. Furthermore, the low impact observed during the maximum phase could be explained by the effect of the dynamo ionospheric disturbance (DDEF). Indeed, dynamo disturbances can be associated with periods of heightened geomagnetic activity, such as recurrent geomagnetic storms, and can cause sudden fluctuations in the TEC. Sur *et al.* [53] showed that the effect of DDEF decreased the VTEC values during the storms of October 29 and 30, 2003. Zhang *et al.* [54] have shown that the weak equatorial eastward electrojet in the dawn and dusk sectors is modulated by the DDEF-induced eastward electric field, which is also mainly controlled by the zonal wind and weakly influenced by the meridional wind. This can also have a negative effect on the TEC.

3.2.2. Diurnal Variations in TEC as a Function of the Level of Disturbance of Recurrent Activity

To gain a better understanding of the effect of recurrent geomagnetic days on the TEC at Koudougou station, an in-depth study according to disturbance intensity has been carried out in **Figure 4**. Disturbed geomagnetic activity in general is ranked by disturbance level, from agitated to extreme storm, according to the three-hourly values of the index Kp as detailed in Section 2. Panels a, b, c and d of **Figure 4** illustrate a comparison between the variation of the TEC on quiet days and that on recurrent days in agitated, active, minor storm and moderate storm geomagnetic conditions, respectively. In all panels, the blue curve represents quiet activity and the orange curve indicates recurrent activity. The right-hand columns show the difference between the TEC on disturbed days and that on quiet days. The available covers the period from 2010 to 2017 for agitated recurrent days, from 2009 to 2017 for active recurrent days and from 2011 to 2017 for minor storm recurrent days. For moderate storms, data are available for four years (2013, 2015, 2016 and 2017).

Panels a, b, c and d in **Figure 4** show that recurrent days have both positive and negative effects on TEC variations during solar cycle 24 at the Koudougou station, regardless of the level of geomagnetic disturbance. However, the effect differs from one disturbance level to another. When the level of geomagnetic disturbance is very low ($27 \le Kp < 37$) *i.e.*, agitated level), the maximum mean value of the difference between the TEC of quiet days and recurrent days is 7.34 TECU (panel a, right-hand column). This value improves to 9.19 TECU (panel b), when the disturbance level becomes active ($37 \le Kp < 47$). When disturbances trigger geomagnetic storms ($Kp \ge 47$), the maximum value of this difference can reach 21.29 TECU (panel d). On the other hand, average minimum values range from −2.76 TECU to −6.78 TECU from the most to the least disturbed level. In particular, during periods of high geomagnetic activity, we generally observe an increase in TEC. This is often due to increased ionosphere heating due to magnetic and kinetic energy associated with geomagnetic disturbances [39]. Dynamic processes such as induced electric currents and the movement of charged particles can also contribute to these variations. In general, at the Koudougou station, recurrent days have a positive effect on diurnal variations in TEC, with the strength of the effect being greatest during the minimum and falling phases of solar cycle 24. However, negative effects are observed during the ascending and maximum phases. In fact, during the descending phase of the solar cycle, high-speed solar ejecta are less frequent and high-speed co-rotative currents are more frequent [55]. Also, it sometimes happens that more solar wind energy is introduced into the magnetosphere/ionosphere annually during

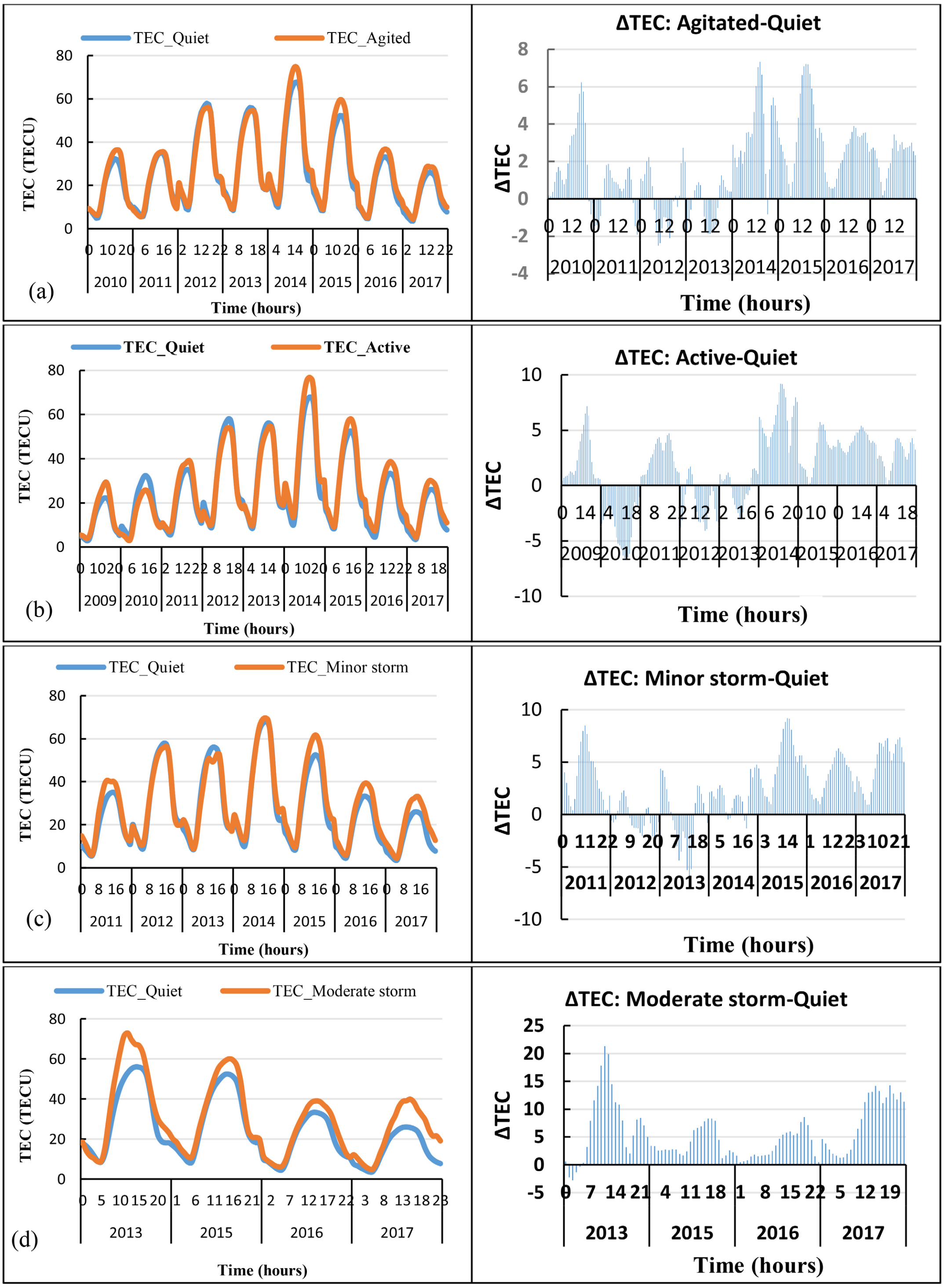

Figure 4. Comparative study of TEC between quiet and recurrent periods as a function of the level of geomagnetic disturbance.

the descending phase than during the solar maximum [38] [56]; this contributes to the increase in TEC during recurrent activity.

The results showed that the diurnal variations in TEC were influenced by the level of disturbance in the recurrent activity. During periods of agitated recurrent activity, variations in diurnal TEC were generally greater. This indicates that increased geomagnetic activity during these periods may cause more pronounced fluctuations in the distribution of free electrons in the ionosphere. On the contrary, during periods of quiet recurrent activity, diurnal variations in TEC were generally less marked. As the electric currents induced in the ionosphere were less intense during these periods, diurnal variations in TEC were more regular and less pronounced. Therefore, in the following section, we will carry out a study of monthly variations to examine this result in greater depth.

3.2.3. Monthly Variations in TEC in Quiet and Recurrent Periods from 2010 to 2017

Figure 5, organized as a panel, shows the average monthly variation of TEC under quiet and recurrent geomagnetic conditions from 2010 to 2017 at the Koudougou station. In all figures, the blue color corresponds to the average monthly values for quiet days and the orange color for recurrent days. Graphs are arranged in ascending year order from left to right, showing all monthly diurnal variations from 2010 to 2017. The discontinuity in the quiet-day curves is explained by the lack of data recorded at the Koudougou station, whereas the discontinuity in the recurrent-day curves is due either to the lack of data or to the absence of recurrent days in certain months of certain years.

A comparative study of TEC between quiet and recurrent days reveals a variable effect of recurrent activity on TEC, with positive impacts for some months and negative effects for others. In 2012 and 2013, the TEC curves showed a slight upward trend from January to December for both recurrent and quiet days. However, in the first six months of these years, the two curves are almost identical, with the TEC for quiet days slightly higher than that for recurrent days for a few hours in March, April and May 2012, as well as March-April 2013. In the second half of these years, the TEC of recurrent days slightly exceeds that of quiet days, with the exception of July 2012 and September 2013, when the opposite effect is observed at certain times of the day. In 2010 and 2011, both curves show a slightly increasing trend throughout the year. However, in 2010, a notable difference is observed in May and August. In 2011, the TEC curve for recurrent days was slightly higher than for quiet days throughout the year, with the exception of February and a few hours in July and August. In 2014, an almost constant trend was observed, with the TEC of recurrent days above that of quiet days, except for certain hours in March and April. On the contrary, during the downward phase in 2015 and 2016, a decreasing trend is observed from January to December. Between 2015 and 2017, every month of the year shows a positive effect of recurrent geomagnetic activity, with the exception of October 2015 and June 2016. During the ascending phase, the TEC of quiet days is higher than that of recurrent days in summer and winter. This phenomenon is also observed in spring during the phase of maximum solar activity (2012, 2013 and 2014), as well as in summer in 2013. In 2015, this phenomenon was observed in the autumn, and in 2016 in summer. In general, the TEC for recurrent days is generally

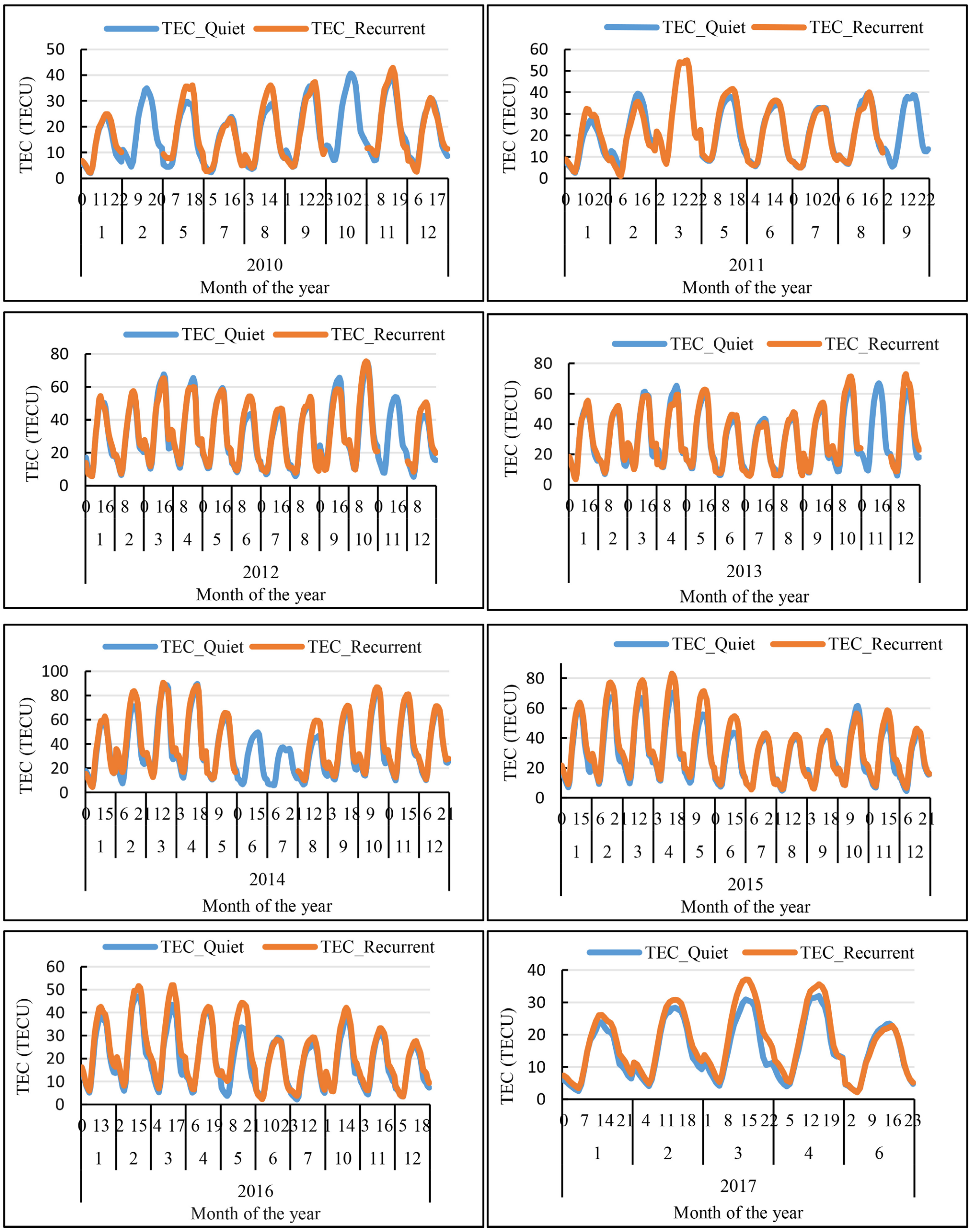

Figure 5. Monthly variation in TEC during quiet and recurrent geomagnetic periods.

higher than that for quiet days, with the exception of a few months between 2010 and 2017. The work of Crooker and Cliver [57] has shown that the Russell-McPherron effect plays a significant role in recurrent activity. Furthermore, CIRs enhance this effect by increasing the amplitude of the predominant ecliptic fields, increasing the peak of the projected component of the recurrent activity peak [58], thus leading to higher TEC values observed during recurrent activity compared to quiet activity. These variations are generally more pronounced at mid- and high-latitudes [42].

The period from March 2014 to February 2015 is a period of high solar activity. For the period of high solar activity, a nocturnal resurgence of anomaly (causing a secondary peak in the GPS-TEC) associated with the increase in the evening pre-reversal is observed at Koudougou station, as shown in **Figure 5**. This type of similar results was observed for the period of high solar activity in 2001 over the South American sector by Jonah *et al.* [59]. The peak occurs around 0000 UT between the different months of the year. The months with peaks differ according to the class of geomagnetic activity. For example, in 2010, a night-time peak was observed on the curve for recurrent days between July and August and another peak between August and September for quiet days. These night-time peaks could be a sign of a pre-reversal of the electric field. Indeed, during the day and in the equatorial regions, in the E and F layers, the eastward electric field reverses to the west during the night [60]. This reversal could stimulate ionization at night by delaying the recombination process of ionized particles in the ionosphere, thus increasing the TEC at certain times of the night.

Figure 5 also shows that TEC exhibits symmetric variations around the months of June-July and December-January for all years from 2010 to 2017. This characterizes the presence of a semiannual anomaly. In reality, a semiannual anomaly is mainly caused by electric currents induced in the Earth's ionosphere in response to variations in solar wind and geomagnetic activity. However, the highest values are observed at the equinoxes (spring and autumn) and the lowest values at the solstices (summer and winter). This is in line with most of the research carried out in equatorial regions. Seasonal variations have been attributed to changes in the concentration of atomic oxygen and molecular nitrogen in the F-region [18] [49] [61]. In addition, at equinoxes, when the inclination of the Earth's axis of rotation to the Sun is at its maximum, electric currents in the ionosphere can generate significant variations in the magnetic field [62]. When the solar wind interacts with the Earth's magnetosphere, it can disrupt the magnetic field and induce electric currents in the ionosphere that also affect the TEC. The semiannual anomaly effect observed in measurements of the Earth's magnetic field is felt on the variation in geomagnetic activity on a semiannual basis, known as the "Russell-McPherron effect" [58] [63]. This effect is also felt in the variation of the TEC at Koudougou, where regular variations are observed every six months, with peaks at the equinoxes.

Also, at Koudougou station, under quiet and recurrent geomagnetic conditions, the TEC values are higher in winter (December-January) than in summer (June-July). This phenomenon is most visible during the maximum (2012, 2013 and 2014) and descending (2015 and 2016) phases of solar cycle 24. However, it is less pronounced during the ascending phase (2010 and 2011). This feature is the signature of the winter anomaly. This result is in agreement with that of Pahima *et al.* [64], who proved the presence of the winter anomaly during fluctuating geomagnetic activity at the Koudougou station. Furthermore, the graphs in **Figure 5** show that the autumn months (September, October and November) exhibited 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. In contrast, the years 2015 and 2016 (descending phase of solar cycle 24) showed a reverse equinoctial asymmetry, where the TEC of the spring equinox was slightly higher than that of the autumn. However, the solar maximum year (2014) shows almost equivocal TEC values at both equinoxes. Equinoctial asymmetry has been attributed to differences in the meridional winds, which led to changes in the neutral composition during the equinoxes.

3.2.4. Average Monthly TEC According to the Level of Disruption in Recurrent Activity

Panels a, b, c and d of Figure 6 show a comparative study of the TEC of quiet days and the recurrent agitated, active, minor storm and moderate storm days, respectively. The blue color corresponds to the average monthly values for quiet days and the orange color corresponds to the recurrent days.

Figure 6 panel a illustrates the monthly mean values of TEC in quiet and recurrent periods at the "agitated" disturbance level. TEC values in agitated periods are higher than those in quiet periods for all months except March, when identical values are observed. However, the highest TEC values in the "agitated" period are observed in February, March, April, September, October and November, corresponding to the equinoxes, and the lowest in January, June and July correspond to the solstices. However, the difference indicated by the error bars remains significant throughout the study period. For the study in the "active" recurrent geomagnetic period shown in panel b, the highest monthly mean

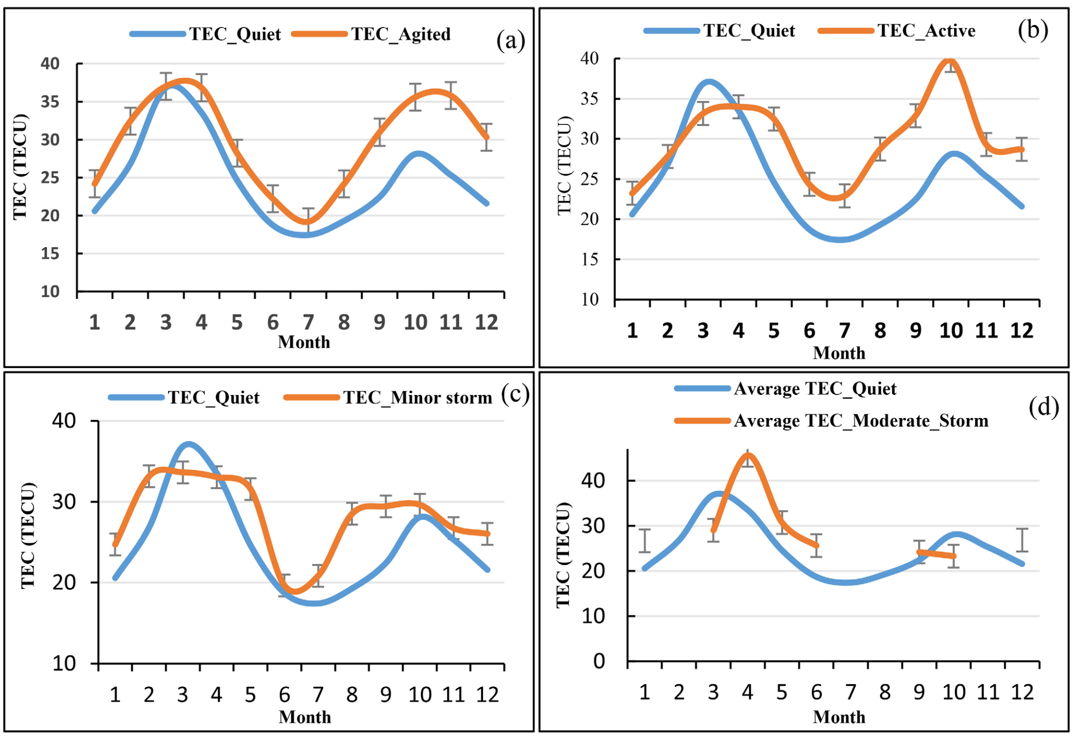

Figure 6. Comparative study of TEC between quiet and recurrent geomagnetic activity according to the level of disturbance on recurrent days.

TEC value (39.75 TECU) is observed in October, and the lowest (22.90 TECU) in July. However, the monthly variation in "active" periods remains almost identical to that in "agitated" periods. As in previous geomagnetic periods, during minor storms (panel c), the TEC is highest at the equinoxes and lowest at the solstices. However, the TEC values in August, September, and October are rather lower than those observed in February, March, April, and May; panel d of **Figure 6** shows the monthly TEC values during periods of "moderate storms" ($57 \le Kp < 67$). During the study period, no moderate storms were detected in the months of February, July, August and November. The highest TEC (45.61 TECU) is observed in April and the lowest TEC (23.31 TECU) in October during recurrent moderate geomagnetic storms.

For all levels of recurrent geomagnetic disturbance studied in this article, the effect of recurrent geomagnetic activity is negative in March, with a more significant effect as the disturbance level increases. Recurrent activity disturbance levels were classified into several categories, including agitated recurrent activity, active recurrent activity, minor storm recurrent activity and moderate recurrent activity. The results showed that the average monthly TEC varied according to the level of disturbance of recurrent activity. In months of turbulent recurrent activity, the TEC average was generally higher than during periods of quiet recurrent activity. These higher TEC fluctuations during agitated periods may be attributed to more intense ionospheric dynamo effects caused by increased geomagnetic activity. However, during periods of quiet recurrent activity, the monthly mean TEC tended to be lower. The induction of electric currents in the ionosphere was less intense during these periods, resulting in a more uniform electron distribution and lower mean TEC values. The monthly mean TEC also showed seasonal variations depending on the level of disturbance caused by recurrent activity. Some seasons were more sensitive to the effects of recurrent activity, while others showed less marked differences. It should be noted that the semi-annual anomaly is added to other components of the variation of the Earth's magnetic field, such as the annual anomaly or the secular anomaly. Together, these different components contribute to the complexity and diversity of TEC variations observed on different time scales.

4. Conclusions

Recurrent geomagnetic activity and quiet geomagnetic activity effect on the ionosphere were studied using the diurnal and monthly mean TEC at the Koudougou station. Comparative studies of TEC as a function of the level of disturbance on recurrent geomagnetic and quiet days were carried out. Furthermore, the annual dependence of TEC on solar activity was evaluated using the F10.7 index in this work. The study period practically covers solar cycle 24.

The TEC average diurnal shows a minimum before dawn (around 0500 UT) and increases rapidly from sunrise, reaching a maximum value around 1400 UT. Then the level gradually decreases after sunset. At Koudougou station, the average diurnal on recurrent days is slightly higher than on quiet days, with an average difference of 7 TECU. This difference increases with the level of geomagnetic disturbance, reaching a maximum value of 21 TECU during a moderate storm. The diurnal difference between recurrent and quiet days shows negative values during the ascending phase and generally positive values during the other phases of solar cycle 24. The diurnal variation also shows peaks on the TEC curve. Looking at monthly variations, March and October show the highest TEC values for quiet and recurrent days, respectively. The equinox months show the highest mean values, whereas the solstice months show the lowest. Signatures of semi-annual, winter and equatorial ionization anomalies were observed. The difference in values between quiet and disturbed GPS-TEC days explains the difference in geomagnetic phenomena in the ionosphere on these days. On an annual scale, the variation in TEC depends on the solar flux F10.7 at 98% during recurrent geomagnetic activity and 92% during quiet geomagnetic activity. The percentage varies with the level of recurrent geomagnetic disturbance.

In summary, this study provides valuable information on the impact of geomagnetic activity, the diurnal, seasonal and annual variation of the TEC, and the signatures of anomalies in the ionosphere. These results are crucial to understanding the interactions between the ionosphere and geomagnetic activity.

Data Availability

The total electron content (TEC) data used to support the results of this study are included in the supplementary file(s). F10.7 solar flux index and 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 that they have no conflict of interest.

Acknowledgements

The authors thank Rolland Fleury of IMT Bretagne, Technopole, Brest Iroise, France, for his cooperation in processing the Koudougou data. They also express their sincere thanks to OMNI Web data https://omniweb.gsfc.nasa.gov/form/dx1.html for providing geomagnetic (Kp) and solar (solar flux F 10.7 cm) index data. We thank SILSO for the sunspot number data. Also, we thank ISGI for the Dst index and CK-days data.

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