

Study of Ionospheric Anomalies at the Koudougou Station during the Moderate Geomagnetic Activity of Co-Rotation during the Solar Cycle 24

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Abstract

This article is part of the ongoing study of the moderate geomagnetic activity of corotation. The aim here is to examine ionospheric anomalies through variations in Total Electronic Content (TEC) recorded at the Koudougou GPS station over solar cycle 24 during periods of corotation activity. Through the diurnal variations by solar phase, we observed a TEC peak at 14:00 TL. The TEC data analysed revealed winter, annual and semi-annual anomalies. However, the equinoctial anomaly was insignificant during corotation activity at the Koudougou station during solar cycle 24.

Keywords

Geomagnetic Activity, Total Electronic Content, Ionospheric Anomalies, Equinoctial, Corotation Activity

1. Introduction

The ionosphere is the ionised region of the Earth's atmosphere. It extends over altitudes ranging from about 50 to 1,000 km [1] and results from the photo-ionisation of neutral particles present in the upper atmosphere by the Sun's UV and EUV rays. The study of electron density in this region is of vital importance, as the development of communications technologies and the position of satellites are heavily dependent on it. Total Electron Content (TEC) is a key ionospheric pa-

parameter in the study of the ionosphere. The TEC is defined as the integration of the electron density along an imaginary tube with a cross-section of 1 m^2 running from the satellite to the receiver on Earth [1]. Wave propagation in the atmosphere is highly dependent on the configuration of the ionosphere, and in particular on the variability of the TEC [2]. This variability in the TEC sometimes leads to irregularities, commonly known as ionospheric anomalies. Understanding these anomalies is of major scientific interest for improving human technologies. Studies are being carried out in various parts of the world to observe and explain these anomalies. Studies by Chavdarov *et al.* [3], Ivanov *et al.* [4] in Russia, Renard [5] in the United States, and Yingbo *et al.* [6] in China are all worth mentioning.

It should also be noted that for a long time, ionospheric studies of co-rotation activity have often been carried out either by including it in fluctuating activity according to the classification of Ouattara *et al.* [7] and Diabaté *et al.* [8] and Legrand *et al.* [9], or by associating it with recurrent activity [10] [11]. In this article, we propose a study of the geomagnetic activity of co-rotation without associating it with the other classes of activity. This study, which focuses on TEC variability and the prediction of ionospheric anomalies, was carried out at the Koudougou GPS station (Latitude $12^{\circ} 15' \text{N}$, Longitude $-2^{\circ} 20' \text{E}$). The aim is to verify the presence of anomalies during co-rotation geomagnetic activity at the Koudougou station as a function of seasonal variations and the phases of the solar cycle 24 of the TEC.

2. Data and Methods

2.1. Data

The TEC data used in this study come from the Koudougou GPS station. This receiving station was installed as part of the International Heliophysical Year (IHY) project in November 2008 and was donated by the UK's Ecole Normale Supérieure des Télécommunications.

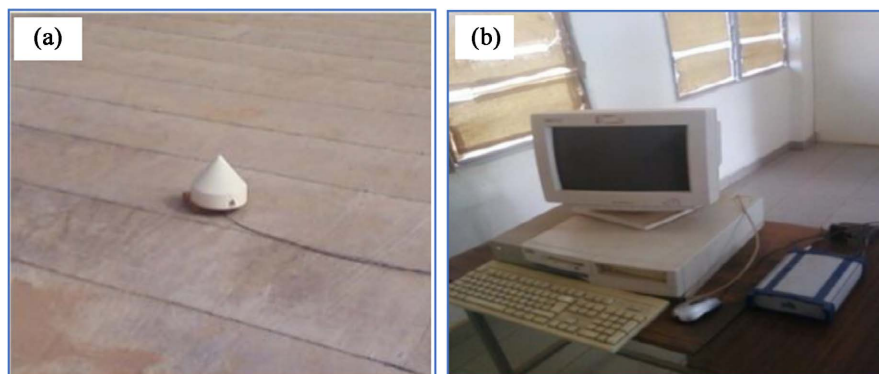


Figure 1. Antenna (a) and data acquisition system (b) at the Koudougou GPS station.

For cycle 24, TEC data for the years 2008, 2018 and 2019 were not recorded at the Koudougou station. Consequently, the study will focus on the other years of

cycle 24, from 2009 to 2017, recorded by the system shown in **Figure 1**.

We use the geomagnetic indices aa established by [12] and the Sudden Storm Commencement (SSC) dates to construct the pixel diagrams for the years of cycle 24. Established in 1868, the aa index is based on the K index measured at two antipodal mid-latitude stations, *i.e.* geomagnetic stations located at diametrically opposite points on the Earth's surface. Hartland in England and Canberra in Australia. This index measures the amplitude of global geomagnetic activity. The aa values are given in 3-hour intervals. The SSC dates indicate the start of a sudden geomagnetic storm. aa and SSC data are available.

To determine the phases of cycle 24, we use data on the Rz index, the annual average sunspot number from Zürich. These data are available.

2.2. Method for Selecting Days Corotation

Geomagnetic activity refers to transient variations in the Earth's magnetic field. These variations are caused by interactions between the Earth's magnetic field and charged particles from the solar wind, mainly electrons and protons. These interactions are influenced by solar activity and the conditions of the interplanetary medium.

The different classes of geomagnetic activity are identified on the basis of a series of aa index data, presented in the form of 27-column tables called pixel diagrams. In these diagrams, each column represents a solar rotation [13]. We are interested in two major classifications: that of Legrand *et al.* [9], confirmed by [14]-[16] and the new classification by Zerbo *et al.* [17].

According to Legrand *et al.* [9], there are four classes of geomagnetic activity: shock activity, calm-day activity, recurrent activity and fluctuating activity. Of the four classes of geomagnetic activity presented by Legrand and Simon, only three have been clearly defined: calm-day activity, recurrent activity and shock activity [17]. The study conducted by Zerbo *et al.* [17] subdivided the class of fluctuating activity into three new categories. The integration of CMEs and the effect of moderate solar winds are avenues to be explored [18]. This approach has made it possible to classify 80% of the days of geomagnetic activity, compared with 60% for the previous classification. Three new classes were thus established: magnetic cloud activity, unclear day activity, and moderate co-rotation activity, which is the subject of our study.

Moderate co-rotation activity is the result of calm solar winds, combined with moderate geomagnetic activity. The value of the aa index for days belonging to this class of activity is between 20nT and 40nT (yellow and green colours on the pixel diagrams: **Figure 2**). They are identified by recurrence zones with no SSC.

2.3. Solar Cycle Phase Classification Method 24

We base ourselves on the new classification established by Sawadogo *et al.* [19] on the basis of new data on the number of sunspots (SN) calculated by the Belgian Observatory.

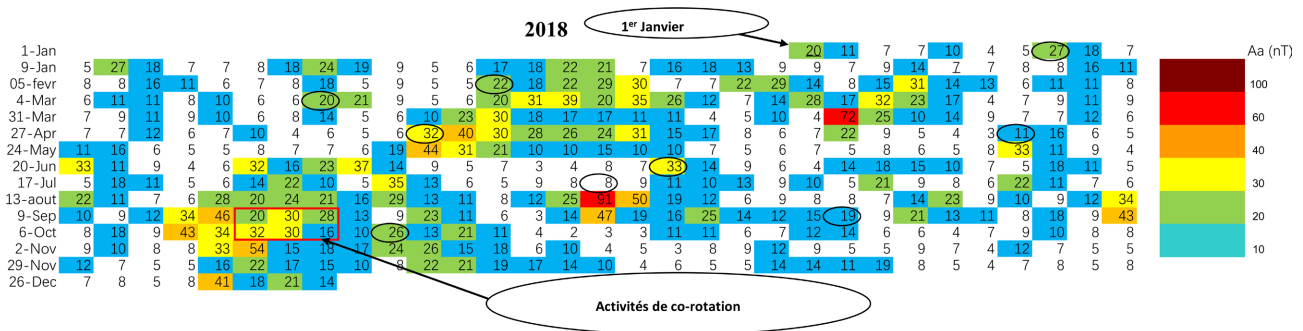


Figure 2. Pixel diagram of the year 2018.

Table 1 shows the different phases of solar cycle 24 from 2008-2009 to 2018.

Table 1. Phases of the solar cycle 24.

Year	Solar cycle phase 24
2008-2009	Minimum
2010-2011	Ascending
2012-2013-2014	Maximum
2015-2016-2017-2018	Downward

The criteria for this classification are defined as follows:

- Minimum phase: $SN < 0.122SN_{max}$
- Ascending phase: $0.122SN_{max} < SN < 0.73SN_{max}$
- Maximum phase: $SN > 0.73SN_{max}$
- Downward phase: $0.73SN_{max} > SN > SN_{min(cycle\ suivant)}$

2.4. Classification of the Seasons of the Year

The year is divided into four main seasons: autumn, spring, winter and summer. The distribution of months for each season is shown in Table 2.

Table 2. Seasons of the year.

Winter	Spring	Summer	Autumn
December	March	June	September
January	April	July	October
February	May	August	November

2.5. Analysis Method

To analyse the curves constructed from the TEC, we use several statistical tools. The error bars used in our study are calculated from the statistical variance using formula (1).

$$V = \frac{1}{N} \sum_{i=1}^N (x_i - \bar{x})^2 \tag{1}$$

N is the total number of observations, \bar{x} the arithmetic mean of the TEC

measurements and x_i a TEC observation or measurement.

The relative deviation of the TEC (or relative error) will be used in the quantitative analysis to assess the extent of the anomalies observed. It was used by Pahima *et al.* [20] to assess the prediction of anomalies at the Koudougou station during the fluctuating activity of solar cycle 24.

Its expression is given by the following formula (2):

$$\delta TEC = \frac{x_i^F - x_i^L}{x_i^L} \tag{2}$$

with x_i^F representing the hourly average of the TEC at the March equinox or the June solstice and x_i^L representing the September equinox or the December solstice.

For $-20\% < \delta TEC < +20\%$. If not, the anomaly will be considered significant [19].

3. Results

3.1. Variation in TEC per Solar Cycle Phase

We construct the TEC variation curves for the four phases of the solar cycle. **Figure 3** shows these diurnal variations in the TEC as a function of phase at the Koudougou measurement station during moderate geomagnetic corotation

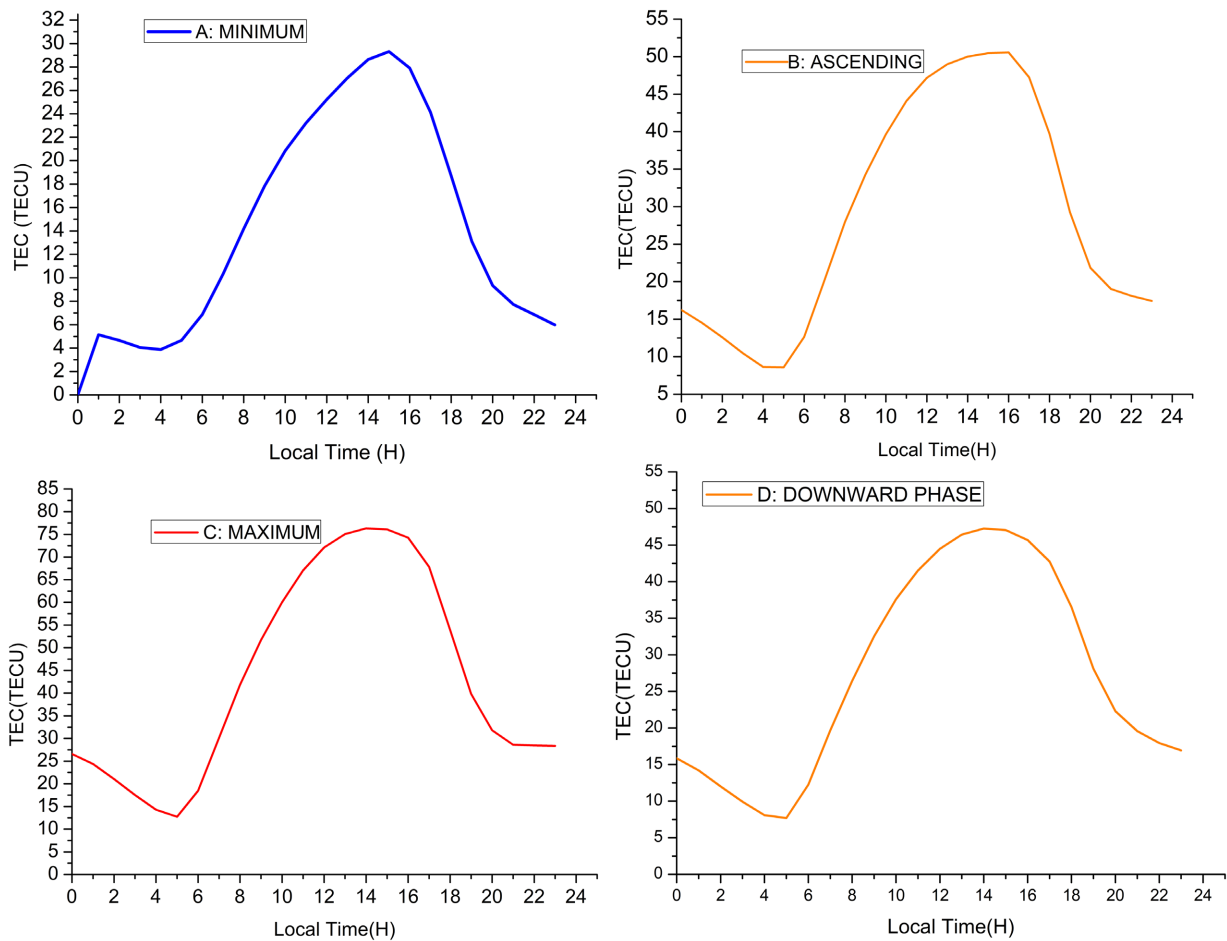


Figure 3. Diurnal variation by solar cycle phase 24.

activity during solar cycle 24. This representation not only provides a better understanding of the evolution of the TEC as a function of solar activity, but also of the influence of solar activity on variations in the TEC during periods of corotation.

Curves A), B), C) and D) in **Figure 3** represent the minimum, ascending, maximum and descending phases of the solar cycle respectively.

Curves A), B), C) and D) in **Figure 3** show an overall dome-shaped profile, with two troughs at around 05:00 and 23:00, and a peak at around 14:00.

On curve A), corresponding to the solar minimum, we see a decrease in the total electron content from 00:00 to 05:00, reaching a minimum value of 4.5 TECU. The maximum value of the TEC is 29 TECU at 2 pm.

On curve B), corresponding to the ascending phase, TEC values decrease from 00:00 to 05:00, reaching a minimum value of 6 TECU. The maximum TEC value was observed at around 2 pm, with 51 TECU.

Curve C) shows the highest TEC values. The minimum value, 10 TECU, is recorded after a decrease in TEC values from 00:00 to 05:00. The peak observed at 2 pm was 78 TECU.

On curve D), corresponding to the descending phase, we note a similar trend to that observed for the ascending phase. The minimum TEC value, observed at 5.00 am, is 4.5 TECU, while the peak at 2.00 pm reaches 48 TECU.

In conclusion, we observe a similarity in the evolution of the TEC over the four phases of solar activity during corotating geomagnetic activity. The TEC rises between 05:00 and 14:00, with a peak at 14:00. This is followed by a rapid fall in electron density from 18:00 TL to 05:00 TL, followed by a moderate decrease from 14:00 TL to 18:00 TL. The values observed for the maximum phase are higher than those for the other phases of the solar cycle.

Electron density depends on the processes by which electrons are produced and destroyed, in particular, ionisation and recombination. These two opposing processes occur at different times of the day. Strong sunlight leads to increased ionisation, while its absence favours recombination. This principle, which is supposed to explain variations in the TEC, is sometimes contradicted by opposite situations, giving rise to anomalies.

3.2. Variation Winter Anomaly

Since solar radiation is more intense in summer than in winter, we would normally expect more ionisation in summer. However, a higher electron density is often observed during the day in winter than in summer, which is referred to as a winter anomaly [21].

The curves obtained from measurements taken at the Koudougou GPS station clearly show the winter anomaly (**Figure 4**). From 0000TL to 0500TL, the TEC falls from 20 TECU to 9 TECU in Winter, compared with 10 TECU to 5 TECU in Summer.

TEC values increase between 0500TL and 1400TL, peaking at 1400TL and decreasing from 1400TL to 2300TL.

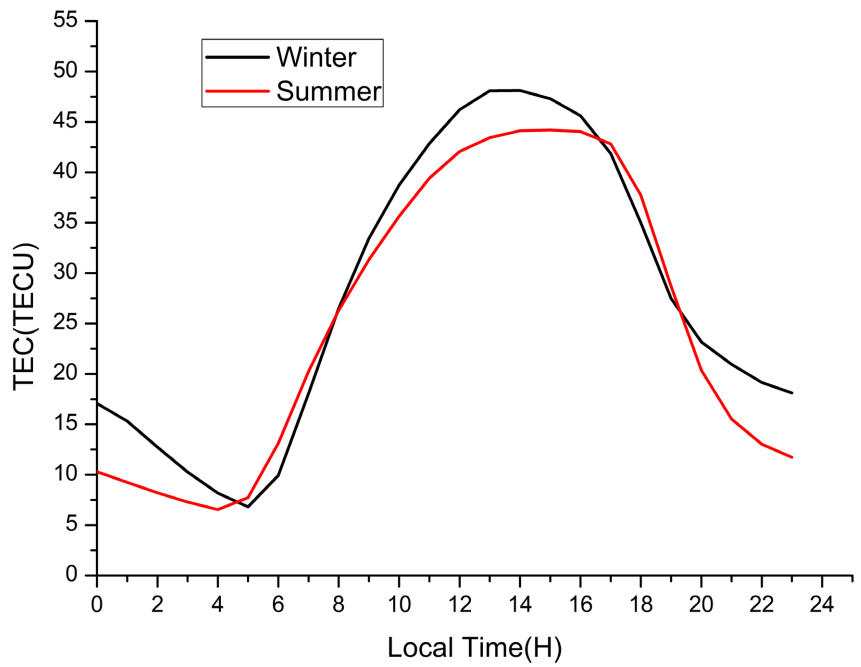


Figure 4. Diurnal variation in TEC in summer and winter.

3.3. Annual Anomaly

The annual anomaly is characterised by a higher electron density in December (cold month) than in June (warm month).

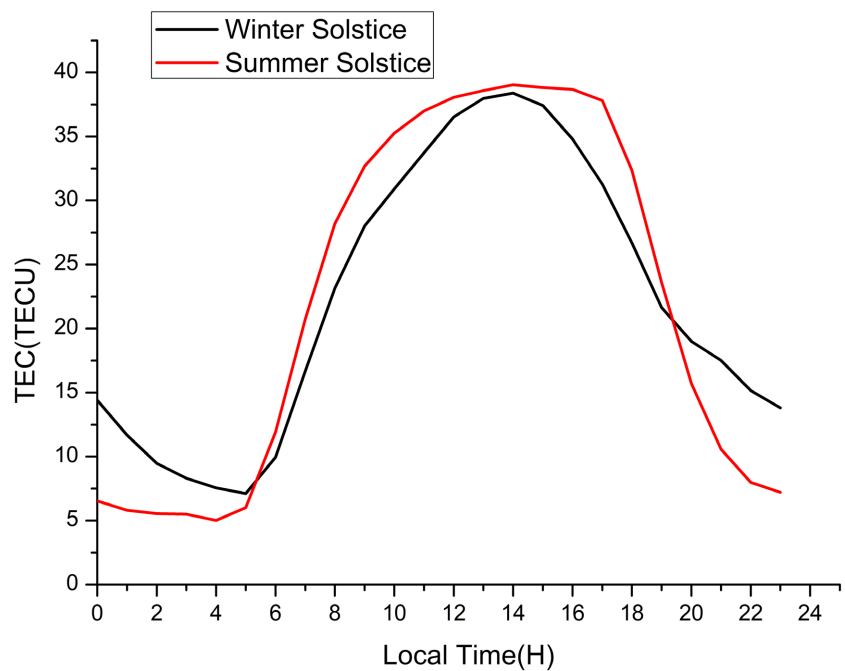


Figure 5. Diurnal variation in TEC at solstices.

Figure 5 shows fairly similar curves with a Dome profile. The annual anomaly appears to be quite large in terms of GPS measurements during the period of ge-

omagnetic activity. The maximum (peak) in TEC values observed at the winter solstice is 60 TECU compared with 40 TECU for the summer solstice.

In addition, calculating the relative deviation of the TEC ($\delta TEC = -33\%$) allows us to assert that the Koudougou GPS station gives the existence of the anomaly in a significant proportion during geomagnetic corotation activity. This result was observed by Pahima *et al.* [20] for the same station and the same solar cycle but during fluctuating activity.

3.4. Semi-Annual Anomaly

The semi-annual anomaly is characterised by a higher electron density at the equinoxes than at the solstices.

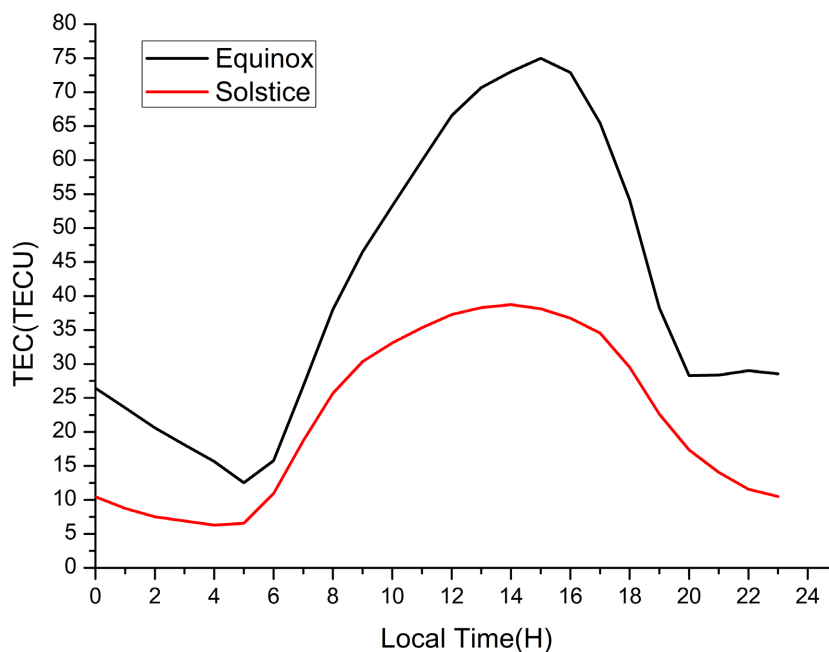


Figure 6. Diurnal variation of the TEC at solstice and equinox.

Figure 6 shows that TEC values are higher at equinox than at solstice from 0000TL to 0500TL and from 0900TL to 2300TL. From 0500TL to 0900TL, the TEC values are almost the same at the solstice and at the equinox. The relative deviation between solstice and equinox is 21%, which means that the semi-annual anomaly is present during moderate geomagnetic corotation activity.

3.5. Equinoctial Asymmetry

The ionospheric equinoctial asymmetry or simply the equinoctial anomaly is the difference observed at the two equinoxes in the variation in electron density.

Figure 7 enables us to assess the equinoctial asymmetry presented by the TEC data from the Koudougou GPS station. We can see that the TEC values in spring and autumn do not overlap at all times except for the time intervals 0000TL to 0400TL and 1700TL to 0000TL. This observation suggests the presence of an

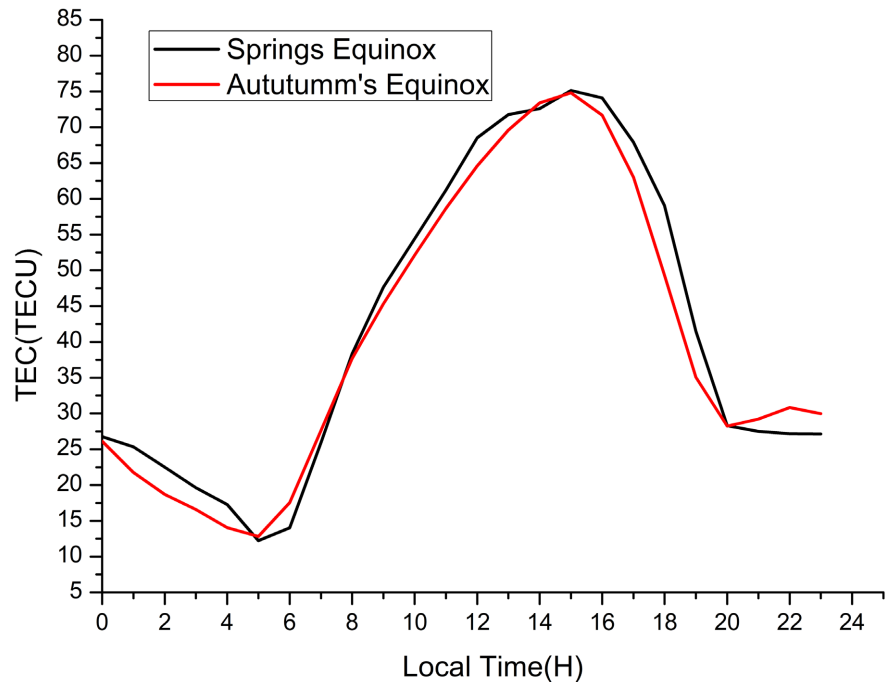


Figure 7. Diurnal variation in TEC at equinoxes.

equinoctial asymmetry. However, calculating the deviation gives 4.74% for this anomaly, which concludes that the anomaly is insignificant.

4. Discussions

Analysis by phase of the solar cycle has shown that solar activity has an influence on TEC values. The maximum TEC values for each phase of the solar cycle are observed around 14:00 TL.

Seasonal analyses of the TEC revealed the presence of winter, annual and semi-annual anomalies at the Koudougou station during moderate geomagnetic corotation activities during cycle 24. The winter anomaly is observed in the following time intervals: from 00h00 TL to 05h00 TL, from 08h00 TL to 18h00 TL, and from 19h00 TL to 00h00 TL. The annual anomaly is observed at all hours, with the exception of the interval from 05h00 TL to 07h00 TL.

However, statistical analysis reveals that the equinoctial anomaly, or equinoctial asymmetry, observed at the Koudougou station is insignificant.

5. Conclusions

The study presented in this article focused mainly on the class of days of moderate geomagnetic activity of corotation of solar cycle 24 at the Koudougou station. The TEC data collected identified a TEC peak at 14:00 TL.

We also observed the presence of ionospheric anomalies, notably the winter anomaly between 00h00 TL and 05h00 TL, between 08h00 TL and 18h00 TL, and between 19h00 TL and 00h00 TL; the annual anomaly; and the semi-annual anomaly.

On the other hand, equinoctial asymmetry was insignificant at the Koudougou station during the days of corotation.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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