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Total Electron Content Diurnal and Seasonal Variations and Response to Solar Events at Koudougou Station in Burkina Faso

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Abstract

In this paper, we studied the seasonal behavior of the total electron content (TEC) during a part of solar cycle 24 ascending, maximum and decreasing phases at Koudougou station (Latitude: 12˚15'09"N Longitude: 2˚21'45"W). Response of TEC to solar recurrent events is presented. The highest values of the TEC in 2014, 2015 and 2016 were recorded on March and October, while in 2013 they were recorded on April and November, corresponding to equinox months. This observation shows that TEC values at the equinoxes are higher than those of solstices. Moreover, the monthly TEC varies in phase with the sunspots number showing a linear dependence of the TEC on solar activity. The ionospheric electron contents are generally very low both before noon and during the night, but quite high at noon and after noon. This pattern of TEC variation is due to the fluctuation of incident solar radiation on the Earth's equatorial ionosphere. During quiet periods, the number of free electrons generated is lower than that generated during recurrent periods, which shows a positive contribution of recurrent activity to the level of the TEC. Investigations have also highlighted a winter anomaly and equinoctial asymmetry in TEC behavior at Koudougou station.

Keywords

Total Electron Content (TEC), Recurrent Activity, Quiet Activity, Seasonal Variation

1. Introduction

The ionosphere is the part of the atmosphere that is highly ionized and includes ions and free electrons in sufficient numbers to affect radio signals. It is a very unpredictable layer and is characterized by the existence of intense irregularities associated with the variabilities of solar activity. Many studies have examined the dynamic of the ionosphere and its characteristics at all latitudes during different phases of the solar cycle under disturbed and quiet conditions. Some of them have highlighted the fact that the variability depends on the level of Sun agitation, the season and the geomagnetic activity [1]-[6]. The seasonal variations of the Total Electron Content in the regions of equatorial anomalies are the combined effects of the neutral transequatorial, sub-solar and towards the equator [7] [8]. These variations are characterized by a maximum around noon or afternoon and a minimum at night and early in the morning [9]. Accurate understanding and modeling of these variations are extremely important for applications and for society, for example for GNSS positioning, satellite communication infrastructures and Earth observation by remote sensing techniques. [10] by analyzing the variabilities of the total electronic content (TEC) at the Niamey station during solar cycle 23 showed that ionization follows the solar cycle and presents a semi-annual variation with equinoctial asymmetry. Moreover, they found that the maximum density of March/April is greater than that of September/October except during the years 1999 and 2001. [3], through a comparative study between GPS TEC observed in African station and an American station equatorial region during the minimum and ascending phases of solar cycle 24, have reported that the seasonal VTEC values were maximum during the March equinox and minimum during the June solstice during the minimum phase of the solar cycle at both stations. They have also reported that during the ascending phase of solar cycle 24, seasonal minimum and maximum VTEC values were recorded during the December Solstice and June Solstice respectively. [11] studied the variability of TEC on the crest of the equatorial anomaly station in Bhopal (India) during the solar activity period (2005-2006) using GPS and observed a greater variability of the TEC on quiet days compared to disturbed days. This study is interested in the recurrent effects of solar activity on the TEC and the morphological behavior of the diurnal, monthly and annual TEC during the ascending, maximum and descending phase of the solar cycle 24. Section 2 concerns materials and methods and Section 3 deals with results and discussion. Section 4 lists the conclusions of the paper.

2. Data and Methods

The TEC data used in this study are obtained from Koudougou station (Geo Lat: 12˚15'09"N; Geo Long: 2˚21'45"W). The data covers the years 2013 to 2016. These data allowed us to make a comparative study of the monthly and annual diurnal variations of the TEC during four years (2013, 2014, 2015, and 216). For the study of the influence of the seasons on the TEC parameter, we defined season as followed: Winter (December, January, February), Spring (March, April, May), Summer (June, July, August) and Autumn (September, October, November). To discuss possible seasonal anomalies, we will make a comparative study of the diurnal variations of the TEC at the equinoxes (spring-autumn) and at the solstices (summer-winter). The intensity of the anomalies will be studied using the parameters $\Delta TEC\_solstice$ and $\Delta TEC\_equinox$ defined as follows:

$$\Delta TEC\_solstices = \frac{TEC_{summer} - TEC_{winter}}{TEC_{summer}} \times 100 \quad (1)$$

$$\Delta TEC\_equinox = \frac{TEC_{spring} - TEC_{automn}}{TEC_{spring}} \times 100 \quad (2)$$

In order to study the influence of solar activity and recurring activity on the TEC, sunspot number data was extracted from http://www.sidc.be/silso/ and those of the index were taken from the site: http://isgi.unistra.fr/. We will compare the seasonal diurnal variations of the TEC under recurrent activity with those of quiet activity during the years concerned by our study. For this, we will use the ΔTEC calculated as follows:

$$\Delta TEC = TEC_{recurrent} - TEC_{quiet} \quad (3)$$

in order to evaluate any increase or decrease in the TEC (of the recurring period compared to the quiet period) and its variation depending on the seasons. Days of recurrent and quiet solar activity are chosen using the criteria of [12] described by the pixel diagram [13] [14]. **Figure 1** shows an example of a pixel diagram. Each horizontal line contains 27 days corresponding to a Bartels solar rotation. The number in each square is the average daily value of the aa index. Quiet activity corresponds to days when Aa < 20 nT (white and blue colors in **Figure 1**); the recurrent activity corresponds to the days when Aa ≥ 40 nT on at least one solar rotation without magnetic storm.

3. Results and Discussions

3.1. Annual Variations of the TEC

Figure 2 shows the diurnal variations of the TEC during the years 2013 (in blue), 2014 (in red), 2015 (in black) and 2016 (in green). This figure shows that the diurnal variation of the TEC is higher during the day than at night for all years. It is a well-known fact that during the day the sun causes variations in

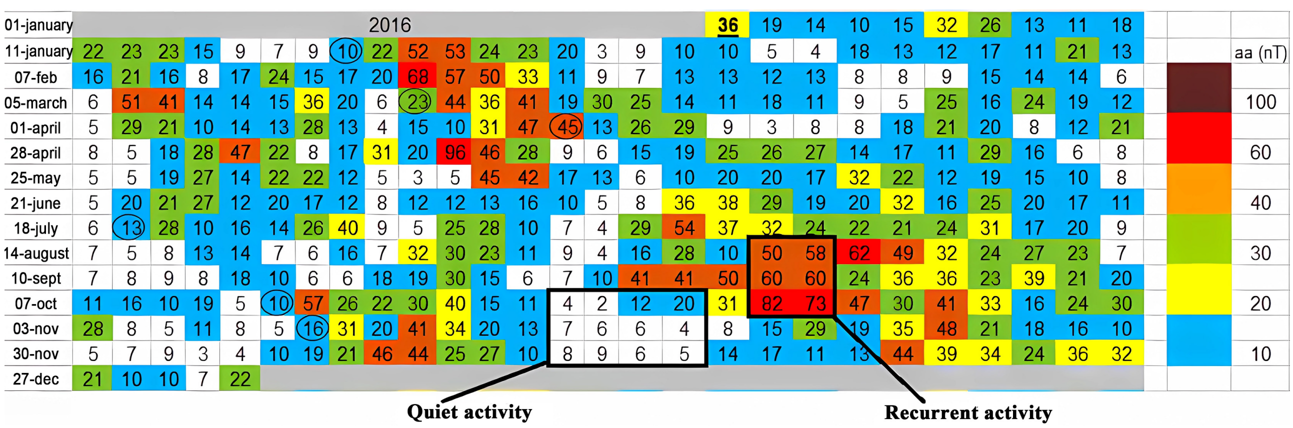

Figure 1. Pixel diagram showing quiet and recurrent solar activity.

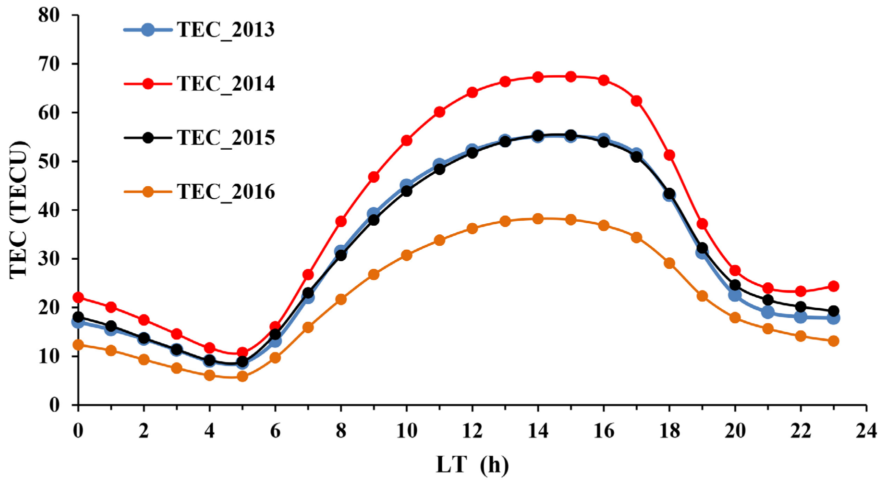

Figure 2. Annual diurnal variations of TEC during years 2013, 2014, 2015 and 2016.

temperature, neutral wind, electron density and electric field, thus modulating the structure and evolution of the ionosphere and the thermosphere [8] [15] [16]. The TEC values decrease between 00:00 LT and 05:00 LT where it reaches its minimum (9 TECU in 2013 and 2015; 10 TECU in 2014 and 6 TECU in 2016). This highlights the preponderance of recombination phenomena. From 05:00 LT, the TEC values increase and reach their maximum between 14:00 UT and 16:00 UT. [17] [18] [19] [20]; attributed the large increase in TEC to the upward vertical drift of the ExB plasma and the rapid filling of the magnetic field tube at sunrise due to solar extreme ultraviolet (EUV) radiation. During the day, an eastward electric field at the equator causes plasma to be lifted to high altitudes. This dynamo-generated eastward electric field combined with the northward directed geomagnetic field lifts the ionospheric plasma, causing further ionization [8] [18] [20]. [21] further mentioned that vertical ExB drift upwards could lead to Equatorial Ionization Anomaly (EIA). After 18:00 LT, the curves show a decreasing trend until 23:00 LT. This illustrates a gradual decline in photo-ionization and an increase in recombination processes. Similar analyzes were made by [8] [22] [23] [24] [25].

Moreover, we notice that the values of the TEC in 2014 are higher than the values of the TEC of the other years. This behavior of the TEC is correlated with sunspots numbers as shown in **Figure 3** where a comparison between the variations of sunspots numbers and the TEC is presented, showing an increase and a decrease of the TEC according to the variations of sunspots numbers. These observations are in agreement with those of [8] [20] [26], who reported a direct effect of the solar cycle on TEC measurements. Variability in solar activity results in huge variations in temperature, ion and electron densities, and electric fields in the ionosphere (Forbes et al., 2006 [16]). The solar cycle dependence of ionospheric parameters such as TEC can provide useful information to study the behavior and variations of physical and photochemical processes in the ionosphere [8] [27].

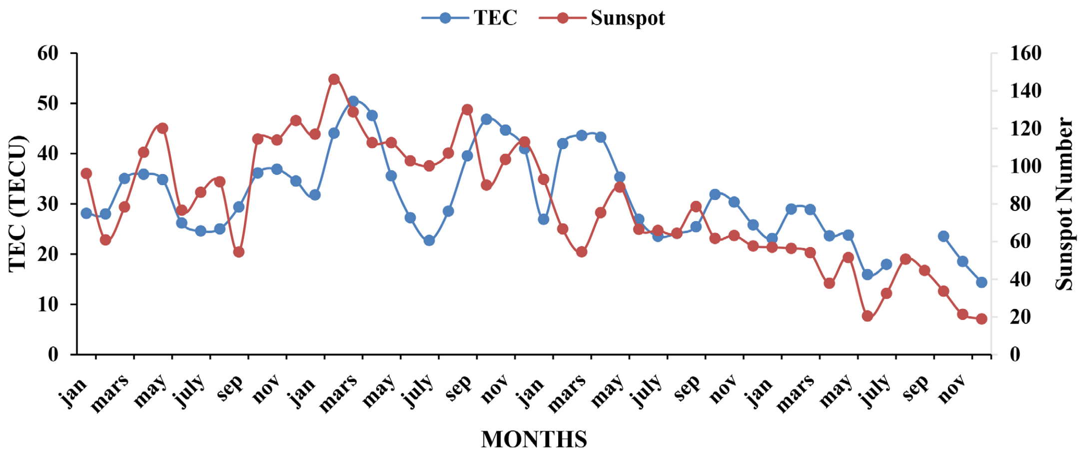

Figure 3. Monthly variations of TEC and Sunspot Number.

3.2. Monthly Variations of the TEC

From Figure 3, we observe that for the year 2013, the peaks in the evolution of the TEC occurred in April and November. On the other hand, for the years 2014, 2015 and 2016, the peaks occurred in March and October. These correspond to spring and autumn months respectively. The spring peak is greater than the autumn peak except in 2013 where the opposite occurs. We deduce that there is an equinoctial asymmetry for all these years except 2013. Moreover, for all the years, the values of the TEC in December are always higher than those in June. This clearly illustrates the presence of the annual anomaly for the four years [28].

Figure 4 presents the monthly variations of the TEC during the four (04) years of our period of investigation. There are missing data for August and September 2016. From this figure we can see that the TEC varies according to the different months of the year and presents two peaks. Depending on the year, the first peak occurred between March and April and the second peak between October and November, separated by a trough between May and August. In addition, the peak between March and April is more pronounced than that between October and November except in 2013 where the opposite is observed. [10] analyzing TEC data at the Niamey station during solar cycle 23 found similar results. So, there is an equinoctial asymmetry in TEC variation at Koudougou station.

3.3. Semi-Annual Variations of the TEC

Figure 5 shows the semi-annual variations of the TEC for the four years (04) studied. In 2013 and 2014, the March Equinox and September Equinox recorded high magnitude followed by the December Solstice. The magnitude of the September Equinox occurs between that of the March Equinox and the December Solstice. The lowest magnitude is recorded during the June solstice. In 2015 and 2016, the March Equinox and December Solstice record high magnitude followed by the September Equinox. The magnitude of the December solstice is

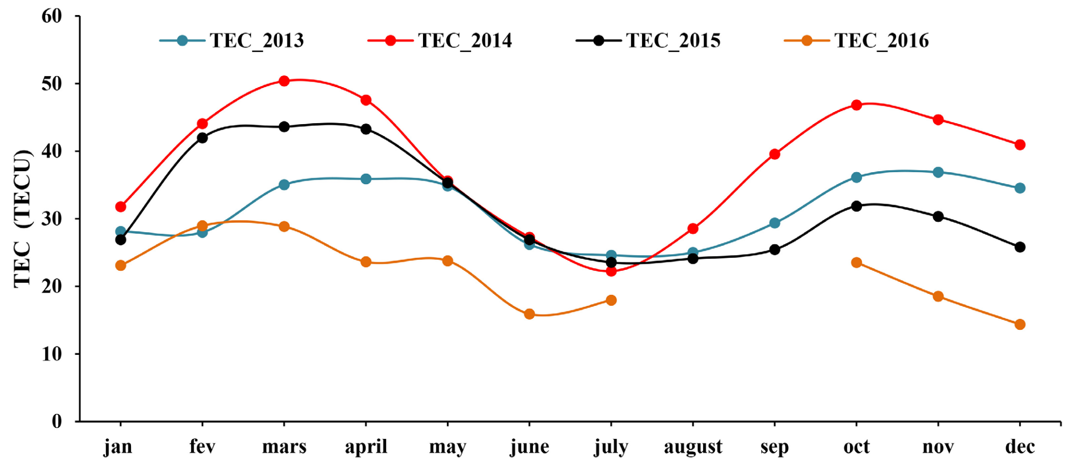

Figure 4. Monthly variations of TEC during years 2013, 2014, 2015 and 2016.

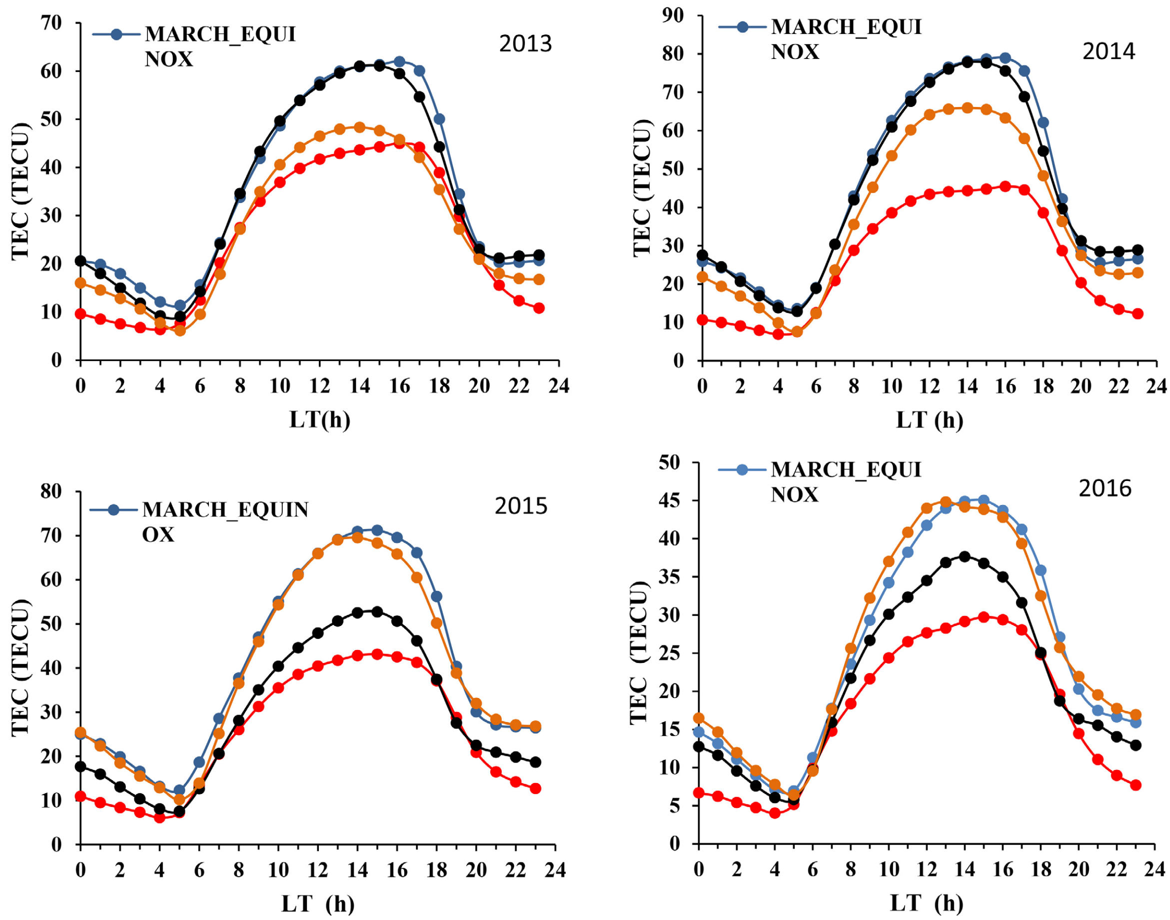

Figure 5. Seasonal variations of TEC during the years 2013, 2014, 2015 and 2016.

between that of the March equinox and the September equinox. The lowest magnitude is recorded during the June solstice.

The semi-annual asymmetry that results in higher equinoctial TEC values than solstitial TEC values is present for all years. However, there is a reversal of the September Equinox and December Solstice. [2] using data from the Ouagadougou station in the study of the climatological parameters of the equatorial ionosphere in the West African sector highlighted the semi-annual anomaly at all phases of a cycle solar.

In addition, the TEC values before midnight (18:00 LT to 23:00 LT) are higher than those after midnight (00:00 LT to 05:00 LT). In 2013, the TEC values before midnight are between 12 TECU and 50 TECU while the values after midnight are between 6 TECU and 21 TECU. In 2014, the values before midnight are between 12 - 62 TECU while those after midnight are between 7 - 27 TECU. In 2015, the values before midnight are between 12 - 56 TECU while those after midnight are between 6 - 25 TECU. In 2016, the TEC values before midnight are between 8 - 36 TECU while those after midnight are between 6 - 16 TECU. The maximum values of the TEC for all the years are observed during the March equinox. These results are in agreement with those of [20], who obtained higher TEC values during the equinoxes than during the solstices in the East African sector; [29] in the Indian sector and [8] in the West African sector.

Figure 6 presents the variations in the difference between the months of the equinox (ΔTEV_equinox) and between the months of the solstice (ΔTEV_solstice). The two curves have similar variations and each curve shows two peaks separated by a cavity. During the equinox, the first peak is observed in the morning between 03:00 LT and 05:00 LT and the second peak at night at 18:00 LT. During the solstices, the first peak is observed at 06:00 LT and the second peak between 06:00 LT and 07:00 LT. On **Figure 6(a)**, we can see that ΔTEV_equinox has positive values all day with 20.96% as maximum value recorded around 06:00 LT. The equinoctial asymmetry is therefore present throughout the day, very pronounced in the evening with greater TEC values in spring than in autumn. On **Figure 6(b)**, ΔTEV_solstice is negative for all day except between 05:00 LT and 07:00 LT. Positive values of ΔTEV_solstice indicate an absence of the winter anomaly; and negative values of ΔTEV_solstice indicate the presence of the winter anomaly. The winter anomaly is therefore present during the solstices except between 05:00 LT and 07:00 LT, and very pronounced in the morning.

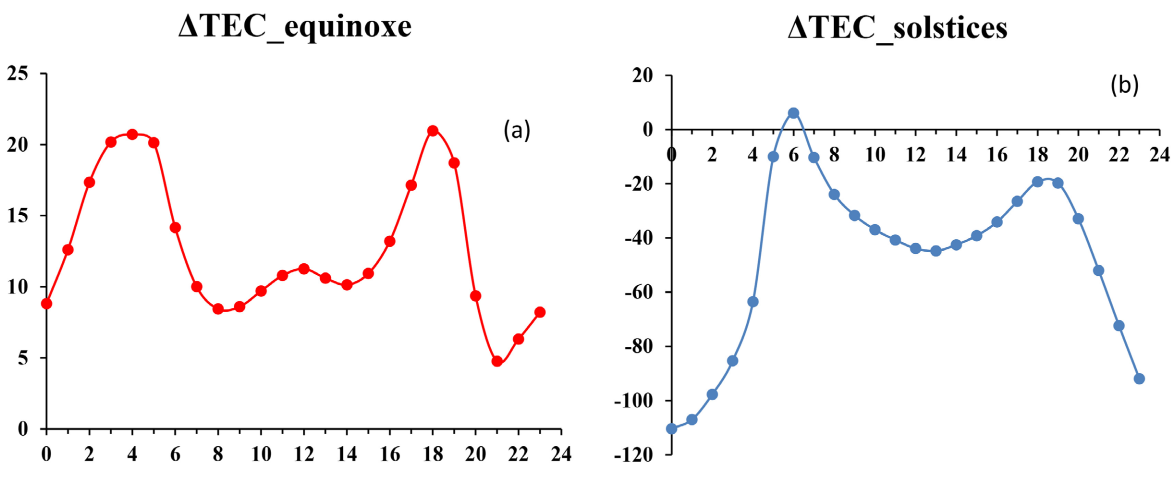

Figure 6. The relative difference between the months of equinox and solstice.

3.4. Variations of the TEC during Quiet and Recurrent Solar Activities

Figure 7 presents the variations of the TEC during quiet and recurrent activity. Panels a; b; c and d respectively present the diurnal variations of the TEC for quiet (in blue) and recurrent (in red) during winter, autumn, spring and summer.

From **Figures 7(a)-(c)** we can observe that the values of the TEC under recurring activity are higher than those under the quiet conditions during winter, spring and summer. However, the difference is very slight in spring between 06:00 LT and 09:00 LT and in summer between 00:00 LT and 07:00 LT; the two curves even tend to equalize between 07:00 UT and 12:00 UT. It is the same in summer between 01:00 LT and 09:00 LT. In autumn (**Figure 7(d)**), the two curves equalize between 00:00 LT and 07:00 LT. Between 07:00 LT and 18:00 LT the values of the TEC during the quiet period are higher than those of recurring period; and between 18:00 LT and 23:00 LT the TEC values during the recurring period are higher than those during the quiet period.

Similar to **Figure 6**, the **Figure 8** and **Figure 9** present the variations of the difference between the months of equinox (ΔTEV_equinox) and between the

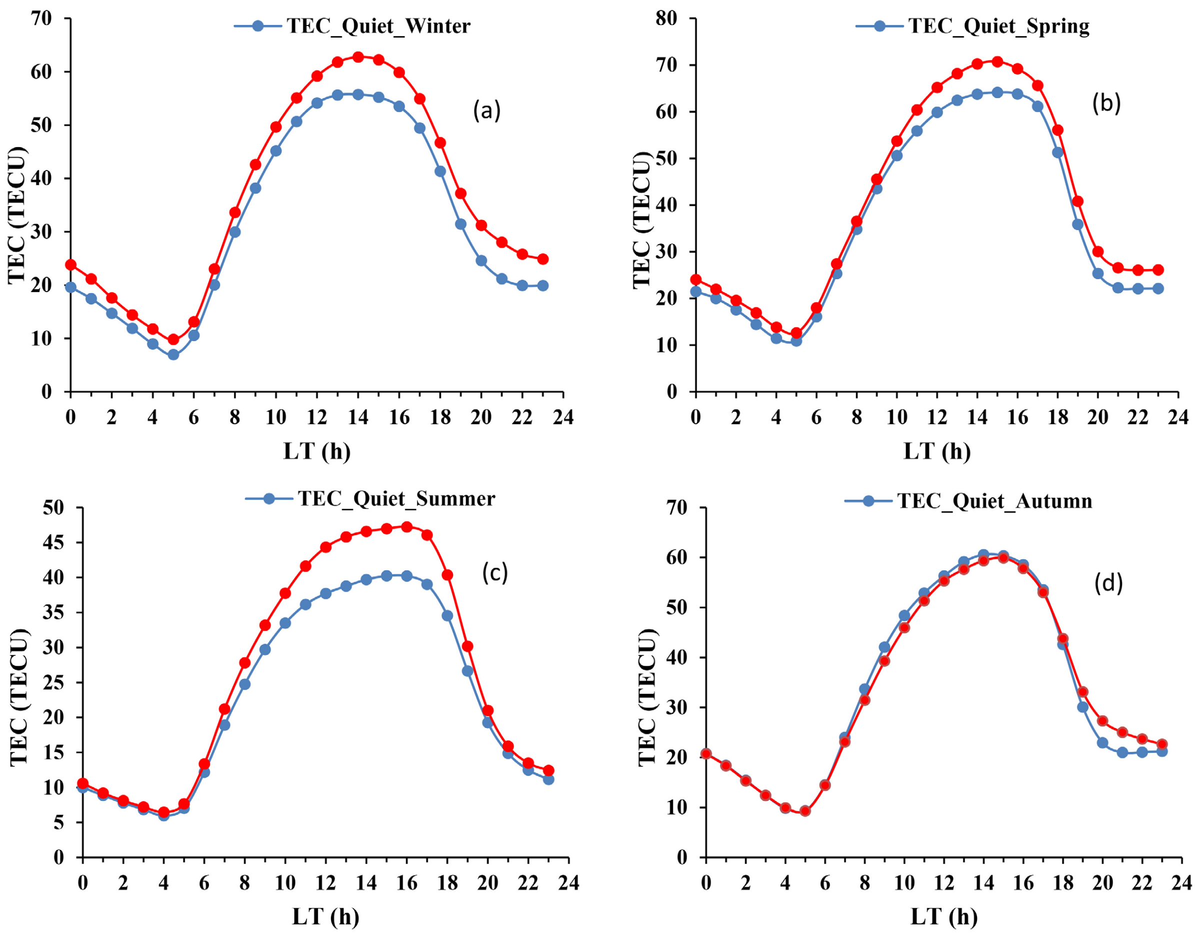

Figure 7. Diurnal variations of TEC during quiet and recurrent solar activity.

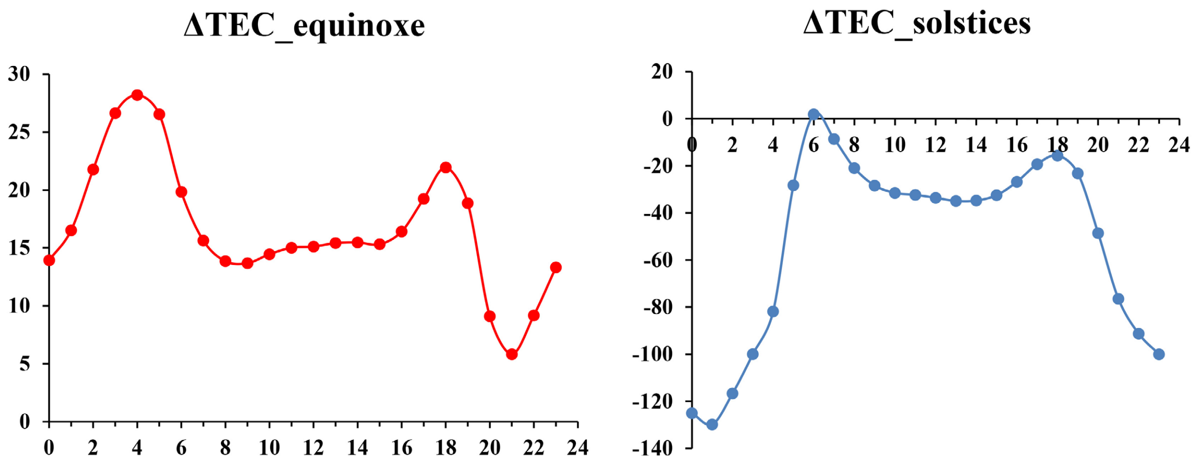

Figure 8. The relative differences of equinox and solstice during recurrent solar activity.

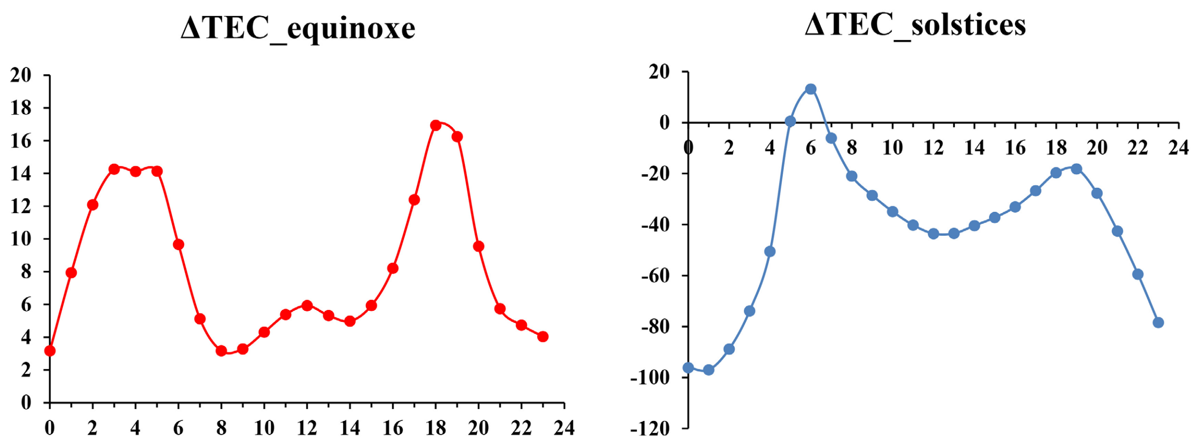

Figure 9. Relative difference of equinox and solstice during quiet solar activity.

months of solstice (ΔTEV_solstice). The two curves present similar variations and each curve shows two peaks separated by a cavity. During the equinox, the first peak is observed in the morning between 03:00 LT and 05:00 LT and the second peak at night at 18:00 LT. During the solstices, the first peak is observed at 06:00 LT and the second peak between 06:00 LT and 07:00 LT. The equinoctial asymmetry is present throughout the day whether during recurrent solar activity or quiet solar activity. However, it is more pronounced in the morning during recurrent activity and in the evening during quiet activity. During the solstices, ΔTEV_solstice is negative all days except between 05:00 LT and 07:00 LT.

The winter anomaly is therefore present during the solstices except between 05:00 LT and 07:00 LT, very pronounced in the morning.

An overview from Figure 8 and Figure 9 shows that the values of ΔTEV_equinox are larger during recurrent solar activity than during quiet solar activity; and the values of ΔTEV_solstice are very small during recurrent solar activity than during quiet solar activity. The recurrent activity therefore does not modify either the equinoctial asymmetry or the winter anomaly but accentuates them.

Figure 10 presents a comparison between the values of the TEC during the

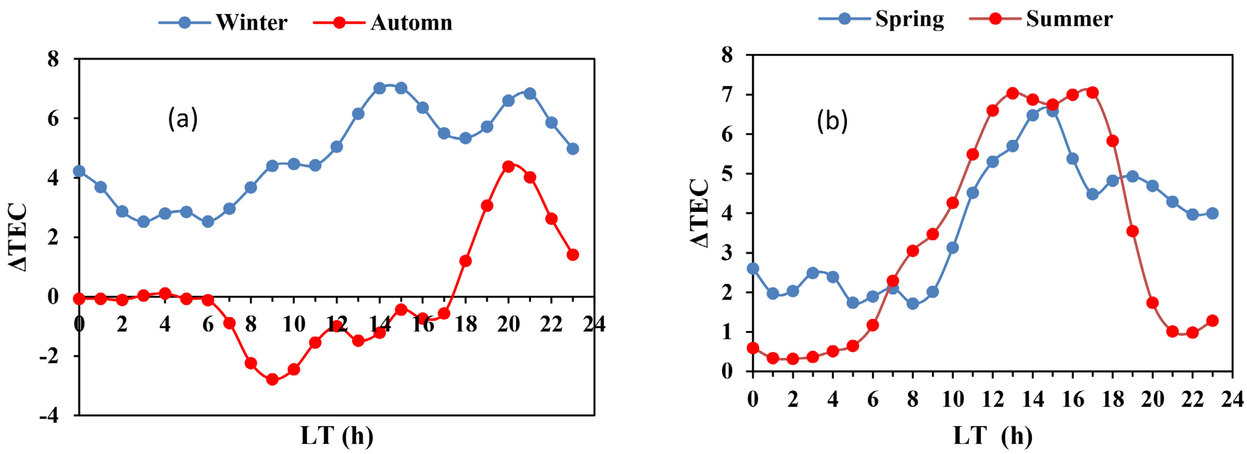

Figure 10. Variations de ΔTEC variations during autumn and winter (a) and during spring and summer (b).

recurring period and the quiet period. On Figure 10(a), the two ΔTEC curves evolve in opposite ways throughout the day except between 19:00 LT and 23:00 LT where the two curves behave similarly. In winter, ΔTEC generally shows an increasing trend with positive values throughout the day and shows two peaks respectively at 15:00 LT and 21:00 LT. In autumn ΔTEC oscillates between positive and negative values. The values are strictly negative from 04:00 LT to 18:00 LT and positive from 18:00 LT to 23:00 LT. On Figure 10(b), the two ΔTEC curves in summer and spring have a similar evolution between 08:00 LT and 17:00 LT and evolve in opposite ways between 00:00 LT and 08:00 LT as well as between 17:00 LT and 23:00 LT and each curve shows two peaks. In spring as well as in summer, all ΔTEC values are positive. The recurring activity therefore had more positive impact on the TEC during the different seasons except in autumn when it had a negative impact between 00:00 LT and 17:00 LT.

4. Conclusion

This study covers part of the ascending phase, the maximum and the descending phase of the 24 solar cycle. Our findings show that the TEC values go from a minimum in the early hours of the day to a diurnal maximum between 14:00 LT. and 16:00 LT before dropping at a minimum in the afternoon. This behavior of the TEC is strongly dependent on the variation of the intensity of the photoionization during the day. For all seasons, the values of TEC before midnight (18:00 LT to 23:00 LT) are higher than the values of TEC after midnight (00:00 LT to 05:00 LT) during all the years of our study. The maximum values of the TEC in 2014, 2015 and 2016 were recorded during the months of March and October, while in 2013 they were recorded during the months of April and November; corresponding to the months of equinox. From the monthly TEC and the sunspots number a linear dependence of the TEC and solar activity is highlighted. Moreover, the variations of the TEC show the presence of the equinoctial asymmetry whatever the season or whether we are in quiet or disturbed solar activity. The winter anomaly is also present during the day whatever the period of quiet or recurring solar activity except between 05:00 LT and 07:00 LT. Our investigation also shows positive impact of recurrent events on TEC.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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